A good opening:

the key to make the most of unilateral climate action

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Abstract

We examine the reaction of non-signatory countries to partial cooperation on climate change. Although free-riding incentives lead countries that do not participate in the environmental agreement to increase their emissions, under some conditions technology advancements within the coalition spill over to non-signatories and induce them to reduce, rather than increase, their emissions. We investigate these conditions analytically, using a Stackelberg game, and numerically, using a calibrated integrated assessment model. Results indicate that if a partial coalition, composed of OECD countries, cooperates to reduce their 2050 emissions between 30 and 35% below 2005 levels, the technology effect would prevail. This suggests that cooperating countries can strategically choose their unilateral climate objective so as to induce a virtuous behaviour in non-signatories countries. Interestingly, in the short-run these reductions are comparable with the Copenhagen pledges for Annex I countries. Conversely, had the OECD coalition embraced a more demanding target (e.g. 2050 emissions 50% below their 2005 levels), then the leakage effect would prevail and non-signatories would erode the coalition's environmental effectiveness. To mitigate the risk of carbon leakage associated with more ambitious targets, credible future commitments for developing countries could be set, as they would reduce lock-in in carbon intense technologies.

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1. Introduction

When dealing with a global externality, stable coalitions are generally small and unable to address the environmental problem they are designed for. This is a well-documented result in the literature, particularly within the non-cooperative theory of coalition formation (e.g. [3, 15, 16, 20]). On the one hand, the reduction of pollution by the coalition might be too small compared to the global discharge of the pollutant. On the other hand, the optimal reaction of non-signatory countries might be to pollute more compared to the case without the coalition, thus partially offsetting the coalition's effort.

The environmental effectiveness of a partial coalition aimed at reducing a global pollutant depends on the behaviour of both coalition members and non-signatories. In fact, the reaction of non-signatory countries shapes the incentives of members to remain in the coalition. A simplified approach often used in the literature assumes that players outside the coalition behave in the least-favourable manner [24]. However, this does not guarantee that their choice is optimal, and the members of the coalition might know that non-signatories do not find it profitable to behave in an extreme fashion. These shortcomings have motivated Chander and Tulkens [14] to define a type of response in which non-signatory counterparts react optimally to the equilibrium choice of the coalition. This implies that the solution of the pollution game is a Nash equilibrium between coalition members playing their best response to non-members, which individually adopt their best reply strategy. This is also the assumption shared by the experiments described in this paper.

The reaction of non-signatory countries becomes more complicated if cooperation generates multiple external effects on them. In the context of climate change, which is the example analysed throughout the paper, the optimal response of non-members to the coalition's strategy is a mix of at least three potentially opposing factors.

First of all, climate change is a global externality. The geographic distribution of the damages induced by the increase in global average temperature does not depend on the location of emission sources. Because green house gases (GHGs) become uniformly mixed in the atmosphere, climate change damages are a function of the total level of emissions. This feature creates an incentive to free ride. Emission reduction in one region lowers the damage perceived everywhere. As a consequence, the optimal response strategy in other regions is to emit more. We call this the "damage" effect. The resulting free-riding incentive very likely increases emissions outside the coalition.

Second, markets are globally integrated and price changes transmit the effect of unilateral GHG emission reduction to other countries. The reduced use of fossil fuels induced by climate policy lowers their prices on the international market. This gives non-cooperating countries an incentive to increase their demand, with positive effects on emissions [6, 19, 21]. Throughout the paper this effect is referred to as "energy market" effect. An additional channel of transmission is the international trade of energy-intensive goods. Facing higher energy costs, the competitiveness of these industries is reduced and production is reallocated to the countries without climate policy. Current literature describes this effect as either "pollution haven hypothesis" or as "terms-of-trade" effect.

How the energy market and the terms-of-trade effect 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. The Fourth Assessment Report [2] provides an overview of the studies that quantify the rate of carbon leakage under different assumptions. The range of estimates is very broad, from low values such as 2-6% obtained with the OECD GREEN model, the MIT-EPPA model, or the G-Cubed model to larger estimates such as 40% in Light et al. [23]. Babiker [1] finds a leakage rate of 130%, which means that unilateral mitigation increases global GHG emissions. The reason behind this result is the presence of increasing return to scale, strategic behaviour in the energy-intensive industry, and the assumption of a homogeneous product. When removing the assumption of economies of scale in industries characterised by imperfect competition, the rate of carbon leakage falls to 60%. When considering differentiated products the leakage rate is further reduced to 20%.

Burniaux and Oliveira Martins [11] analyse the determinants of carbon leakage and they conclude that the non-energy market mechanism and the degree of international capital mobility play only a minor role. The energy market channel is the most relevant. Inelastic energy supply curves, of coal in particular, can lead to very high leakage rates. They also highlight the importance of the production structure and of the substitution possibilities between different inputs and different fuels. Overall, they conclude that real world conditions and realistic values for the parameters used in integrated assessment models make the risk of significant carbon leakage unlikely. Along the same line, Barker et al. [2] argue that studies finding high leakage rates assume that climate policy has strong re-location effects on energy-intensive production. In practice, this is an unlikely outcome because countries adjust policies in order to avoid these effects, for example by exempting trade-exposed sectors[3]. Carbon leakage via the terms-of-trade effect can be expected to be limited because of transport costs, local market conditions, and other relocation costs. In a recent paper, Böhringer et al. [7] add evidence to the aforementioned considerations. They decompose carbon leakage into energy market and trade effects and show that leakage is predominantly driven by the international energy market effect.

Finally, climate policy stimulates innovation in the implementing countries and induce technical change. The virtuous behaviour of the coalition’s members might eventually lead to global diffusion of knowledge and of cleaner technologies to the point of lowering emissions in non-cooperating countries as well. Therefore, knowledge spillovers and technology transfers between signatory and non-signatory countries might have a negative effect on emissions, reverting the sign of carbon leakage . This is the “technology” effect.

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[3] For example, the EU decided to protect trade-exposed sectors by guaranteeing them a free allocation of allowances, see 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.

A number of papers rely on numerical models to quantify the size of the technology effect. Using bottom-up models of the energy sector, Barreto and Kypreos [5] and Barreto and Klaasen [4] show that technology spillovers can induce technical change and emission reduction outside the group of countries facing an emission constraint. Using a Computable General Equilibrium (CGE) model that links the energy sector to the rest of the general economy, Gerlagh and Kuik [17] estimate the rate of carbon leakage associated with the Kyoto Protocol and show that even for moderate levels of technology spillover, carbon leakage can become negative.

Other works identify the theoretical conditions under which a stronger environmental policy in one country might lead to lower emissions elsewhere [18]. Van der Werf and Di Maria [34], using a stylised model, show that, even without international spillovers, the presence of induced technical change can lower carbon leakage.

Hoel and de Zeeuw [22] highlight the trade-off between two competing effects, the innovation and the energy-market channels. When technical change can be directed to develop zero-carbon alternatives to fossil fuels, there are interactions that may eventually counteract the positive effect of technical change on emissions, such as the contraction of fossil fuel demand and the associated price reduction. 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 paper advances the existing literature by evaluating the consequences of incomplete cooperation when all three factors outlined above (the damage, the energy market, and the technology effect) compete with each other. To study the reaction of non-signatory countries and to identify the conditions for each effect to prevail, we introduce a stylised, two-region model and solve it as a Stackelberg game.

To describe the optimal reaction function under more realistic assumptions that cannot be treated analytically, we use an integrated assessment model. The WITCH model is a suitable tool for this type of analysis because it has a game-theoretic set-up. In addition, fossil fuel prices are endogenously influenced by the global use of exhaustible resources, and technical change endogenously accounts for both knowledge and experience international spillovers. In fact, the calibrated models that have been used to quantify carbon leakage share a number of limitations. Either they have a simplified treatment of innovation and technology diffusion or models that present a better technology detail, neglect the interdependency of the energy sector with the rest of the economy.

We explore the case of partial cooperation between OECD countries, a coalition that is interesting in several respects. To date, industrialised countries have been the leading innovators. Therefore, the OECD group might be the proper starting coalition, both in size and composition, to lead the technological transition towards lower carbon development pathways while creating the minimum condition to dynamically broaden the number of cooperating countries. The central question we investigate is whether the OECD coalition can set a target that triggers technological diffusion while keeping the negative “damage” and “energy market” effects under control. In other words, is there an “optimal” abatement effort that minimises carbon leakage?

Numerical results indicate that when the OECD coalition reduces emissions between 30 and 35% below 2005 levels, carbon leakage is negative, meaning that non-OECD respond to OECD abatement with lower emissions. For lower and higher abatement efforts, either abatement effort is not enough to trigger the technology effect or the damage and energy market effects are too large to be counteracted by innovation. We decompose the technology effect in two components, the knowledge and the learning-by-doing effects, and study which of the two plays a greater role. As expected, we find that the latter is more effective at fostering the diffusion of carbon-free alternatives outside the coalition, indicating the importance of policies promoting the diffusion of technology, even at very early stages. Although strengthening emission reduction efforts in the range of 40% below 2005 levels and above might actually reduce the overall environmental effectiveness of the coalition, the risk of leakage is significantly reduced if developing countries sign up for future credible commitments.

The remainder of the paper is organised as follows. Section 2 frames the problem using a stylised, two-region Stackelberg game and highlights the key mechanisms that underlie the subsequent analysis. Section 3 illustrates how the three different effects are accounted for in the numerical model WITCH and explores the case of partial cooperation among OECD countries. The robustness of results is tested across alternative model specifications and challenged through extensive sensitivity analysis. We finally analyse the issue of carbon leakage when the coalition dynamically expands from the group of OECD countries to eventually include developing countries. A discussion of results and their policy implications concludes the paper in Section 4.

2. Framing the Leader-Follower climate policy game

We begin with a stylised model where the world is divided in two regions: the climate policy leaders, Region 1, who enthusiastically adopt different forms of mitigation action in order to internalise the climate externality; the climate policy followers, Region 2, representing the rest of the world that does not participate in climate cooperation.

