HARVARD Kennedy School
JOHN F. KENNEDY SCHOOL OF GOVERNMENT

The Harvard Project on Climate Agreements

March 2012
Discussion Paper 12-49

A Good Opening: The Key to Make the Most of Unilateral Climate Action

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Prepared for

The Harvard Project on Climate Agreements

This paper has been previously released by Fondazione Eni Enrico Mattei (FEEM; www.feem.it). The Harvard Project on Climate Agreements is grateful to FEEM and the authors.

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Acknowledgements

The Harvard Project on Climate Agreements receives generous support from the Harvard University Center for the Environment; Christopher P. Kaneb (Harvard AB 1990); the James M. and Cathleen D. Stone Foundation; and ClimateWorks Foundation. The Project is very grateful to the Doris Duke Charitable Foundation, which provided major funding during the period July 2007–December 2010. The Project also receives ongoing support from the Belfer Center for Science and International Affairs at the Harvard Kennedy School.

The closely affiliated, University-wide Harvard Environmental Economics Program receives additional support from the Enel Endowment for Environmental Economics at Harvard University, the Alfred P. Sloan Foundation, the Mossavar-Rahmani Center for Business and Government at the Harvard Kennedy School, Chevron Services Company, and Shell.

Citation Information

Bosetti, Valentina and Enrica De Cian. "A Good Opening: The Key to Make the Most of Unilateral Climate Action," Discussion Paper 2012-49, Cambridge, Mass.: Harvard Project on Climate Agreements, March 2012.

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A good opening:

the key to make the most of unilateral climate action

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Abstract

In this paper we argue that when a subgroup of countries cooperate on emission reduction, the optimal response of non-signatories countries reflects the interaction between three potentially opposing factors, the incentive to free-ride on the benefits of cooperation, the incentive to expand the demand of fossil fuels, and the incentive to adopt cleaner technologies introduced by the coalition. Using an Integrated Assessment Model with a game theoretic structure we find that cost-benefit considerations would lead OECD countries to undertake a moderate, but increasing abatement effort (in line with the pledges subscribed in Copenhagen). Even if emission reductions are moderate, OECD countries find it optimal to allocate part of their resources to energy R&D and investments in cleaner technologies. International spillovers of knowledge and technology diffusion then lead to the deployment of these technologies in non-signatory countries as well, reducing their emissions. When the OECD group follows more ambitious targets, such as 2050 emissions that are 50% below 2005 levels, the benefits of technology externalities do not compensate the incentives deriving from the lower fossil fuels prices. This suggests that, when choosing their unilateral climate objective, cooperating countries should take into account the possibility to induce a virtuous behaviour in non-signatories countries. By looking at a two-phase negotiation set-up, we find that free riding incentives spurred by more ambitious targets can be mitigated by means of credible commitments for developing countries in the second phase, as they would reduce lock-in in carbon intensive technologies.

Key words: Technology spillovers, climate change, partial cooperation

JEL: Q54, Q55, C72

1. Introduction

Stable coalitions addressing a global externality such as Green House Gases (GHGs) emissions are generally small and do not succeed to involve all players of the game [3, 4, 16, 17, 26]. When cooperation on a global public good is partial, the agreement can fail to be environmental effective. On the one hand, the pollution reduction by the coalition might be too small compared to the first-best level of abatement. On the other hand, the optimal reaction of non-signatory countries might be to increase pollution compared to the case with no agreement in place. Whether this is the case or not depends on a number of forces. We argue that, when a number of countries cooperate on emission reduction, the optimal response of non-members is a mix of at least three potentially opposing factors.

First, countries have an incentive to free ride on the environmental improvement brought about by signatory regions. Because GHGs become uniformly mixed in the atmosphere, the perceived damage of emitting one additional ton of carbon is independent of the emission source location. A second element that can provide incentives for strategic increases in emissions is the global integration of markets. Even if climate policy is enforced only in a few countries, demand reduction of fossil fuels driven by the policy can depress the international price of these fuels. Consumers and producers not facing climate policies will respond with an increase in fossil fuels

demand [7, 25, 27]. The literature has referred to this as energy market effect.[3] A second mechanism of policy transmission is the international trade of energy-intensive goods. By increasing production costs of energy-intensive industries, climate policy can reallocate production outside the coalition. Still, the pollution haven hypothesis has not found robust evidence and production location choices are only marginally determined by climate policies. In particular, Barker et al. [2] argue that studies finding high leakage rates assume that climate policy has strong re-location effects on energy-intensive production. However, in practice, this is an unlikely outcome because countries adjust policies in order to avoid these effects, for example by exempting trade-exposed sectors[4]. Burniaux and Oliveira Martins [12] show that what actually matters in producing carbon leakage is the structure of energy markets and of fossil fuel supply. However, they conclude that real world conditions and realistic values for key parameters make the risk of significant carbon leakage due to terms-of-trade effects unlikely. The relative importance of the energy market effect compared to the pollution haven hypothesis is also emphasised by Böhringer et al. [8]. They show first in an analytical framework and then using a numerical Computable General Equilibrium (CGE) model that when either the USA or the EU reduce unilaterally emissions, carbon leakage is predominantly driven by the international energy market effect.