Both regions have a similar objective, to minimise the cost of producing a predetermined quantity of energy, $\bar{y}_i$, with i=1,2, given two alternative technologies: a polluting technology, based on fossil fuels, e_i, characterised by a unit cost C_e, and a clean, but initially more costly technology, b_i, with unit cost C_b. The cost of the polluting technology is bound to increase with its use because of fossil fuel exhaustibility. Hence C_e positively depends on the global stock of fossils used to fuel the polluting technology, E. In contrast, the cost of the clean technology, C_b, decreases with the global deployment of the clean technology, B, which is triggered by innovation. This technology is assumed to be fuelled by an infinitely available resource.

Region 1 could represent OECD countries. They cooperate and they internalise the social cost of carbon they perceive, D_1. Being the leader, Region 1 sets the optimal level of polluting and clean technologies, e_1 and b_1, knowing that the follower, Region 2, will choose the optimal reaction levels of e_2 and b_2 taking the leader's effect on technology costs, C_e and C_b, as given. The cost-minimisation problem for Region 1 (climate policy leader) is given by:

$$
\begin{aligned}
&\min_{e_1,b_1} c_1(E,B) = c_b(B)b_1 + c_e(E)e_1 + D_1(E) \\
&st \\
&\begin{cases} f(e_1,b_1) = y_1 \geq \bar{y}_1 \\ e_2 = \arg\min c_2(E,B) \end{cases}
\end{aligned}
\tag{1}
$$

The cost-minimisation problem for Region 2 is given by:

$$
\begin{aligned}
&\min_{e_2,b_2} c_2(E,B) = c_b(B)b_2 + c_e(E)e_2 + D_2(E) \\
&st \\
&f(e_2,b_2) = y_2 \geq \bar{y}_2 \\
&\\
&\text{where} \\
&B = b_1 + b_2 \\
&E = e_1 + e_2
\end{aligned}
\tag{2}
$$

The following conditions on the cost functions hold:

$$
\frac{\partial c_b(B)}{\partial b_i} < 0, \frac{\partial c_e(E)}{\partial e_i} > 0, \frac{\partial^2 c_b(B)}{\partial b^2{}_i} \geq 0, \frac{\partial^2 c_e(E)}{\partial e^2{}_i} \geq 0, \frac{\partial c_b(B)}{\partial b_j} < 0, \frac{\partial c_e(E)}{\partial e_j} > 0, \frac{\partial^2 c_b(B)}{\partial b^2{}_j} \geq 0, \frac{\partial^2 c_e(E)}{\partial e^2{}_j} \geq 0
$$

The positive relationship between the cost of the polluting option, $C_{e,}$ and emissions captures the energy market effect, whereas the negative relationship between the cost of the clean option C_b and global technology deployment accounts for the technology effect. While Region 1 internalises the total damage of the coalition, countries in Region 2 see only their own individual damage.. For this reason, we start by assuming that the social cost of carbon in Region 2 is negligible. We will relax this assumption in Section 4, where we will investigate the extent of the damage effect in the free-riding regions using a numerical model.

The choice variable of both players is the amount of each type of technology. The game can thus be characterised as competition on quantity where Region 1 plays the role of quantity leader. When making her decision, the leader is aware of her influence on technology costs and, as a consequence, on the follower's reaction. In other words, she will choose the cost-minimising point on the follower's reaction function. In turn, the follower will take leader's technological choice as fixed and select the cost minimising combination of technologies, given the predetermined relative cost of the two technologies.

The question of interest is whether the reaction of the follower will lead to positive or negative carbon leakage. This depends on her technological choice to produce the minimum amount of energy. In fact, the sign of Region 2's reaction function can be directly related to the shape of the technology cost functions and their relative slopes. In order to characterise the reaction function of Region 2, f'_2, we solve Region 2's First- and Second-Order Conditions (details can be found in Appendix I). Differentiating the First Order Condition with respect to leader's emissions, e_1, the reaction of the follower (Region 2) is given by the following expression:

$$f'_2(e_1) \equiv \frac{\partial e_2}{\partial e_1} \equiv -\frac{\dfrac{\partial^2 c_2(e_1, f_2(e_1))}{\partial e_2 \partial e_1}}{\dfrac{\partial^2 c_2(e_1, f_2(e_1))}{\partial^2 e_2}} \qquad (3)$$

Because the sign of the denominator is determined by the Second-Order Condition (which is positive), the sign of the reaction function depends on that of the second mixed derivative at the numerator. When the reaction function, f'_2, is positive, Region 2 responds to a more stringent abatement level chosen by the OECD region in a proactive way by reducing emissions itself. When the reaction function is negative, Regions 2 free rides and its optimal reaction is to pollute more.

Whether the clean technology is adopted in Region 2 solely depends on the relative cost of the two technologies because the follower does not give any consideration to the social cost of carbon. Conversely, the leader will base her optimal strategies considering i) the social cost of carbon, $\frac{\partial D_1(E)}{\partial e_1}$; ii) the perverse effect decreasing fossil fuel consumption has on the follower's emissions via the cost effect, $\frac{\partial c_e(E)}{\partial e_1} > 0$; iii) the potential of making the clean option attractive elsewhere by investing in the clean technology, $\frac{\partial c_b(B)}{\partial b_1} < 0$. The leader's first order condition describes the trade-off between the two technology cost effects:

$$\begin{aligned} &\frac{\partial C_1(E,B)}{\partial e_1} \equiv \frac{\partial c_b(B)}{\partial e_1} b_1 + c_b(B)\frac{\partial b_1}{\partial e_1} + \frac{\partial c_e(E)}{\partial e_1} e_1 + c_e(E) + \frac{\partial D_1(E)}{\partial e_1} \\ &\text{where} \\ &E = e_1 + e_2 \\ &e_2 = f_2(e_1) = f(c_b, c_e) \end{aligned} \tag{4}$$

Below we discuss the reaction function of Region 2 under alternative functional forms describing technologies' costs. Appendix I contains the analytical derivation of the three cases here discussed and Table A1 summarises the various cases. We assume identical cost functions in different regions. More realistic assumptions on heterogeneous cost functions will be considered in Section 3.

Because the total amount of energy, $\overline{y}_i$, is given, we can simplify the minimisation problem by expressing the clean technology b_i as a function of the polluting option e_i, $b_i = g_i(\overline{y}_i, e_i)$ with $\frac{\partial g_i}{\partial e_i} = g'_i < 0$. The simplest case is that of perfect substitution between the two sources of energy, $b_i = \bar{y}_i - e_i$. When Region 1 internalises the climate externality, emissions are reduced by linearly substituting the dirty technology with the clean one[4], (first row and third column in Table A1),. Region 2's reaction is proactive if, as the overall amount of the dirty input demanded by Region 1

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[4] Because the total amount of energy used is fixed, we abstract implicitly from energy saving options. This assumption will also be dropped in the subsequent sections (Section 4).

diminishes, the cost of the clean technology declines faster than that of the fossil-fuel-based technology. This occurs when the marginal cost of the clean option is greater than that of the polluting technology, provided the initial price gap between the two options is not too large, $(C_b - C_e < (C'_b - C'_e)e_2)$. When relaxing the perfect substitution assumption (first row and second column in Table A1), the reasoning remains very similar, but the degree of substitutability between the two technologies also plays a role. In the case of perfect substitutes $g_2' = -1$ the two energy sources are in a one to one relationship. When $g_2' < -1$, a reduction in the polluting source must be compensated by a more than proportional increase in the clean technology (i.e. greater than one). When $g_2' > -1$, a reduction in the polluting source must be compensated by a less than proportional increase in the clean technology (i.e. less than one). This suggests that when the two sources can be easily substituted ($g_2' < -1$), then the condition on the marginal cost, $(-g_2' C_b > C_e)$ is less demanding. When the marginal cost of the fossil-fuelled technology is greater than the clean one, the cost of the fossil-fuelled technology responds quicker to a contraction of fossil fuels consumption, $(-g_2' C_b < C_e)$. This prevents the diffusion of the clean technology into Region 2, where it remains optimal to rely on the traditional technology, making the sign of the reaction function negative.[5]

When removing the linearity assumption on cost functions (second row in Table A1), a positive reaction function requires that the gap between the first derivatives is not only positive, as in the linear case, but sufficiently large. By how much is determined by the difference in the second derivatives of the technology's marginal costs. If the effect of emissions on the marginal cost of the clean option is greater than that on the dirty substitute and the overall amount of energy used in Region 2 ($\bar{y}_2$) is sufficiently low, then the technology option is likely to penetrate also in Region 2,

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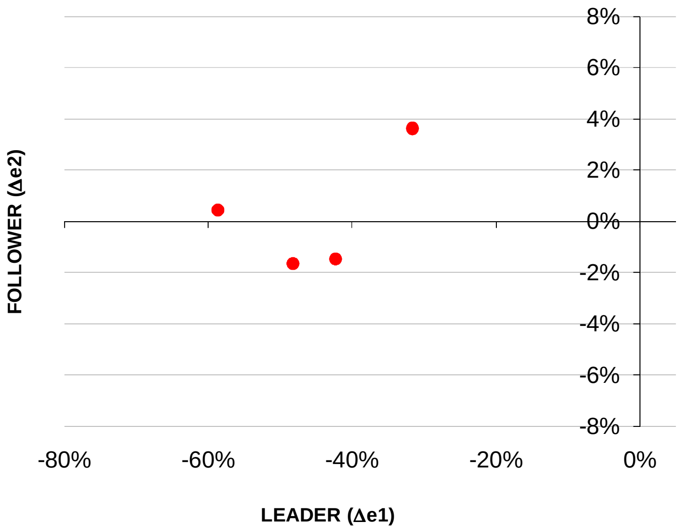
[5] A trivial case is when the cost functions are parallel (identical first and second order derivative), the free-riding incentive always prevails and the sign of the reaction function is negative (provided the initial cost of the dirty technology is lower). The initial price gap persists over time and the cost of the clean technology can never be reduced to the level of the polluting substitute.

driven by the initially high returns on innovation, $C''_b\,\bar{y}_2 + (C''_e - C''_b)e_2 < C'_b - C'_e$. As the clean technology penetrates, the effect of emission reduction on marginal cost is reduced. The intuition is that the technology effect tends to prevail when i) returns on clean technology innovation are sufficiently high and ii) the overall amount of energy used in Region 2 is sufficiently low.