The damage and energy market effects, as well as the pollution haven hypothesis, imply that countries outside a climate coalition would increase their emissions. However, climate policy

[3] 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. As the international prices of such goods increases, countries outside the abating coalition have an incentive to expand their production of these goods and export them to signatory countries. The "pollution haven hypothesis" effect is not included in the present analysis.

[4] 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.

provides a price signal that triggers innovation in carbon- and energy-saving technologies. This is the well-known induced technical change hypothesis. Increasing factor prices give an incentive to develop technologies that save the most expensive input. Since markets are increasingly more integrated, it is quite unlikely that new technologies developed under the stimulus of climate policy remains confined to the policy forerunner countries. Technology transfers can occur through climate policies linkages (see for example the work by Dechezleprêtre et al. [18] and Seres et al. [37] on technology transfers through the Clean Development Kyoto mechanism), but also simply because of trade flows, multinational enterprises, and skill-labour mobility (Eaton and Kortum [19,20], Keller, [23]).

Unilateral climate policy can thus induce technology transfers from the coalition to non-signatories countries, reducing emissions outside the climate coalition. Using bottom-up models of the energy sector, Barreto and Kypreos [6] and Barreto and Klaasen [5] show that technology spillovers can induce technical change and emission reduction outside the group of countries facing an emission constraint. Using a CGE model that links the energy sector to the rest of the general economy, Gerlagh and Kuik [21] 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. Similar results come also from the theoretical literature [22, 41].

The two strands of literature on markets effects, on one hand, and on technology spillovers, on the other hand, have remained separated, with few exceptions. This is quite surprising as there is in fact a close connection between the energy market and the innovation effects. Whether a zero-carbon technology is widely adopted depends largely on its price relative to that of fossil fuels. In turn, this relative price depends on the stringency of the climate policy, the scarcity of fossils, the speed of technology diffusion, and on the price elasticity of energy demand.

To our knowledge, only Hoel [27] discusses these issues jointly, using a simplified analytical model. Hoel compares the direct effect of an exogenous cost reduction of a clean substitute to fossil fuels with the induced energy market effect. He shows that emissions are more likely to increase in the short-run, the higher the elasticity of demand, the scarcer the fossil fuels, and the lower the substitution possibilities between clean and dirty substitutes. That paper provides very clear intuitions on the interaction between energy market and technology effects, but taking the evolution of technical change as given and neglecting the dynamics characterising the climate system. An integrated assessment model with endogenous technical change can complement the above analysis and provide more general insights because it allows characterising the optimal reaction function of non-signatories under more realistic assumptions.

This is the approach adopted by this paper, which uses a numerically calibrated integrated assessment model to generalise some of the considerations on the trade-off between the energy markets and the technology effects. The model chosen is suitable for this analysis because it has a game-theoretic set-up where players, regions of the world, choose their optimal intertemporal strategies taking in consideration other regions' reactions. 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 (as in Chander and Tulkens [15]). Fossil fuel prices are endogenously influenced by the global use of exhaustible resources. In addition, and differently from Hoel [27], technical change endogenously accounts for both knowledge and experience international spillovers.

We start the analysis by looking at partial cooperation between OECD countries, a coalition that is interesting in several respects. To date, industrialised countries have been the leading innovators. For this reason, the OECD group can be expected to lead the technological transition

towards lower carbon development pathways while creating more incentives for developing countries to join. The central question we investigate is whether the OECD coalition can set a target that triggers technological diffusion while keeping the damage and energy market effects under control. In other words, is there an "optimal" abatement effort that minimises carbon leakage? To generalise the validity of our results, we explore the influence of a number of elements, including the structure of energy markets, energy supply and international trade elasticities, substitution possibilities in final production, speed of innovation, composition and differences in climate damages, and the nature and composition of the coalition.

The remainder of the paper is organised as follows. Section 2 illustrates how the energy market, technology, and damage effects are described in the numerical model WITCH. Section 3 discusses how the interaction between the three effects determines the optimal reaction of non-members to partial cooperation among OECD countries. Because the magnitude of each of these effects depends on the effort undertaken by the coalition, Section 4 investigates the consequences of varying the stringency of the emission objective and the composition of the coalition. In Section 5 the robustness of results is tested across alternative model specifications and challenged through extensive sensitivity analysis. A discussion of results and their policy implications concludes the paper in Section 6.

2. Energy market, technology, and damage effects in the WITCH model

Our analysis is based on the WITCH model, which incorporates a detailed representation of the energy sector into an inter-temporal growth model of the economy. This allows technology-related issues to be studied within a general equilibrium framework characterised by environmental (expected future climate change damages), economic (international energy

markets), and technology (international spillovers of knowledge and experience) externalities (Bosetti et al. [9,10,11]).

The players of the game are twelve forward-looking regions that cover the global economy. They can play either cooperatively (global and partial coalitions can be considered) or non-cooperatively. In the first case, regions maximise the global social welfare, fully internalising environmental and economic externalities. This leads to the first-best optimum. When playing a non-cooperative game, regions optimise their individual welfare, taking as given each other region's choice. This is done through an iterative procedure, which is capable of reproducing the outcome of a non-cooperative, simultaneous, open membership game with full information, and thus achieve a second-best Nash equilibrium.[5] The non-cooperative game can involve only singletons, coalitions of different size, or coalitions of different size and singletons. Both singletons and coalitions best-respond to other players' move, but singletons maximise individual welfare while coalition maximises aggregate joint welfare. In particular, coalitions evaluate the weighted sum of discounted per capita consumption, with weights calibrated to equate marginal utilities across members, the Negishi weights. As the model describes both the environmental and technology externalities, cooperation can address each of these market failures. In the second stage countries choose their intertemporal path of investments. The game is solved backwards.

In each region *n* of the model, a social planner maximises welfare Eq.(1) subject to economic constraints below [Eqs. (2)-(11)]:

$$\max W(n,t) = \sum_{t=0}^{T} R(t)U(c(n,t),L) \qquad (1)$$

[5] The model is solved as a one-shot meta-game. In the first stage countries decide on their participation and coalitions are formed.

In Eq. 1, *U(.)* is the utility function of the representative agent, $c(n,t)$, is per capita consumption at time *t* in region *n*, and *L* represents population, which is also the measure of labor inputs. *R(t)* is a discount factor to represent the rate of time preference.

The regional social planner chooses an entire sequence of consumption levels and investments subject to the budget constraint that describes how total final production, $Y(n,t)$, can be allocated to final consumption, $C(n,t)$, investments in final goods, $I_FG(n,t)$, investments in various energy technologies *i*, $I_E_i(n,t)$, at the unit cost of installation C_E_i, investments in R&D in each of these energy technologies, $I_RD_i(n,t)$, and expenditure on fuels, $Q_F_i(n,t)$, at unit cost $P_F_i(n,t)$:

$$C(n,t) = Y(n,t) - I_FG(n,t) - \sum_i [I_RD_i(n,t) + C_E_i(n,t) I_E_i(n,t) + P_F_i(n,t) Q_F_i(n,t)] \quad (2)$$

where the technologies available *i* include energy efficiency improvements, *EE*, fossil-fuel-based technologies in power sector, fossil-fuel-based technologies in final use sectors, carbon-free technologies in power sector, carbon-free technologies in final use sectors.[6]

As mentioned above, WITCH specifically incorporates the emission externality, the technology externality via international knowledge and experience spillovers, and carbon leakage through international energy markets.

[6] Electricity can be generated using fossil fuel based technologies and carbon-free options. Fossil-fuel-based technologies include natural gas combined cycle (NGCC), oil- and pulverised coal-based power plants. Integrated gasification combined cycle power plants equipped with carbon capture and storage (CCS) are also modelled. Zero carbon technologies include hydroelectric and nuclear power plants, wind turbines and photovoltaic panels (Wind&Solar). The end-use sector uses traditional biomass, biofuels, coal, gas, and oil. Oil and gas together account for more than 70% of energy consumption in the non-electric sector. Instead, the use of coal and traditional biomass is limited to some developing regions and decreases over time. First generation biofuels consumption is currently low in all regions of the world and the overall penetration remains modest over time given the conservative assumptions on their large scale deployment.

The *climate externality* is represented by a damage function, *D*, that depends on global temperature, computed through a simplified climate module. Global temperature ultimately depends on global GHGs emissions, $T(t) = \sum_n E(n,t)$. The reduced-form damage function, *D*, accounts for the regional effects of global mean temperature increase on regional Gross Domestic Product (GDP). Because climate change damages have a direct impact on output, the net output available for consumption and investments can be different from what actually produced, driving a gap between net output available, $Y(n,t)$ and produced gross output, $\bar{Y}(n,t)$:

$$Y(n,t) = \frac{\bar{Y}(n,t)}{1+D(n,t)} \tag{3}$$

$$D(n,t) = \alpha_1(n)\,T(t) + \alpha_2(n)\,T(t)^2 \tag{4}$$

For an increase in temperature below 1.27°C, climate change impacts on GDP can be either positive or negative, depending on regional vulnerability and geographic location. Above that level, damages are negative throughout the world and increase in a quadratic relationship with temperature. Final gross output, $\bar{Y}$, is produced by combining physical capital, $K_FG(n,t)$, energy services, $ES(n,t)$, and labour , $K_FG(n,t)$,using a CES production function:

$$\bar{Y}(n,t) = A(n,t)F[K_FG(n,t), L(n,t), ES(n,t)] \tag{5}$$

Labour force is approximated with (exogenous) population. At each point in time, the capital stock accumulates with the perpetual rule:

$$K_FG(n,t) = K_FG(n,t-1)(1-\delta) - I_FG(n,t) \tag{6}$$

Overall technological progress is described by the exogenous dynamics in total factor productivity, $A(n,t)$.

Whereas there are several options that can be used to decarbonises the power generation sector, the non-electric sector features fewer zero-emission options. Although there can be some switching from direct energy use to electricity, substitution possibilities are constrained by the limited elasticity of substitution assumed between electric and non-electric inputs to the production of energy services. The two inputs enter a CES function where elasticity is assumed to be equal to 0.5. This low value accounts for path dependencies and lock-in effects in existing capital stock.

The technology portfolio of both the electric and the non-electric sector is not static and it can be expanded by investing in innovation. The WITCH model provides a simple, but reasonable representation of the process of innovation as well as of technology diffusion. Regions can invest part of their savings to accumulate new knowledge in the energy sector. R&D can lead to incremental energy efficiency improvements as well as radical discoveries.