Under these more general assumptions, the best response of Region 2 does not need to be monotonic, but it might change signs, depending on the interaction between energy market and technology effects, which are ultimately driven by the effort undertaken by Region 1. This situation is exemplified in the double-crossing case (last row in Table A1). Consider the case in which Region 1 undertakes a moderate level of abatement dictated by a low social cost of carbon, $e_1 > \underline{e}_1$. In this situation, most energy would still be produced using the fossil-fuelled technology, and the effect on innovation would be minimal. As the social cost of carbon increases and the cost of the clean technology responds to its deployment fast enough, provided the price elasticity of fossil fuels is sufficiently low, $C_e' < C_b'$, then the clean technology beats the polluting one even in Region 2. However, high returns on innovation might be exhausted quickly or constraints on the penetration of the clean technology might appear. Hence, as the social cost of carbon in Region 1 increases or the target is set at a very low level, $e_1 < \underline{e}_1$, the contraction of fossil fuels demand, is likely to prevail again and the marginal cost reduction for the fossil-fuelled technology is larger than that of the clean technology, $C_e' > C_b'$. There is a window of abatement levels within which the clean technology becomes competitive also in Region 2. Outside that window the energy market effect dominates the technology one and thus the polluting technology emerges as a better alternative.

In Figure 1 we represent the case of the U-shaped reaction function just described. On the x-axis we represent the reduction in emissions (fossil-fuelled technology) in the leader group, while on the y-axis is reported the reduction/increase in emissions in the follower group. When abatement in Region 1 is low, innovation is not sufficient to make the clean technology competitive in Region 2 as well. For moderate emission reduction levels, the technology effect dominates the price reduction induced by the lower demand of fossil fuels. As abatement becomes very ambitious, the latter effect becomes predominant and the polluting technology becomes once again more competitive. As a consequence, the reaction function switches signs depending on the level of abatement chosen by Region 1.

Figure: 1 Example 2. A U-shaped reaction function.



Because the leader internalises the follower's reaction, she can exploit her position and chose the technology combination that minimises her adverse reaction, which enters the leader cost objective function through the damage component, $\frac{\partial D_1(E)}{\partial e_2} > 0$ and the clean technology cost, $\frac{\partial c_b(B)}{\partial b_1} < 0$. This section has discussed how, under a set of simplifying assumptions, the sign of the reaction function can be related to the relative marginal costs of the two competing technologies and to their respective sensitiveness to emission reduction. We have underlined the role of two competing forces, the energy market and the technology one, whose strength depends on the level of technology deployment, the relative initial costs and the reaction to changes in capacity installed, the substitutability between the two technologies, and on the optimal level of abatement. The next section examines how these basic mechanisms interact when several of the simplifying assumptions made until now are dropped. To this end, we introduce an integrated assessment model that provides a more realistic representation of the macroeconomic and environmental relationships among countries, including economic, technology, and climate change externalities.

3. Framing the Leader-Follower climate policy game using the WITCH model

WITCH [9,10] is a dynamic optimal growth model fully integrated with a bottom-up structure of the energy sector. In this section we provide an intuitive description of the model and we refer the reader to Appendix II for a detailed account of model equations.

The model has a game-theoretic set-up that accounts for different levels of cooperation among the twelve regions, which represent the players of the game. The model is solved as a one-shot meta-game. In the first stage countries decide on their participation and coalitions are formed. In the second stage countries choose their optimal investments and emission levels depending on whether they are part of a partial or global agreement or reacting as singletons. Both simultaneous and sequential games can be modelled. Coalition members maximise aggregate joint welfare, whereas non-participants behave as singletons and maximise individual welfare. The game is solved backwards. Climate change damage as well as energy markets and innovation externalities are fully accounted for. The model is fully intertemporal and, although we drop the time dimension in the description below for simplicity, all stock variables are characterised by cinematic equations and the optimisation of each region planner is throughout the entire time horizon, as shown in Appendix II.

The WITCH model includes a carbon cycle and a climate module. Climate change impacts on Gross Domestic Product (GDP) can be either positive or negative, depending on regional vulnerability and geographic location. For each of the twelve WITCH regions[6], *i*, climate change damage, D_i, is a reduced-form function of mean global temperature increase above pre-industrial levels and ultimately depends on global emissions (*E*)[7]:

$$
\begin{aligned}
&D_i = d_i(E) \\
&E = e_1 + e_2 + \ldots + e_n \qquad (5) \\
&\frac{\partial d_i(E)}{\partial E} > 0
\end{aligned}
$$

Technological advances within the energy sector are endogenous processes driven by innovation and deployment. R&D investments lead to incremental innovations that advance the performance of existing technologies, determining improved energy efficiency. They can also result in radical innovations that lead to the introduction and diffusion of breakthrough technologies (Learning-By-Researching).

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

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[6] The WITCH model divided the global economy into twelve macroeconomic regions: 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).

[7] The reduced-form damage function used in the WITCH model follows the specification introduced by Nordhaus and Boyer [29b]. This paper uses a higher damage function that has been extrapolated from the IPCC ranges reported in UNFCCC [33]. The WITCH high damage function follows UNFCCC data quite closely until a 1.5°C rise in global temperature, and increases more sharply beyond, moving closer to – but remaining lower than –Stern's [29] estimates. A deeper discussion on the damage function can be found in OECD (2009), "The Incentives to Participate in and the Stability of International Climate Coalitions: A Game-Theoretic Approach Using the WITCH Model", OECD Economics Department Working Papers, No. 702, OECD publishing, © OECD. doi:10.1787/223552487415

$$H_i = h(I)$$
$$I = i_1 + i_2 + \ldots + i_n \tag{6}$$
$$\frac{\partial h(I)}{\partial I} > 0$$

The contribution of the foreign stock to the creation of domestic knowledge depends on the absorptive capacity and the distance from the technology frontier, which is represented by the stock of knowledge accumulated in OECD countries. Learning-By-Doing effects reduce the costs of deployed technologies worldwide, triggering technology diffusion also outside the group of innovating countries. To capture both Learning-By-Researching and Learning-By-Doing effects, regional investments costs of the clean technologies ($C_{b,}$) decline with the global investments in innovation (*I*) and global installed capacity (*B*)[8]:

$$C_b = c_b(B, I)$$
$$B = b_1 + b_2 + \ldots + b_n \tag{7}$$
$$\frac{\partial c_b(B,I)}{\partial I} \leq 0; \frac{\partial c_b(B,I)}{\partial B} < 0$$

In the case of mature, already patented technologies, we assume the marginal effect of innovation is zero, $\frac{\partial c_b(B,I)}{\partial I} = 0$.

The markets of fossil fuels are internationally integrated. The cost of the fossil-fuelled technologies in each region, C_e, depends on the global demand (*E*), ultimately determined by the use of exhaustible resources in every world region[9]:

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[8] For simplicity we cluster clean and polluting technologies into two groups. However, the model includes a portfolio of clean and dirty options, see Appendix 2. For a thorough description of how technology spillovers and technological change of equations (3) and (4) are treated in the WITCH model see Bosetti et al [9, 10].

[9] See Bosetti et al [8,9] for a detailed description of how exhaustible resources and extraction costs are modelled in the WITCH model.

$$
\begin{aligned}
&C_e = c_e(E) \\
&E = e_1 + e_1 + \ldots e_n \qquad (8) \\
&\frac{\partial c_e(E)}{\partial E} > 0
\end{aligned}
$$

The cost increases with global demand to reflect resource scarcity. The WITCH model does not include international trade and international capital flows, and therefore terms-of-trade effects are not considered. However, as discussed in the introduction, most of the literature confirms that carbon leakage takes place mainly through the international energy market effect [2,7], which is fully modelled.

As in the simple set-up presented in the previous section, the decision of a sub-group of countries to cooperate on climate change affects the strategic behaviour of both members and non-members. Non-signatories' emissions can be either lower, equal or higher compared to the non-cooperative baseline, when no climate agreement is in place. As a rule of thumb, coalitions that undertake a thorough decarbonisation of the economy (either because they include many players, because the marginal damage of the coalition is large, or because they choose a very stringent target) lead to a stronger energy market effect. In contrast, smaller or less environmentally active coalitions might see the technology effect prevail. The size of the technology effect depends not only on the reduction target but also on the nature of the decarbonisation pathway followed by the coalition and on the efficiency of the innovation process.

In addition, we can also analyse energy-saving behaviours and how they impact the technology effect. In particular, the more efficient the coalition is, the larger the need to introduce alternatives and expand the deployment of zero-carbon technologies to meet a given target. This is the case of the coalition considered in the next section, composed of OECD countries. Its average energy-output ratio is already low and therefore it requires significant technology transformation even for modest emission reduction targets.

The next section explores the issue of carbon leakage when OECD countries play the role of climate leaders and choose the optimal level of pollution, knowing that non-OECD countries (follower region) will react optimally as in a Stackelberg game.

3.1 The Stackelberg solution

Optimal abatement should be substantiated by a cost-benefit evaluation of the costs and benefits associated with emission reduction. However, this requires the very difficult task of balancing near-term, certain abatement costs with long-term, uncertain benefits. Indeed, the choice of the optimal policy goal contains controversies because the cost-benefit 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 [7] and Tol [32][10], on the one hand, and Stern [31] on the other hand well clarifies the importance of these assumptions. The debate is still open on whether any discounting at all should be associated with very long-term normative analysis, as it is ethically hard to justify that the present generation should get a greater slice of the cake, but for the fact that future generations might not be there. In this sense, discounting would weight the likelihood of human extinction.

In this paper we start by taking a normative perspective and perform the analysis by assuming a pure rate of time preference of 0.1%[11]. We then investigate the effect of a higher discount rate, 3%, and show how this has major effects on innovation strategies.

As far as damage is concerned, the central case that we analyse in the following pages assumes damage estimates in the mid, high range between UNFCCC's estimates [33] and the values proposed in the Stern Review[12].

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[10] Similar results are shared by Manne and Richels [25], Mendelsohn et al. [26] and Pearce [30].

[11] We did not adjust the curvature of the utility function to reflect the lower pure rate of time preference and to keep the interest unchanged according to the Ramsey rule. As shown in Nordhaus [28], lowering the pure rate of time preference and adjusting accordingly the curvature of the utility function leads to a result that is basically unchanged from that based on the original parameter value. Instead, we base the experiment on an interest rate that is exceptionally low, following a normative approach, to observe the effects and compare them with experiments based on a higher pure rate of time preference. The next section will analyse how myopic behaviour, modelled with a higher discounting, affects the results.