A first channel of endogenous technological change affects energy intensity. A stock of knowledge capital, $K_RD_{i=EE}(n,t)$, augments the quantity of energy services that can be produced by each unit of physical energy used, $E(n,t)$:

$$ES(n,t) = F[K_RD_{i=EE}(n,t), E(n,t)] \tag{7}$$

When enough resources are allocated to dedicated R&D, breakthrough innovation can happen[7] making brand new clean technological options economically viable. Once technologies are

[7] The model simplifies the representation of the innovation process by assuming a deterministic specification.

deployed, investment costs decrease further with the learning process that is proportional to global adoption. The two stages of innovation and diffusion are combined together in a two-factor learning curve specification for investment costs, which are an endogenous function of the knowledge stock (Learning-By-Researching) and installed capacity (Learning-By-Doing). Learning-By-Researching occurs before the technology penetrates the market, while Learning-By-Doing operates when technology deployment starts. The general form is described in equation (8):

$$\frac{C_E_i(n,t)}{C_E_i(n,0)} = \left(\frac{K_RD_i(n,t-2)}{K_RD_i(n,0)}\right)^{-\theta_1} \left(\frac{\sum_n K_E_i(n,t)}{\sum_n K_E_i(n,0)}\right)^{-\theta_2} \tag{8}$$

where the investment cost in technologies *i* at time *t* depends on the cumulated stock of R&D investments, $K_RD_i(n,t)$, and on the cumulated capacity, $K_E_i(n,t)$, aggregated over the whole world. The two exponents, the Learning-by-Doing (LBD) index, $-\theta_2$, and the Learning-by-Researching (LBR) index, $-\theta_1$, define the speed of learning. In particular, the rate at which investment costs decline each time the cumulative capacity or the knowledge stock doubles[8] is given by the learning ratios, defined as one minus the progress ratio, $\text{LBR ratio} = 1 - 2^{-\theta_1}$; $\text{LBD ratio} = 1 - 2^{-\theta_2}$. While regions when optimising know that they can affect costs by investing in R&D, LBD occurs as an external effect.

For the sake of simplicity we assume two broad types of breakthroughs can occur, one in the final use sector and one in power generation. For example, innovation could introduce a new substitute for oil in the transport sector, such as cellulosic biofuels, electric or hydrogen-full-cell

[8] A two time period (corresponding to 10 years) lag is assumed for R&D, to capture the inertia of bringing research to the market.

vehicles. Or new power generating technologies might become competitive, such as concentrated solar power or advanced nuclear power. Once breakthroughs occur, the uptake of the new technologies will not be immediate and complete, but the pace of transition is controlled by a penetration limit. Both learning effects influence investment costs in breakthrough technologies in the power and final sectors. In the case of more mature options, such as wind and solar PV, the contribution of the knowledge stock is negligible, that is $\theta_1=0$, while the Learning-By-Doing mechanism keeps reducing investment costs. We assume that both learning mechanisms are zero in the case of fossil-fuel-based technologies, hydroelectric power, and third generation nuclear technologies.

The *innovation externality* takes the form of international spillovers of *knowledge* embodied in the energy sector. The dynamic evolution of the *knowledge* is described the following perpetual rule:

$$K_RD_i(n,t+1) = K_RD_i(n,t)(1-\delta_i) + I_RD(n,t)_i^{\alpha} K_RD_i^{\beta}(n,t) SPILL_i^{\gamma}(n,t) \qquad (10)$$

where investments in R&D are combined with cumulated stock of existing national knowledge, K_RD_i, to account for standing on shoulder effects, and foreign knowledge, $SPILL_i$, to account for international spillovers effect, as described in equation (11):

$$SPILL_i(n,t) = \frac{K_RD_i(n,t)}{\sum_{j\in OECD} K_RD_i(j,t)} \left(\sum_{j\in OECD} K_RD_i(j,t) - K_RD_i(n,t)\right) \qquad (11)$$

The spillover term depends on the interaction between the countries' absorptive capacity, measured by the ratio of the stock of the country to that of the frontier, and the distance of each

region from the technology frontier itself. The frontier is represented by the total stock of knowledge available in top innovator countries, the OECD, and it is taken as an externality by each optimising region. This formulation implies that foreign knowledge has a positive contribution to domestic knowledge formation only if the recipient country has a sufficiently high absorptive capacity, which is measured in terms of domestic knowledge stock. The distance from the technology frontier, which is defined as the gap of each region from the international pool of knowledge, plays also a role. The technology frontier consists of knowledge capital stocks in different countries, reflecting the idea that there is not a single innovator. In this manner, countries in frontier can still benefit from spillovers because of the heterogeneity of knowledge capital across countries.

Finally, the last channel of interaction across regions is that of the international energy market. International prices of fossil fuels are determined by the equilibrium between global demand and supply. As a consequence, a domestic policy enforced in one region has an impact on consumption and production in other regions as well through the price mechanism. International prices endogenously reflect fossil fuels exhaustibility, which is ultimately driven by regional consumption. The cost increases with global demand to reflect resource scarcity. Four non-renewable fuels are considered: coal, crude oil, natural gas, and uranium. A set of reduced-form cost functions accounts for the non-linear effect of both depletion and extraction. Assuming competitive markets, the domestic price P_F_i is equal to the marginal cost and it depends on the cumulative quantity of fossil fuels extracted, $\sum_n Q_F_i(n,t)$:

$$P_F_i(n,t) = F[\sum_n Q_F_i(n,t)] \tag{12}$$

The distinguishing features of the model are summarised in Table 1.

Table 1: Distinguishing feature of the WITCH model

key distinguishing feature	**WITCH model**
Solution concept	Intertemporal optimisation (Ramsey-type growth model)
Expectations/Foresight	Default: perfect foresight
Substitution possibilities within the macro-economy / sectoral coverage	CES production function of generic final good from primary inputs capital and labour and intermediate inputs energy
Link between energy system and macro-economy	Economic activity determines demand; energy system costs (investments, fuel costs, operation and maintenance) are included in macroeconomic budget constraint. Hard link, i.e. energy system and macroeconomy are optimised jointly.
Production function in the energy system / substitution possibilities	Non-linear substitution between competing technologies for electricity generation modelled with CES production functions. Supply curves for exhaustible resources.
Land use	MAC curves for deforestation
International macro-economic linkages / Trade	Single market for some commodities (permits) International spillovers of knowledge (energy R&D) and of experience (learning-by-Doing for wind and solar)
Implementation of climate policy targets	Emission caps-and-trade, with different allocation rules across or taxes. Banking and borrowing can be switched on/off Optimal level of emissions based on Cost Benefit Analysis
Technological Change / Learning	Global learning-by-Doing for wind and breakthrough technologies in power and final sector; learning-by-Researching for breakthrough technologies with international spillovers of knowledge; energy efficiency R&D investments with international spillovers
Representation of end-use sectors	Electric (power generation from gas, coal, and oil; coal IGCC on combination with CCS, nuclear, hydro, wind, solar), non-electric (final use of coal, oil, gas, biomass, first and second generation biofuels), final good sector
Cooperation vs. non-cooperation	Nash equilibrium (non-cooperative) or Pareto equilibrium (cooperative)
Externalities	Environmental externality (a damage function can be switched on/off), international energy markets, technology externalities are not internalised in the Nash equilibrium
Utility	Log utility. Risk aversion coefficient equal to 1.
Investment dynamics	Capital motion equations, no vintage

Although this model represents a step-up over standard integrated assessment modelling that normally features only the climate externality, it must nonetheless be recognised that it does not thoroughly represent all possible sources of global interaction. More specifically, no

international trade of capital is assumed 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 [2,8], which is fully modelled. Our model captures market failures related to international spillovers only in the energy sector, as no general purpose R&D is assumed. No learning is considered for known, yet potentially improvable technologies, such as nuclear power and carbon capture and storage (CCS). Thus, this exercise provides an account of only some of the most relevant sources of global interaction. Finally, each region internalises only the regional externalities associated with climate change damages, the accumulation of knowledge, and the use of fossil fuels, but not the international ones.

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 will react optimally.

3 OECD partial cooperation

Given the numerous sources of global interaction described in the previous sections, the implementation of climate policies in a sub-group of countries will inevitably affect the behaviour of non-members as well. Non-signatories might react by increasing, decreasing, or leaving unchanged their emission. The reaction of non-signatories depends not only on the interaction between the energy, damage, and technology effects, but also on composition and size of the coalition of climate leaders. When the level of ambition of the coalition is high, either because the coalition is big or because the perceived damages are large, the energy market effect is likely to prevail. In contrast, smaller or less environmentally active coalitions might see the

technology effect prevail. In addition, what also matters is the nature of the decarbonisation pathway followed by the coalition. In particular, if coalition members already have a good performance in terms of energy intensity, emission reduction will need to rely on decarbonisation of the energy mix, which means introducing cleaner alternatives and expanding the deployment of zero-carbon technologies. Conversely, if the energy intensity of the coalition is high, a large margin of reduction will be achieved through energy saving measures. In the case of the coalition considered in this section composed of OECD countries, the average energy-output ratio is relatively low and therefore significant technology transformation is required even for moderate emission reduction targets. The optimal endogenous level of abatement for a coalition reflects the weighting of benefit from avoided damage and the costs of mitigation, which in turn is based on innovation expenditures, the cost of shifting to more expensive technologies and fuels and towards more efficient ways of production. The cost-benefit criterion is sensitive to value judgements, such as the economic evaluation of climate change impacts and the choice of the discount rate. The role of discounting and that of cost-benefit analysis in the context of climate change has been discussed and documented in several papers as in, among many others, Nordhaus [8], Tol [39][9], Stern [38] and Weitzman [42]. It is still debated 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 weigh the likelihood of human extinction [36]. 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%[10]. We then investigate the effect

[9] Similar results are shared by Manne and Richels [30], Mendelsohn et al. [31] and Pearce [35].

[10] 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 [33], lowering the pure rate of time preference and adjusting accordingly the curvature of the utility function leads to a result that is basically unchanged

of a higher discount rate, 3%, and show how this has major impacts 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 [40] and the values proposed in the Stern Review[11].

3.1 The optimal OECD Target and the optimal non-OECD reaction

Given the assumptions just described, the optimal, non-cooperative baseline would result in an increase in global average temperature of about 3.4°C above pre-industrial levels in 2100. This pattern would lead to a global damage of about 7% of the Gross World Product (GWP in 2100). Cooperation on emission reduction by the group of OECD countries would slow down climate change only slightly, with 0.2°C less warming in 2100.