This starting set of assumption implies, in the absence of climate cooperation, a baseline global average temperature increase of 3.4 °C above pre-industrial levels in 2100, leading to a global climate damage in 2100 that is equal to a 7% loss of Gross World Product (GWP).

Given this specific set of assumptions and postulating that OECD countries agree to cooperate on the climate change externality, the optimal abatement path for the OECD coalition entails initially moderate emission cuts, while effort increases over time. Following their cost-benefit rationale, OECD countries would abide by a 32% CO2 (34% CO2-eq) emission cut with respect to 2005 emissions in 2050. In absolute levels this corresponds to an emission reduction of 4.5 GtCO2 (5.6 GtCO2-eq) compared to 2005, from 13.8 to 9.4 GtCO2 (from 16.5 to 10.8 GtCO2-eq). Short-run emission reductions fall in the range of the Copenhagen pledges for Annex I countries. The optimal path requires a 2020 emission reduction of 2% compared to 2005, increasing to 7% and 14% in 2025 and 2030, respectively. Annex I conditional pledges have been estimated to lead to a 2020 reduction between 0% and 14.3%, with a median value between 1% and 12.5%, depending on the assumptions on LULUCF accounting and the use of surplus emissions units[13].

Figure 2 shows the OECD optimal abatement path along with the optimal reaction of non-OECD countries. The non-OECD reaction function is positive and its optimal emission path is slightly below baseline. However, giving the growing share of non-OECD emissions, their emission path throughout the century is nearly unchanged compared to baseline.

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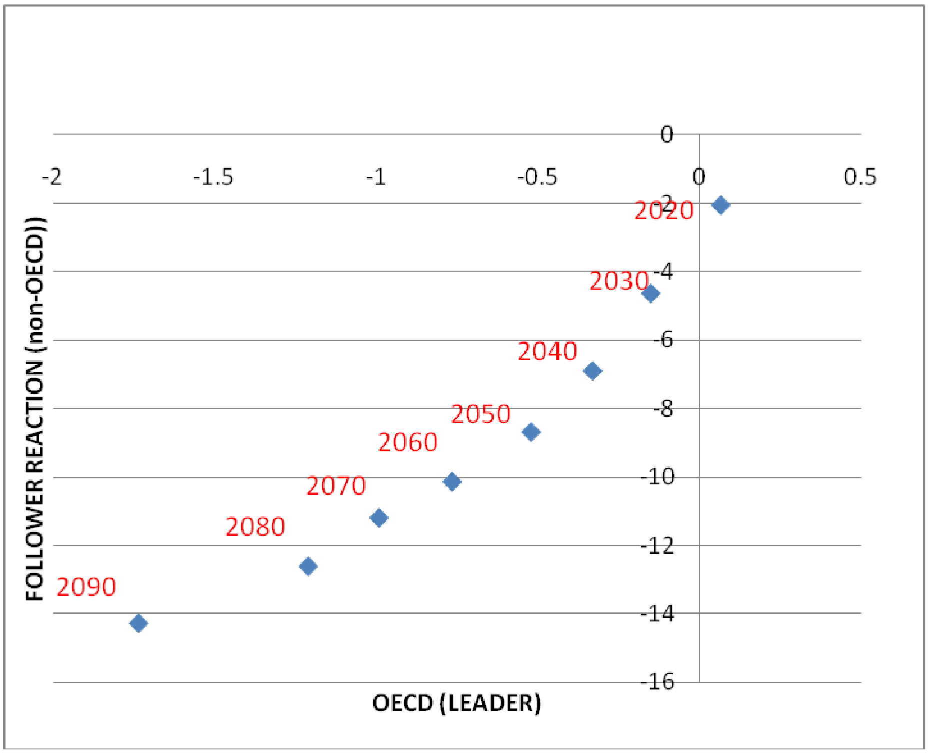
[12] The chosen damage and a pure rate of time preference are such that global cooperation results in the 2.5°C degree target.

[13] These are the estimates presented in the UNEP Assessment “The Emission Gap Report” which reviewed the assessment of the Copenhagen Pledges made by thirteen different models. The report, containing a detailed description of the assumptions made in the different cases, is available at http://www.unep.org/publications/ebooks/emissionsgapreport/

Figure 2: Optimal CO2 emission reductions in OECD countries and optimal reaction of non-OECD countries, through time. GtonCO2 difference of energy-related CO2 emissions compared to non-cooperative baseline (BaU)



The reaction function is positive showing that, over time, the technology channel dominates the damage and energy market effects. These results indicate that, even though non-signatories could free ride on the emission reduction commitment of the OECD, they do not have an incentive to do so.

This is a combination of different factors. First, most damages occur in non-OECD countries and they are not internalised by the OECD coalition, which perceives a modest social cost of carbon. To give some perspective, global emissions resulting from the OECD coalition effort are far above any stabilisation path, and GHG concentration in 2100 is only 80ppme less than in the non-cooperative baseline. Global mean temperature in 2100 increases up to 3.2 °C, as opposed to the 3.4°C. This implies that the benefits from cooperation are very small, dwarfing the incentive to free ride on the total damage reduction.

In addition, when abatement is moderate, the influence on international fuel prices is also contained. The international price of oil is at most 34%[14] lower compared to the case without global cooperation and such reduction is not sufficient to induce a rebound effect in non-constrained countries.

In contrast, the innovation effort of the coalition induces a reduction in the costs of the clean alternatives also elsewhere. OECD countries increase their expenditure in clean energy R&D, from the current 0.05% of their GDP up to 0.24%. These investments bring down the costs of breakthrough technologies, which are deployed first in OECD and, with a time lag, in non-OECD countries as well. As discussed in Section 3, the size of the technology effect depends on the nature of the decarbonisation pathway followed by the coalition. Because OECD energy-output ratio is already low, even modest emission reduction requires new technologies. In addition, OECD countries represent the technology frontier, at least today, and most R&D expenditure occurs there. They are a major source of knowledge and technology spillovers, stimulating a cleaner technological development also outside the coalition. Finally, if the OECD coalition factors in all spillovers and the effect they have on the reaction of non-signatory countries, then it has a further incentive to choose a moderate level of abatement. As this conclusion is the result of a numerical model, it is crucial to test its robustness to changes in all key parameters controlling the described effects, which is what is laid out in the remaining sections.

3.2 Sensitivity to three different factors

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[14] The oil price reduction increases with the level of abatement and it reaches the highest reduction of 34% in 2100.

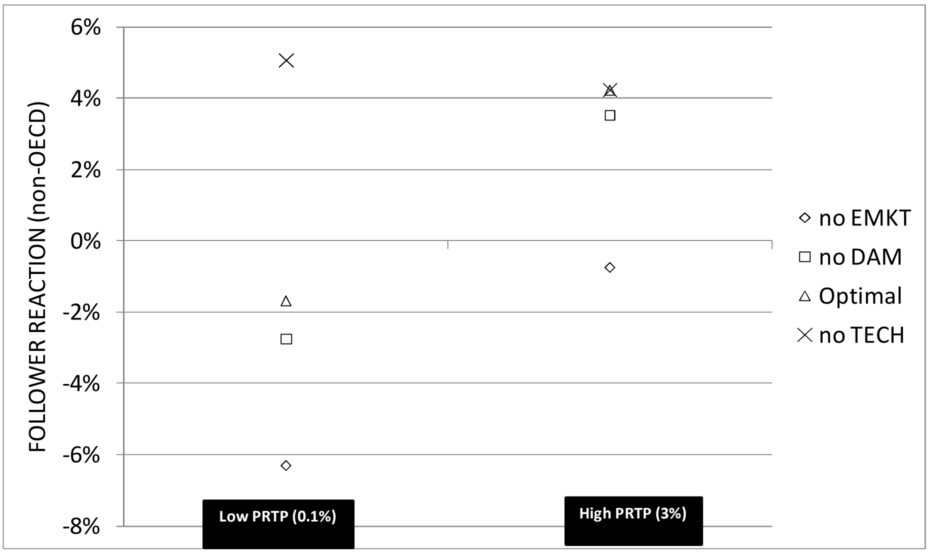
The previous Section illustrated how the damage, energy market, and technology effects play out in shaping technology cost functions and thus the optimal response of non-signatory countries. In this Section we disentangle the magnitude and the direction of each of these three factors. To this end, we compare the optimal solution analysed in the previous section with three hypothetical scenarios in which any of the three mechanisms is turned off.

The first of these variations assumes that knowledge and Learning-By-Doing effects are completely excludable and kept within the coalition. To model this we assume that non-signatories cannot reap any of the innovation advancements induced by the OECD climate agreement. We refer to this case as the “no TECHNOLOGY effect” 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 that of the non-cooperative baseline level. We refer to this second case as the “no ENERGY MARKET effect” case. Third, we assume that the mitigation of the temperature increase resulting from the action undertaken in OECD countries can be excludable and that non-OECD countries continue to face a temperature increase as in the non-cooperative baseline. We refer to this final case as the “no DAMAGE effect” case.

Figure 3 reports the resulting change in non-OECD emissions with respect to the non-cooperative baseline for the three scenarios (no TECHNOLOGY, no ENERGY-MARKET and no-DAMAGE cases) and the case where all three effects are in place (which we name Optimal case). Results are shown for high and low discounting. We first concentrate on the case analysed in the previous sub-section (left markers in Figure 4), which assumes a low pure rate of time preference (i.e. 0.1%).

The different reaction function in the three cases helps to understand the link between each mechanism and the cost profile of the two technologies, the fossil-fuelled option and the clean substitute. When the technology effect is turned off, the cost of the clean technology in non-OECD countries is unaffected by the virtuous behaviour of OECD countries. Therefore, non-signatories’ emissions are higher than they would be in the non-cooperative baseline, as lower fuel prices and free-riding incentives coming from lower temperature are not counterbalanced by clean innovation. This is the “no TECH” case. When the technology effect is silenced, the sign of carbon leakage flips. Conversely, ruling out the energy market effect implies that in non-signatory countries the cost of the fossil-fuel-based technology does not decrease when OECD countries reduce their demand, while the cost of the clean technology benefits from technology spillovers and diffusion. As a consequence, the marginal cost of the clean option falls below that of the polluting technology, unaffected by the coalition action, leading to a contraction of non-OECD countries’ emissions. When non-OECD countries are excluded from DAMAGE benefits due to the OECD’s action, the perceived temperature slightly increases returns on energy efficient and clean investments in non-OECD countries. However, the relative incentive to adopt the clean and polluting technology does not change as significantly as in the no ENERGY MARKET case and therefore the effect of this mechanism is smaller.