Cost-benefit considerations would lead the OECD coalition to follow initially moderate emission cuts, while effort would increase over time. In 2050, the optimal CO2 emission reduction is only 32% (or 34% CO2-eq considering all GHGs) compared to 2005. 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). It is interesting to note that short-run emission reductions fall in the range of the Copenhagen pledges for Annex I countries, which largely overlap with the model definition of OECD region. In 2020, the optimal emission reduction compared to 2005 is 2%. This increases 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%,

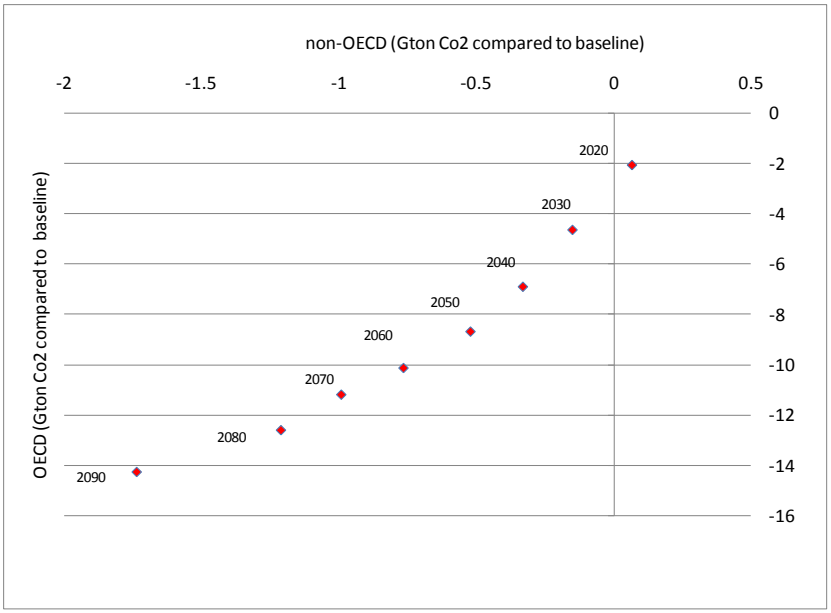
from that based on the original parameter value. Instead, we base the experiment on an interest rate that is exceptionally low, following a normative approach, to observe the effects and compare them with experiments based on a higher pure rate of time preference. The next section will analyse how myopic behaviour, modelled with a higher discounting, affects the results.

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

with a median value between 1% and 12.5%, depending on the assumptions on LULUCF accounting and the use of surplus emissions units[12].

Figure 1 shows the dynamics of the OECD group's optimal abatement path (measured as emissions with respect to baseline) along with the optimal reaction of non-OECD countries. Overall, the non-OECD countries' reaction is proactive, and their optimal emission path lies slightly below baseline. This is a little improvement, when compared the absolute increase in emissions in non-OECD countries throughout the century, but still it implies no leakage. Only in the very short-run, some leakage occurs, but over time the technology channel dominates the damage and energy market effects.

Figure 1: 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



[12] 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/

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 the result of different factors. First of all, the OECD effort is moderate. 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 80 ppm less than in the non-cooperative baseline. As said above, global mean temperature in 2100 increases up to 3.2 °C, as opposed to the 3.4°C.

When abatement is moderate, the influence on international fuel prices is also contained. The international price of oil is at most 34%[13] lower compared to baseline and such reduction is more than compensated by innovation and deployment of clean technologies. Even if the emission reduction is moderate, technology investments in OECD countries increase significantly. Expenditure in clean energy R&D grows from 0.05% to 0.24%,measured as a share of GDP, for a total amount of 74 US$ Billion in 2010. A small fraction (2.9 US$ Billion) is allocated to energy efficiency improvement, while most additional investments are dedicated to the development of breakthroughs in the power and final-use sector. These investments reduce the costs of breakthrough technologies, which are introduced first in the OECD and subsequently, with a time lag of five to ten years, in non-OECD countries. This result substantiates the discussion above concerning the nature of the decarbonisation pathway and how this determines the strength of the technology effect. Because OECD energy-output ratio is already low, even modest emission reduction requires new technologies. In addition, OECD countries represent the

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

technology frontier, at least today[14], and most R&D expenditure occurs there. Therefore, they represent the major source of knowledge and technology spillovers.

3.2 The optimal non-OECD reaction: trade-off between the energy, technology, and damage effects

The previous Section discussed how the damage, energy market, and technology effects play out in shaping technology cost functions and the optimal response of non-signatory countries. In this Section we disentangle the magnitude and the direction of the three factors. For the purpose of this analysis, we compare the optimal solution analysed in the previous section with three hypothetical scenarios in which any of the three mechanisms is turned off. This should obviously be considered as a purely speculative exercise, as in real life it would be obviously impossible to turn off either effect.

The first of these variations assumes that Learning-By-Researching and Learning-By-Doing effects are completely excludable and kept within the coalition. We assume that non-signatories cannot reap any of the innovation advancements induced by the OECD climate agreement. Technology investment costs and energy efficiency in non-OECD countries cannot be affected by R&D investments choices and new installed capacity in OECD countries, as in shown in Table 2, first two rows. We refer to this case as the "no TECHNOLOGY effect" case (no TECH), which can be thought of as situation in which channels that vehicle international transfers of knowledge and technologies, such as trade, FDI, skill-labour migration, patenting in different countries, are for some reasons not effective.