Figure 3: Cumulative CO2 emissions (2010-2100) in non-OECD countries when reacting to the optimal abatement in OECD countries. Low (0.1%) and high (3%) pure rate of time preference (PRTP)



If we perform the same analysis but now assuming a higher pure rate of time preference (3%, right markers in Figure 3) the direction of each effect does not change, but the magnitude differs. In order to keep our focus on the non-signatories reaction we assume the OECD are constrained to the same amount of abatement as in the optimal case. This now leads to a very different result. High discounting significantly shortens the time horizon of the social planner and every benefit and damage occurring after 2050 is almost irrelevant for cost-benefit considerations. Because damages increase exponentially and technology benefits also take time to materialise, both the damage and the technology effects lose significance when the pure rate of time preference is 3%.This is true in both regions. In particular, OECD countries meet their goal adopting a different strategy. As they invest less in innovation, future benefits of present investments in advanced technologies are not fully perceived and this reduces the incentive to undertake risky investments, while spending more later in direct mitigation. This effect together with more myopic investment strategies of the non-signatories group and the more immediate energy market effect lead to positive carbon leakage. It is only excluding the latter effect completely that we can again reverse the sign of carbon leakage. Had we also considered the effect of a higher discount rate on the OECD countries optimal emission, we would have seen an even stronger upward shift in the follower reaction as the lower abatement objective in the coalition dilutes the innovation effort even more, resulting in weaker spillovers.

Our numerical model explicitly distinguishes between knowledge and technology diffusion, in the form of Learning-By-Doing effects. Therefore we can go a step forward and explore the relative contribution of each of these two mechanisms. To this end, we consider two additional variations. First, we assume that only knowledge investments are completely excludable. This affects the timing required for clean technologies to become competitive while allowing low carbon technologies that are either invented or improved in OECD countries to diffuse freely outside the coalition by means of technology transfers. 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 “no LEARNING-BY-RESEARCHING” case. In the second case, there can be knowledge spillovers, but non-OECD countries do not have access to the improvement in cost due to learning-by-doing effects following the breakthrough and due to the technology adoption in OECD countries. We refer to this case as the “no LEARNING-BY-DOING” case.

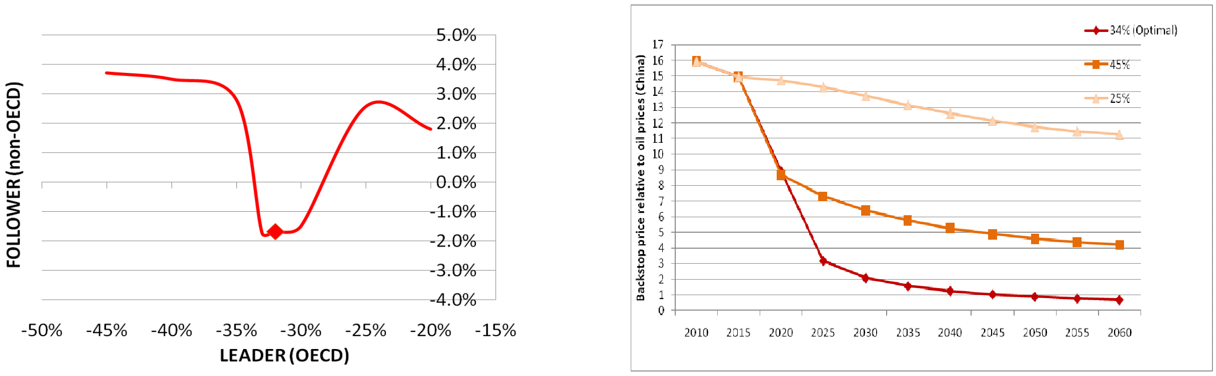
Results indicate that the major vehicle of the technology effect is Learning-By-Doing. The contribution to emission reduction in non-OECD is larger when only the LBD channel is active (“no LEARNING-BY-RESEARCHING” case). The benefits of early cost improvements following the breakthrough are more effective at fostering adoption than the knowledge spillovers preceding the breakthrough. Indeed, the former effect does not require a minimum absorptive capacity. Conversely, before translating into emission reduction, knowledge spillovers need to be embodied into new innovations and new technologies and this is a process that requires a pre-existing knowledge stock and indigenous inventive capacity. Once embedded in final products or processes, technology diffusion is instead more immediate. Therefore, learning-by-doing effects are less demanding in terms of domestic knowledge capacity [13]. However, it is important to stress that the model does not consider other barriers that could hinder technology adoption such as institutions, governance or access to financial markets, and the fact that in some countries technology adaptation might be needed to make the imported technology suitable to the local context.

3.3 Sensitivity to different reduction commitments in OECD countries

The previous Section showed that when the technology effect is taken into account, partial cooperation on emission reduction does not necessarily lead to carbon leakage, provided economic agents are sufficiently forward-looking and do not apply a too high discount rate. The follower's best response can be either positive or negative depending on the interaction between the damage, energy market, and the technology effects. In turn, the influence of each of these factors ultimately depends on the effort undertaken by, and the nature of, the coalition. In this Section we keep our focus on the OECD coalition and we analyse how the proactive reaction of non-OECD countries varies with the stringency of the emission objective of the coalition. This exercise identifies a window of emission reduction targets in 2050 that triggers proactive behaviour in non-signatory countries. We analyse 2050 targets ranging from 20% to 50% emission reduction compared to 2005.

Figure 4, left panel, shows non-OECD cumulative emissions in reaction to different OECD targets, a response function which brings us back to the U-shaped function discussed in Section 2. Extreme commitments by OECD countries, both too loose and too strict, are associated with a positive leakage rate: non-OECD countries emit more than in the non-cooperative baseline. Intermediate targets, however, have the opposite effect. The optimal OECD target lies within this intermediate interval (red dot in Figure 4). As described in the stylised model in Section 2, this pattern can be explained in terms of relative technology costs. The right panel of Figure 4 shows the cost of a breakthrough technology, a carbon-free alternative to oil in the final-use sector relative to the cost of its direct competitor, oil.

Figure 4: Reaction function of non-OECD countries: cumulative CO2 emissions (2010-2100) compared to BaU (left panel). The red dot refers to the optimal case. Technology costs (right panel).



On the one hand, when the coalition target is very loose (less than 30%) there is no need to introduce new and expensive technologies and the abatement effort required is achieved mostly by means of energy efficiency and substitution. On the other hand, fairly ambitious targets (above 35%) exert a positive effect on technology deployment and diffusion but also imply a very deep contraction of fossil fuels demand. Although the clean technology costs are reduced, the even lower international price of oil prevents the carbon-free technology to become competitive in any country that does not have a sufficiently high social cost of carbon. A lower relative oil price in the short-term locks in the energy system of non-OECD countries to fossil–fuel-based options throughout the century. Because energy system investments are long-lived, this creates a path dependency that sets non-signatory countries on a course of dirty economic growth. In addition, the damage effect becomes more important. As the abatement level increases, there are more benefits to reap and therefore larger incentives to free ride.

In between these two extremes, there is a window of emission reduction targets in which the long-run cost of the breakthrough technology is ultimately reduced below that of the dirty substitute. Because of the perfect foresight assumption of the model, expectations affect short-run investments in non-OECD countries as well, thus redirecting their development path away from carbon-intensive technologies.

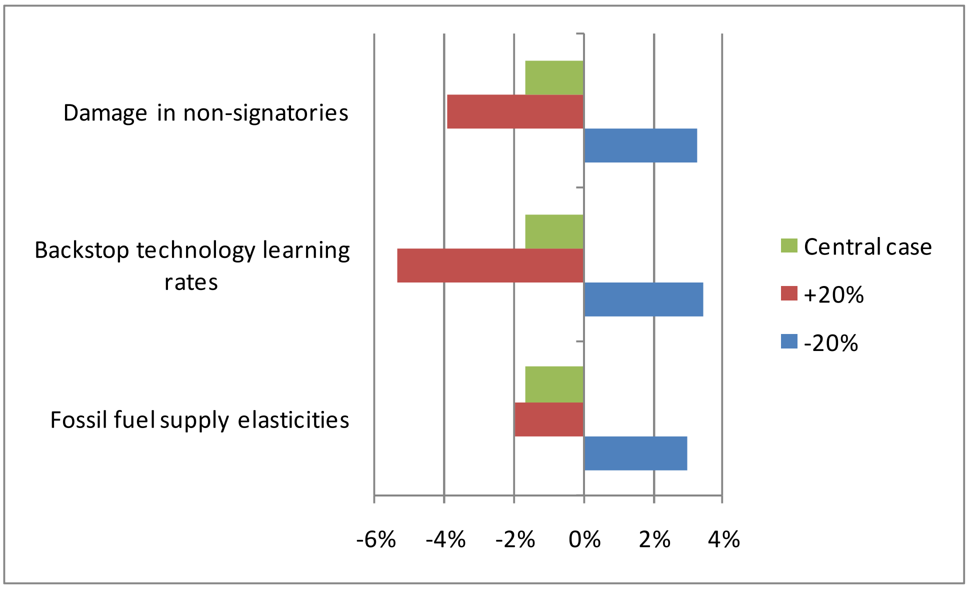
3.4 Sensitivity to technology diffusion, elasticity of energy markets and climate change damages

The previous section has shown that, in the presence of partial cooperation on emission reduction, technology spillovers can induce non-signatories to emit less carbon compared to their baseline, reducing the risk and the magnitude of carbon leakage, under certain conditions. This section assesses the robustness of this result to alternative assumptions concerning technology cost and climate change damage functions.