The second case assumes that the OECD reduction in fossil fuel consumption does not influence the fossil fuel prices faced by non-OECD countries. They continue to buy energy at the same, higher price they perceived in the non-cooperative baseline. We refer to this second case as the

[14] Consider that the base year of the model is 2005.

"no ENERGY MARKET effect" case (no EMKT). Table 2, third row, shows how this case has been parameterised.

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 the higher temperature increase observed in the non-cooperative baseline. We refer to this final case as the "no DAMAGE effect" case (no DAM, Table 2, fourth row).

Table 2: Modelling technology, damage, and energy market effect in the WITCH model

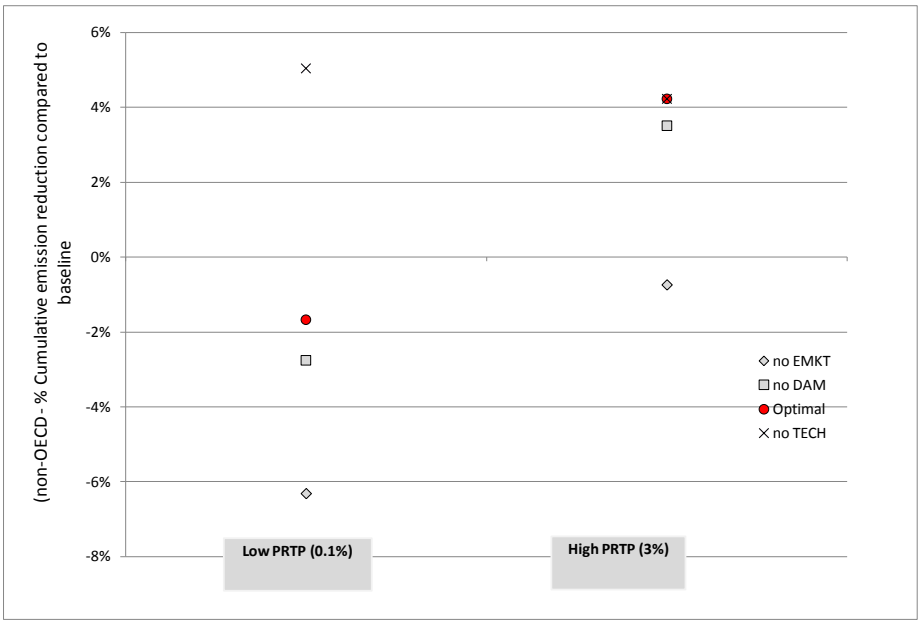
No Technology effect	**OECD**	**Non-OECD**
no international spillovers of knowledge	$\gamma = 0.15$ *For clean technologies*	$\gamma = 0$ *For all technologies*
no international spillovers of experience(no LBD)	$\theta_2 \neq 0$ *For clean technologies*	$\theta_2 = 0$ *For all technologies*
No Energy market effect	$P_{F_i} = F(\sum_n Q_{F_i}(n,t))$ *For fossil technologies*	$P_{F_i} = \bar{P}_{F_i}$ *as in baseline For fossil technologies*
No Damage effect	$D(n,t) = g(T(t))$	$D(n,t) = \bar{D}(n,t)$ *as in baseline*

Figure 2 reports the resulting change in non-OECD emissions with respect to the non-cooperative baseline in these three scenarios (no TECHNOLOGY, no ENERGY-MARKET and no-DAMAGE cases) as well as the case where all three effects are in active (the Optimal case). Results are shown for high and low discounting. We first concentrate on the low pure rate of time preference case (i.e. 0.1%), which is in line with the analysis in the previous section (left markers in Figure 2).

As an indicator of the non-OECD group' reaction function we plot the aggregate cumulative emissions reduction throughout the century with respect to the baseline. When the technology effect is turned off, the cost of clean technologies in non-OECD countries is unaffected by OECD innovation and technology use. Still, non-OECD countries see the reduced energy prices and perceive a lower damage. As a consequence, non-signatories' emissions are higher than in the optimal case because the energy and damage effects are not counterbalanced by clean innovation transfers. When the technology effect is silenced, the sign of carbon leakage becomes negative.

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 they still perceive the induced innovation in clean technologies. As a consequence, the adoption of the clean options is even more pronounced than in the optimal case, as reflected by the even lower cumulative emissions. Finally, when non-OECD countries are excluded from the environmental benefits due to the OECD's action, and they perceive the same temperature they would in the absence of any policy, this 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. The damage effect turns to be the smaller, in this example, as the temperature changes we are considering are very modest.

Figure 2: 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)



When a higher pure rate of time preference is considered (3%, right markers in Figure 2), the direction of each effect does not change, but the magnitude of each of them is largely and asymmetrically affected. In order to keep our focus on the reaction of non-signatories we assume the OECD level of emission reduction remain unchanged in the higher discount rate case, while

focusing on the changes in non-signatories' optimal reaction.[15] High discounting significantly shortens the time horizon of the social planners, making the benefits of technical change and reduced damage occurring after 2050 irrelevant compared to shorter term costs. Damages increase exponentially (see equation 4) and technology benefits take time to materialise. New inventions take between ten and five years to reduce investment costs or improve energy efficiency (equations 8 and 10). As a consequence, both the damage and the technology effects lose significance when the pure rate of time preference is 3%. The energy market effect, which has a shorter term nature, tends to prevail. This is true in both regions. OECD countries meet their goal adopting a different strategy. They invest less in innovation to bring down the cost of future carbon-free technologies, while spending more later in direct mitigation (e.g. substitution) and output contraction. The effect on technology costs due to OECD countries' myopic behaviour adds to non-signatories own myopia leading to overall positive carbon leakage, even in the optimal case when all three effects are at play. It is only excluding the energy market effect completely that we can again reverse the sign of carbon leakage.