The literature on carbon leakage has identified some of the key assumptions that significantly affect the estimated leakage rates and we start from those. Supply elasticities of fossil fuels play a pivotal role. The potential for increasing or reducing emissions ultimately depends on the incentive to extract the exhaustible resources from the ground, which is a decision responding to non-linear increases in fossil fuel costs with cumulative extraction. When the supply is inelastic, the extraction of an additional marginal unit does not raise costs significantly. Therefore, the extent of a price increase associated with a larger demand is lower than in the case of elastic supply. In addition to fossil fuel elasticities, we have highlighted the role of the technology effect. Finally, we perform sensitivity to climate change damages, which are highly uncertain and yet another important factor influencing the response of non-signatory countries.

Figure 5 shows non-OECD's reaction to the optimal abatement in OECD regions when varying the assumptions on the most influential parameters controlling for fossil fuel supply elasticities, learning rates in carbon-free technologies, and the climate change damage perceived by non-signatory countries. We consider variations of these key parameters up to 20% around their central value.

Figure 5: Sensitivity analysis on different model parameterisation. Cumulative CO2 emissions with respect to the non cooperative baseline (2010-2100) in non-OECD countries when reacting to the optimal abatement in OECD countries.



When the elasticity of fossil fuel prices to cumulative extraction decreases, the leakage rate of a given level of emission reduction in the OECD region is higher, in line with previous studies (e.g., Burniaux and Oliveira Martins [11]). Non-OECD countries increase their fossil fuel demand more than they would in a world with higher elasticity, as the effect on prices is smaller. As a consequence, emissions are higher. The range of variation due to different learning rates is quite substantial and when learning rates are 20% above their central value, emissions in non-OECD countries can diminish more than 5% with respect to the non-cooperative baseline. The sensitivity to changes in climate damages can also be quite large, especially when forthcoming damages are (or perceived as) lower than expected. Asymmetry in the effect mainly depends on the non-linearity of damages.

Overall, the sign of leakage can be reversed depending on the magnitude of each of the three effects. However, it is worth noticing that the rate of leakage remains contained even for very pessimistic assumptions of the parameters. The highest leakage rate, 15%, is observed when learning rates are low.

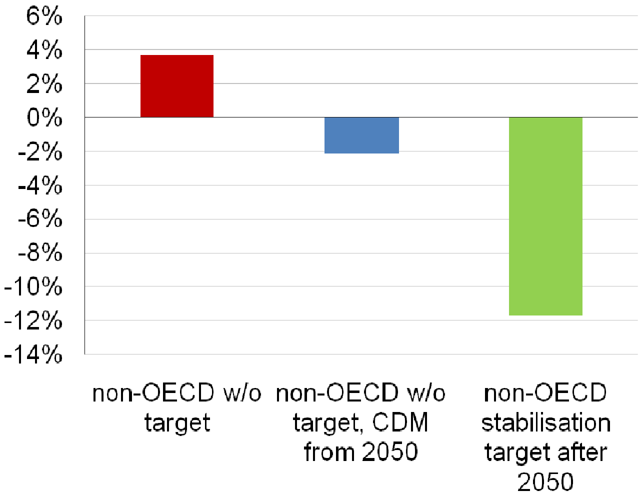
3.5 Dynamic coalition

We have argued that very ambitious unilateral climate policies can be counterproductive because countries outside the coalition have the incentive to take advantage of lower energy prices and rely more on fossil fuel-based energy. Section 3.4 showed that, to avoid boomerang effects, unilateral climate policies should aim at moderate targets. Because OECD countries are already on a path of low energy efficiency, a mild objective would be sufficient to induce technological change, without prompting excessive reduction in the cost of fossil fuels.

However this is true if countries anticipate that they will never be part of the coalition. Should developing countries anticipate a future credible commitment this would allow more ambitious efforts by the OECD group. To show this we analyse the case in which unilateral action turns into a global coalition by 2050.

Results indicate that if developing countries fully anticipate the forthcoming commitment, in 2050, they will already start modifying their investment strategy in the short-run. To show how expectations about future commitments could reverse the sign of carbon leakage, Figure 6 depicts non-OECD reaction to a 2050 emission cut of 45% by OECD countries under three different assumptions. The red bar shows the optimal response in the absence of any future commitment, while the blue and green bars represent the optimal response by non-OECD countries when they fully anticipate they will have a credible commitment in 2050, with and without clean development mechanisms (CDM) in place before 2050, respectively. Both engagements would motivate proactive behaviour even in a myopic world.

Figure 6: Non-OECD CO_2 cumulative emissions (2010-2100) when the OECD 2050 target is 45% compared to 2005. Percentage change compared to non-cooperative baseline



4. Some concluding remarks

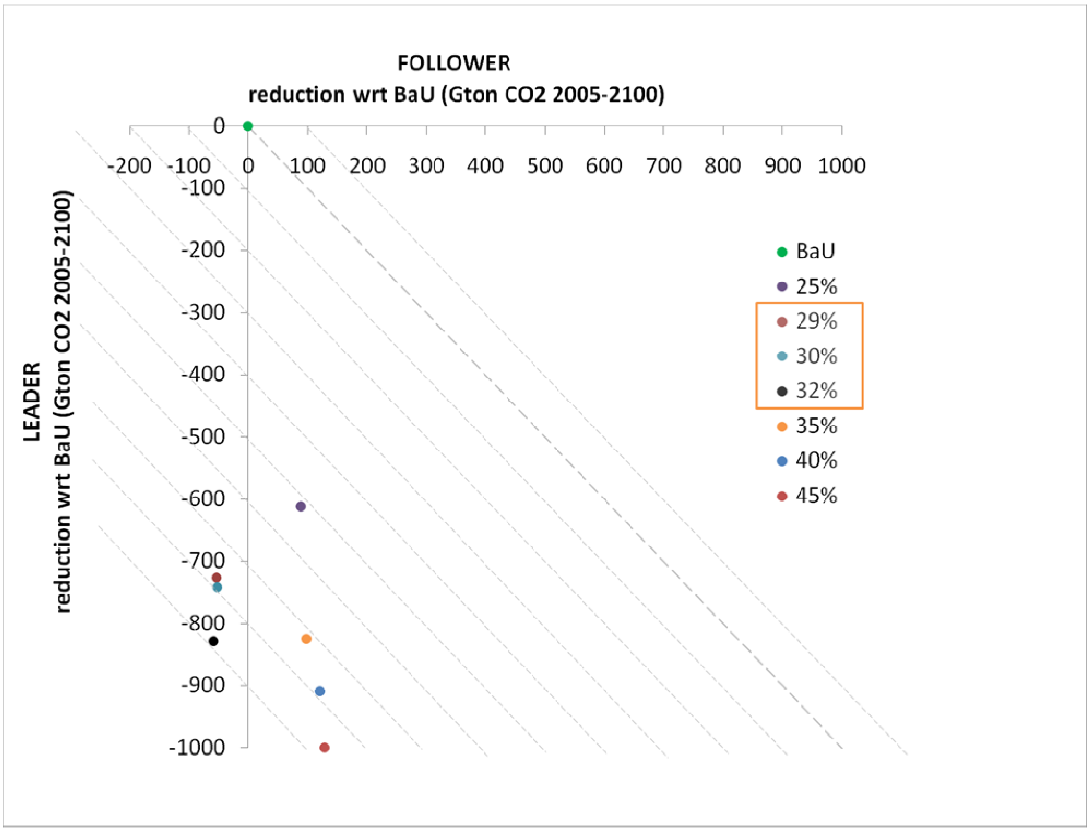
A global approach to climate change, although warranted, has turned out to be slow and inefficient. Rather, a bottom-up mix of architectures has emerged in which regions pursue different, although to some degree homogeneous, domestic policies. A sort of *de facto* cooperation between major OECD countries is emerging and developed economies have made spoken agreements on long-term common targets several times. In Cancun, during the sixteenth Conference of the Parties (COP), developed country Parties acknowledged the need for them to take the lead in combating climate change by taking notes of the emission reduction targets informally proposed during the COP15 in Copenhagen and by increasing the ambition of their economy-wide emission reduction targets. However, they also share the common fear that, given unilateral action, the response of non-signatories could erode their mitigation action.

In the present paper we argue that an ensemble of factors drives the response of non-participatory countries: a reduced perceived 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 induce non-members to increase emissions compared to their non-cooperative behaviour. On the other hand, innovations and technology advancements achieved within the coalition spill over to non-signatories, lowering their emissions. Hence, a carefully and comprehensive analysis is crucial in order to evaluate whether paralysing concerns on carbon leakage are justified or not, and under what assumptions.

The interplay of these three effects is accurately examined when a coalition between OECD countries is formed. Results indicate that when the OECD coalition follows an abatement path entailing 2050 emissions 30-35% below 2005 levels, it triggers a proactive behaviour in non-OECD countries. In this case, knowledge spillovers and technology transfers induce emission reduction in non-signatory countries as well. A comparison of these two channels suggests that technology transfers are more effective at fostering the diffusion of carbon-free alternatives outside the coalition compared to pure spillovers of knowledge preceding the deployment of the technology. The short-run optimal emissions path falls within the estimates of the Annex I’s emissions resulting from the Copenhagen conditional pledges.

Figure 7 reports the cumulative emission change in OECD and non-OECD countries compared to the no-policy baseline in absolute terms for different OECD emission targets (labelled for the effort they entail in 2050 relative to 2005). By projecting each target on the y-axis one can read the global cumulative emission cut. As the OECD coalition becomes more ambitious by bringing 2050 emissions in the range of 40% below 2005 levels or more, the overall environmental effectiveness of their effort is actually lower than in the case of a 35% target. Carbon leakage becomes negative because the energy market and damage effects prevail. Only when the OECD targets increase above ≥45% compared to 2005, does the overall effect match again that of the optimal target, as the OECD extra effort compensates the increase in emissions outside the coalition. This result is, however, reached in a strictly inefficient way, as it is more costly and it implies that non-participatory countries remain on an unsustainable growth path.

Figure 7: OECD and non-OECD emission strategies on each axis. The projection on the y-axis of each scenario represents the global emission cut



The main policy lesson to be drawn from the present analysis weakens the concern that unilateral action is going to erode OECD country competitiveness and the environmental efficacy of the agreement. In addition, it points away from extremely aggressive mitigation targets as a potential solution. As long as the unilateral target is moderate, near-term cooperation between technologically advanced countries could trigger a virtuous behaviour in non-signatory countries as well. The faster the international transmission of innovation in non-signatory countries, the lower the risk of carbon leakage. This implies that policies aiming at adjusting the regimes of intellectual property rights accordingly can play a very important role.

Given that developing countries condition their decision to cooperate on the mitigation effort undertaken by industrialised countries on the basis of ethical motivations, the OECD represents the appropriate starting coalition, to be followed by a subsequent enlargement of the coalition in the mid, longer-term future. Carbon leakage can be addressed more effectively by means of policies that promote the international transfer of technologies, rather than by threatening border adjustment measures that might actually hinder the diffusion process and should not be used as a scapegoat for inaction.

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Appendix I

The appendix described a two-region model. Region 1 represents the climate leader whereas Region 2 is the follower. Both regions minimise the cost of producing a predetermined quantity of energy, $\bar{y}_i$, given two alternative technologies: a polluting technology, based on fossil fuels, e_i, characterised by a unit cost C_e, and a clean, but initially more costly technology, b_i, with unit cost C_b. The cost-minimisation problem for Region 2 is given by:

$$
\begin{aligned}
&\min_{e_2, b_2} c_2(E, B) = c_b(B)b_2 + c_e(E)e_2 + D_2(e_2) \\
&st \\
&f(e_2, b_2) = y_2 \geq \bar{y}_2 \\
&\text{where} \\
&B = b_1 + b_2 \\
&E = e_1 + e_2
\end{aligned}
$$

and given the following conditions on the cost functions:

$$\frac{\partial c_b(B)}{\partial b_i} < 0, \frac{\partial c_e(E)}{\partial e_i} > 0, \frac{\partial^2 c_b(B)}{\partial b^2{}_i} \geq 0, \frac{\partial^2 c_e(E)}{\partial e^2{}_i} \geq 0$$

We can simplify the minimisation problem expressing b_i as a function of e_i and the total amount of energy, $\bar{y}_i$, $b_i = g_i(\bar{y}_i, e_i)$ with $\frac{\partial g_i}{\partial e_i} < 0$. In the most simple case, we can assume $b_i = \bar{y}_i - e_i$, that is the two sources of energy are perfect substitutes. For simplicity we assume that the social cost of carbon in Region 2 is negligible, since it is determined only by the singleton's emissions. The First-Order Condition (FOC) for Region 2's problem is given by:

$$
\begin{aligned}
&\frac{\partial c_2(e_1, f_2(e_1))}{\partial e_2} \equiv 0 \\
&C'_b\, g_2 + C_b g_2' + C'_e\, e_2 + C_e \equiv 0
\end{aligned}
$$

The Second-Order Condition is given by:

$$\frac{\partial^2 c_2(e_1, f_2(e_1))}{\partial^2 e_2} \geq 0$$

The reaction of the follower to a change in the choice of the leader is found by differentiating the First-Order Condition with respect to *e₁*, $\frac{\partial^2 c_2(e_1, f_2(e_1))}{\partial e_2 \partial e_1} + \frac{\partial^2 c_2(e_1, f_2(e_1))}{\partial^2 e_2} f'_2(e_1) \equiv 0$.

The reaction of the follower (Region 2) is thus given by the following expression:

$$f'_2(e_1) \equiv \frac{\partial e_2}{\partial e_1} \equiv -\frac{\dfrac{\partial^2 c_2(e_1, f_2(e_1))}{\partial e_2 \partial e_1}}{\dfrac{\partial^2 c_2(e_1, f_2(e_1))}{\partial^2 e_2}}$$

Because the sign of the denominator is positive, the sign of the reaction function depends on the sign of the second mixed derivative at the numerator:

$$sign(f'_2(e_1)) = -sign\left(\frac{\partial^2 c_2(e_1, f_2(e_1))}{\partial e_2 \partial e_1}\right)$$

The expression for the second mixed derivative is given by:

$$\frac{\partial^2 c_2(e_1, f_2(e_1))}{\partial e_2 \partial e_1} \equiv C''_b\, g_2 + C'_b\, g_2' + C''_e\, e_2 + C'_e$$

where:

$$C_e' = \frac{\partial c_e(E)}{\partial e_2} \geq 0; C_b' = \frac{\partial c_b(E)}{\partial e_2} \geq 0; C_e'' = \frac{\partial^2 c_e(E)}{\partial e_2 \partial e_1} \geq 0; C_b'' = \frac{\partial^2 c_b(E)}{\partial e_2 \partial e_1} \geq 0$$

In the special case of perfect substitutes, $b_2 = g_2(\overline{y}_2, e_2) = \bar{y}_2 - e_2$, the FOC can be re-written as follows:

$$C'_b(\overline{y_2} - e_2) - C_b + C'_e\, e_2 + C_e \equiv 0$$

And the expression for the second mixed derivative is given by:

$$\frac{\partial^2 c_2(e_1, f_2(e_1))}{\partial e_2 \partial e_1} \equiv C''_b(\overline{y}_2 - e_2) + C''_e e_2 + C'_e - C'_b$$

Below we study the conditions that determine the sign of the reaction function under different cost function specifications. The three cases considered are summarised in Table A1.

Table A1 summarises the conditions that yield a positive or negative reaction function, both in the general case ($b_2 = g_2(\overline{y}_2, e_2)$, in the second column) and when the two technologies are perfect substitutes ($b_2 = \bar{y}_2 - e_2$, in the third column).

Table A1: Follower's reaction function under alternative cost functions

Case	General rule $b_2 = g_2(\overline{y}_2, e_2)$	Rule for perfect substitutes $b_2 = \bar{y}_2 - e_2$
Linear cost curves $C_e'' = C_b'' = 0$	/+/ if $0 < -C_b' g_2' - C_e'$ and $C_b - C_e$ sufficiently small /-/ if $C_e' > -C_b' g_2'$	/+/ if $0 < C_b' - C_e'$ and $C_b - C_e < (C'_b - C'_e)e_2$ /-/ if $C_e' > C_b'$
Crossing cost curves $C_e' < C_b'$	/+/ if $C''_b g_2 + C''_e e_2 < -C'_b g' - C'_e$ and $C_b - C_e$ sufficiently small /-/ if $C''_b g_2 + C''_e e_2 > -C'_b g' - C'_e$	/+/ if $C''_b(\bar{y}_2 - e_2) + C''_e e_2 < C'_b - C'_e$ /-/ if $C''_b(\bar{y}_2 - e_2) + C''_e e_2 > C'_b - C'_e$

Double crossing cost curves for $e_1 > \overline{e_1}$ and $C_e' < C_b'$ for $e_1 \le \overline{e_1}$ and $C_e' \ge C_b'$	/+/ or /-/ depending on e_1	/-/ if $e_1 \le \overline{e_1}$ and $C_e' \ge C_b'$ /-/ if $e_1 > \overline{e_1}$ and $C_e' < C_b'$ and $C''_b \left(\bar{y}_2 - e_2\right) + C''_e\, e_2 > C'_b - C'_e$ /+/ if $e_1 > \overline{e_1}$ and $C_e' < C_b'$ and $C''_b \left(\bar{y}_2 - e_2\right) + C''_e\, e_2 < C'_b - C'_e$

Case 1: linear cost curves

$$C_e'' = C_b'' = 0$$

$$\frac{\partial^2 c_2(e_1, f_2(e_1))}{\partial e_2 \partial e_1} \equiv C'_b\, g' + C'_e$$

$$(i)\ \ C'_b\, g' + C'_e > 0 \Rightarrow sign(f_2(e_1)) < 0$$

$$(ii)\ \ C'_b\, g' + C'_e < 0 \Rightarrow sign(f_2(e_1)) > 0$$

provided that the initial price difference between the two technologies is sufficiently low.

When e_2 and b_2 are perfect substitute : $g_2(\bar{y}_2, e_2) = \bar{y}_2 - e_2$

$$(iii)\ \ C'_b\,(-1) + C'_e = C'_e - C'_b > 0 \Rightarrow sign(f_2(e_1)) < 0$$

$$(iv)\ \ C'_b\,(-1) + C'_e = C'_e - C'_b < 0 \Rightarrow sign(f_2(e_1)) > 0$$

provided that the initial price difference between the two technologies is sufficiently low. In the case of linear cost function we can identify the maximum difference between the two initial prices:

$$C_b - C_e < (C'_b - C'_e)e_2$$

If the cost curves are also parallel, then the sign of the reaction function is pinned down by the initial price gap. As we assume that the polluting alternative is initially cheaper, then the sign would always be negative:

$$C_e' = C_b' \text{ and } C_e'' = C_b''$$
$$\Rightarrow sign(f_2(e_1)) < 0$$

provided that $C_b - C_e > 0$, which is always true by assumption.

Case 2: crossing cost curves

The second case generalises the results for linear cost functions to the non-linear case in which second derivatives are positive. Provided that $C_e' < C_b'$ and the initial cost gap is not too large, then the sign of the reaction function depends on the gap between the first derivatives:

$$\frac{\partial^2 c_2(e_1, f_2(e_1))}{\partial e_2 \partial e_1} \equiv C''_b\, g_2 + C'_b\, g_2' + C''_e\, e_2 + C'_e$$
$$(i)\ C''_b\, g_2 + C''_e\, e_2 < -(C'_e + C'_b\, g_2') \Rightarrow sign(f_2(e_1)) > 0$$

Note that becuase $C''_b\, g_2 + C''_e\, e_2$ is always positive, $-(C'_e + C'_b\, g_2')$ must also be positive.

$$(ii)\ C''_b\, g_2 + C''_e\, e_2 > -(C'_e + C'_b\, g_2') \Rightarrow sign(f_2(e_1)) < 0$$

When e_2 and b_2 are perfect substitute: $g_2(\bar{y}_2, e_2) = \bar{y}_2 - e_2$

$$(iii)\ C''_b\left(\bar{y}_2 - e_2\right) + C''_e\, e_2 < C'_b - C'_e \Rightarrow sign(f_2(e_1)) > 0$$
$$(iv)\ C''_b\left(\bar{y}_2 - e_2\right) + C''_e\, e_2 > C'_b - C'_e \Rightarrow sign(f_2(e_1)) < 0$$

Case 3: double crossing cost curves

If the relative slope of the two cost curves, $C'_b - C'_e$, changes sign, then the sign of the reaction function can also be reverted, depending on the level of abatement undertaken by Region 1, e_1.

Suppose there exists a threshold level of emissions $\overline{e_1}$ above which the relative slope of the clean technology cost is positive:

for $e_1 > \overline{e_1}$ $C_b' - C_e' > 0$

Below the threshold the relative slope of the clean cost functions is negative:

for $e_1 \leq \overline{e_1}$ $C_b' - C_e' \leq 0$

Then, the optimal reaction of Region 2 might change sign, depending on the level of abatement undertaken by Region 1 and the consequent amount of fossil fuel used. The initial cost gap must also be sufficiently low. Consider the case of perfect substitute:

When $e_1 > \overline{e_1}$ and $C_e' < C_b'$:

$$(i)\ C''_b\left(\bar{y}_2 - e_2\right) + C''_e\, e_2 < C'_b - C'_e \Rightarrow sign(f_2(e_1)) > 0$$
$$(ii)\ C''_b\left(\bar{y}_2 - e_2\right) + C''_e\, e_2 > C'_b - C'_e \Rightarrow sign(f_2(e_1)) < 0$$

When $e_1 < \overline{e_1}$ and $C_e' > C_b'$

$$(iii)\ C''_b\left(\bar{y}_2 - e_2\right) + C''_e\, e_2 > C'_b - C'_e$$

which is alway true.

Hence:

$sign(f_2(e_1)) < 0$

In the general case, the sign of the reaction function also depends on the degree of substitutability between the two alternative technologies, that is g’:

When $e_1 > \overline{e_1}$ and $C_e' < C_b'$:

$$(v)\ C''_b\left(\bar{y}_2 - e_2\right) + C''_e\, e_2 < -C'_b\, g_2' - C'_e \Rightarrow sign(f_2(e_1)) > 0$$
$$(vi)\ C''_b\left(\bar{y}_2 - e_2\right) + C''_e\, e_2 > -C'_b\, g_2' - C'_e \Rightarrow sign(f_2(e_1)) < 0$$

When $e_1 < \overline{e_1}$ and $C_e' > C_b'$:

$(vii)\ C''_b\left(\bar{y}_2 - e_2\right) + C''_e e_2 < -C'_b g_2' - C'_e \Rightarrow sign(f_2(e_1)) > 0$
$(viii)\ C''_b\left(\bar{y}_2 - e_2\right) + C''_e e_2 > -C'_b g_2' - C'_e \Rightarrow sign(f_2(e_1)) < 0$

Appendix II: The WITCH model

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 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 non-cooperative 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 non-cooperative 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. Full details on the WITCH model can be found in Bosetti et al. (2007) and Bosetti et al. (2009). This Appendix provides a general overview of the model structure.

In each region, indexed by *i*, a social planner chooses a number of variables (decision variables) so as to maximise an intertemporal utility function subject to a set of equations describing the evolution of the capital stock of different technologies and subject to a budget constraint:

$$\max_{C_{i,t}} \sum_{t=0}^{\infty} u(C_{i,t}, L_{i,t}) R_t \qquad \text{(A1)}$$

where t are 5-year time spans and R_t is a declining discount factor. The budget constraint describes how final output $Y_{i,t}$, can be allocated across different productive usages, namely final good consumption ($C_{i,t}$), investments in final goods ($I_{i,t}$), investments in fossil-fuel-based technologies ($C_{e_{i,t,f}} e_{i,t,f}$) and investments in green technologies ($C_{b\,i,t,g} b_{i,t,g}$)[15]:

$$Y_{i,t} = C_{i,t} + I_{i,t} + C_{e_{i,t,f}} e_{i,t,f} + C_{b\,i,t,g} b_{i,t,g} \qquad \text{(A2)}$$

Equation (A2) is a simplified version of the real budget constraint, where all energy-related costs have been condensed into two terms. With this formulation we wanted to stress that energy can come from clean and dirty sources. The dirty technologies are based on fossil fuels (see equation

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[15] WITCH includes six fuels (coal, oil, natural gas, uranium, traditional biomass and biofuels) and seven technologies for power generation. The green technologies include nuclear power, wind turbines and photovoltaic panels, hydroelectric power, integrated gasification combined cycle with carbon capture and storage. Fossil fuel-based technologies are traditional pulverised coal technologies and thermoelectric power plants fuelled with natural gas and oil.

A8). The model explicitly accounts for all different cost components, distinguishing between investment costs, expenditure for fossil fuels in the case of dirty technologies, operation and maintenance costs.

Final output is produced by combining labour, energy, and physical capital with a Constant Elasticity of Substitution (CES) production technology:

$$Y_{i,t} = f\left[TFP_{i,t}, D_{i,t}, L_{i,t}, K_{i,t}, EN_{i,t}\right] \qquad \text{(A3)}$$

$TFP_{i,t}$ indicates total factor productivity, which grows exogenously. $D_{i,t}$ describes regional climate change damages, which are connected to global CO2 ($\sum_{i=1}^{12} e_{i,t}$) and non-CO2 ($\sum_{i=1}^{12} oghg_{i,t}$) emissions through a climate module:

$$D_{i,t} = d\left(\sum_{i=1}^{12} e_{i,t}, \sum_{i=1}^{12} oghg_{i,t},\right) \qquad \text{(A4)}$$

The WITCH model portrays the carbon and climate cycles connecting 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. 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.

The model assumes full employment and there is a perfect correspondence between labour and population, which follows exogenous trends as extrapolated by the annual estimates and projections produced by the UN Population Division[16]. Physical capital evolves over time according to a standard capital accumulation equation:

$$K_{i,t+1} - K_{i,t} = g(K_{i,t}, I_{i,t}) \tag{A5}$$

The total amount of energy used in final production ($EN_{i,t}$), can come from a set of clean ($b_{i,t,g}$) and dirty sources ($e_{i,t,f}$.):

$$EN_{i,t} = f_{EN}(H_{i,t}, b_{i,t,g}, e_{i,t,f}) \tag{A6}$$

The first term, $H_{i,t}$, is a stock of energy knowledge that allows for energy efficiency improvements. When $H_{i,t}$ increases, because technologies embed new scientific knowledge and become more efficient, the same amount energy can be generated using less inputs, $b_{i,t,g}$ and $e_{i,t,f}$. The stock of energy knowledge is upgraded by combining new domestic R&D investments with the exiting domestic and foreign stock of energy knowledge. This idea is modelled by linking the stock of energy knowledge in each country to the R&D investments in all model's regions:

$$\begin{gathered} H_i = h\left(\sum_{i=1}^{12} i_{i,t}\right) \\ I = \sum_{i=1}^{12} i_{i,t} \\ \frac{\partial h(I)}{\partial I} > 0 \end{gathered} \tag{A7}$$

The contribution of foreign knowledge is not immediate, and depends on countries' absorptive capacity and the distance of each region from the technology frontier. The technology frontier is

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[16] Data are available from http://unstats.un.org/unsd/cdb/cdb_simple_data_extract.asp?strSearch=&srID=13660&from=simple.

represented by the stock of knowledge in high-income countries (USA, WEURO, EEURO, KOSAU, and CAJANZ). This formulation captures the idea that there are international knowledge spillovers because new knowledge cannot be fully protected by patents and there is some unintended diffusion. However, in order to reap some benefits from spillovers, each region has to invest some resources on domestic innovation.

Within the energy sector, the model distinguishes between fossil fuels used as input in power generation and fossil fuels for final consumption (e.g. residential, industrial, transport). In the first case, the demand of fossil fuels is explicitly linked to the stock of physical capital in the power sector. In both cases, CO2 emissions are ultimately derived from the use of fossil fuels by applying stoichiometric coefficients ω_f:

$$e_{i,t} = e_f(\omega_f, e_{i,t,f}) \qquad \text{(A8)}$$

The substitution between green and dirty technologies is not linear and it is articulated in a nested-production tree. The choice between clean and dirty alternatives for given usages of energy ultimately depends on their relative costs.

The markets of exhaustible resources are represented as an international market for each fuel. 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. Cumulative extraction depends on the demand for fossil fuels of all twelve regions in the model. Therefore, the cost of fossil-fuel-based technologies is ultimately driven by the global use of fossil fuels. Using equation (A8), we can link fossil-fuel-based technology cost directly to the global level of CO2 emissions:

$$C_{e_{i,t,f}} = c_e(\sum_{i=1}^{12} e_{i,t})$$
$$E = \sum_{i=1}^{12} e_{i,t}$$
$$\frac{\partial c_e(E)}{\partial E} > 0 \qquad \text{(A9)}$$

In contrast, the cost of clean technologies decreases over time because of technical progress. The model distinguishes between mature technologies that have already been patented and technologies that have not yet been developed, are referred to as breakthrough technologies. In the case of mature technologies, the unit cost only declines with additional global deployment:

$$C_{b_{i,t,g}} = c_b(\sum_{i=1}^{12} b_{i,t,g}, \sum_{i=1}^{12} i_{i,t,g})$$
$$B_g = \sum_{i=1}^{12} b_{i,t,g}; I_g = \sum_{i=1}^{12} i_{i,t,g})$$
$$\frac{\partial c_b(B_g, I_g)}{\partial B_g} < 0; \frac{\partial c_b(B_g, I_g)}{\partial I_g} = 0 \qquad \text{(A10)}$$

Breakthrough technologies do not exist yet and necessitate dedicated R&D investments to become economically competitive. Once developed, they diffuse through a two-stage process. First, investments in R&D reduce costs to competitive level. Once available and commercialised, deployment by an increasing number of countries further contributes to cost reduction:

$$\frac{\partial c_b(B_g, I_g)}{\partial I_g} < 0; \frac{\partial c_b(B_g, I_g)}{\partial B_g} < 0 \qquad \text{(A11)}$$

Learning processes during knowledge accumulation will not be confined within the boundaries of the investing country, but knowledge is likely to spill, with some lag, worldwide because knowledge cannot be fully protected. However, benefits from disembodied knowledge spillovers can only occur if sufficient domestic absorptive capacity is developed. The lack of such capacity can represent a barrier that reduces the scope for spillovers. In contrast, technology spillovers are full and immediate within the five-year time step of the model. The implicit assumption is that investments in additional capacity by virtuous regions drive down investment costs globally and therefore the technology can be purchased and adopted by any region in the model. International spillovers of knowledge and experience are accounted for by linking the cost functions to the global, rather than the regional, level of technology and innovation.