In the model international spillovers of knowledge and experience are two distinct channels (see equation 10 and 8). Therefore, we consider two additional variations and explore the relative contribution of each of these two mechanisms. First, we assume that only knowledge investments are completely excludable. Think, for example, to a very tight property right system. This would affect the timing clean technologies would become competitive, as non-OECD countries could not benefit from knowledge spillovers nor affect knowledge in the coalition. Once a clean technology becomes competitive, though, cost improvements can diffuse freely outside the coalition by means of technology transfers. Under this scenario, non-signatories

[15] 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.

would 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 OECD countries. We refer to this case as the "no international knowledge spillovers" case (Table 2, first row). In the second case, there are 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 (Table 2, second row). We find that these two channels similarly contribute to emission reduction in non-signatory countries. Excluding either effect leads to an emission increase of about 3% each (note that the overall effect due to the technology effect is 5%, see Figure 2). While the "no Learning-By-Doing" case emphasises the benefits of cost improvements following technology adoption, the "no international knowledge spillover" case highlights the role of unintended knowledge diffusion preceding the breakthrough. 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.

4. Varying the coalition's effort

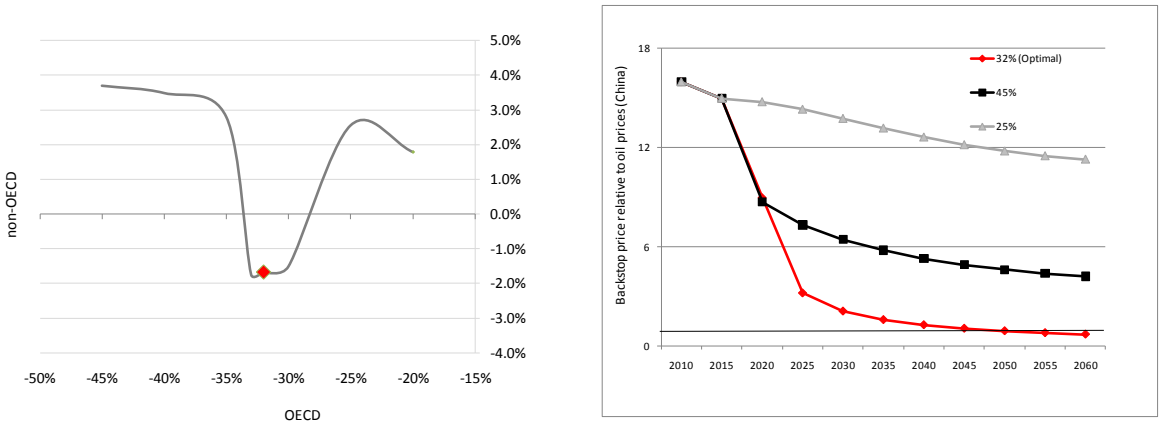
4.1 Varying the reduction commitments in OECD countries

We argued before that damage, energy market, and the technology effects depend on the effort undertaken by the coalition and by the decarbonisation pathways followed. In this Section we analyse how the reaction of non-OECD countries varies with the stringency of the coalition's target. We analyse 2050 target for the OECD coalition ranging from 20% to 50% emission

reduction compared to 2005 and identify a window of emission reduction targets that triggers proactive behaviour in non-signatory countries.

Figure 3, left panel, shows non-OECD cumulative emissions in reaction to different OECD targets. The U-shaped reaction function suggests that for extreme commitments by OECD countries, both too loose and too strict, leakage is positive. There exist however an intermediate range of targets for which leakage goes to zero or even switch sign. The endogenous OECD target from the previous section lies within this intermediate interval (dot in Figure 3 left panel).

Figure 3: Reaction function of non-OECD countries: cumulative CO2 emissions (2010-2100) compared to baseline (left panel). The red dot refers to the optimal case. Technology costs (right panel).



The key determinant of the reaction function shape is the trade-off between the energy market and the technology effect. When the coalition target is very loose (less than 30%) the abatement effort is achieved mostly by means of energy efficiency and substitution, which, being cheaper,

are the first measures to be adopted. Conversely, 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. Since players are forward-looking, non-OECD countries foresee a lower relative oil price path and lock in into a fossil–fuel-based energy portfolio.

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. The right panel of Figure 3 illustrates the trade-off between the energy market and technology effect. It shows the evolution of the cost of a carbon-free substitute to oil in the final-use sector, relative to oil price. When the coalition reduces emissions by 25%, the price of this alternative remains high and the clean technology is not adopted in non-signatories. When abatement increases to 35%, the technology penetrates also outside the coalition. When emissions are reduced by 45%, the decline in the oil price prevails, preventing the diffusion of the clean technologies despite its significant cost reduction.

4.2 Varying the coalition structure

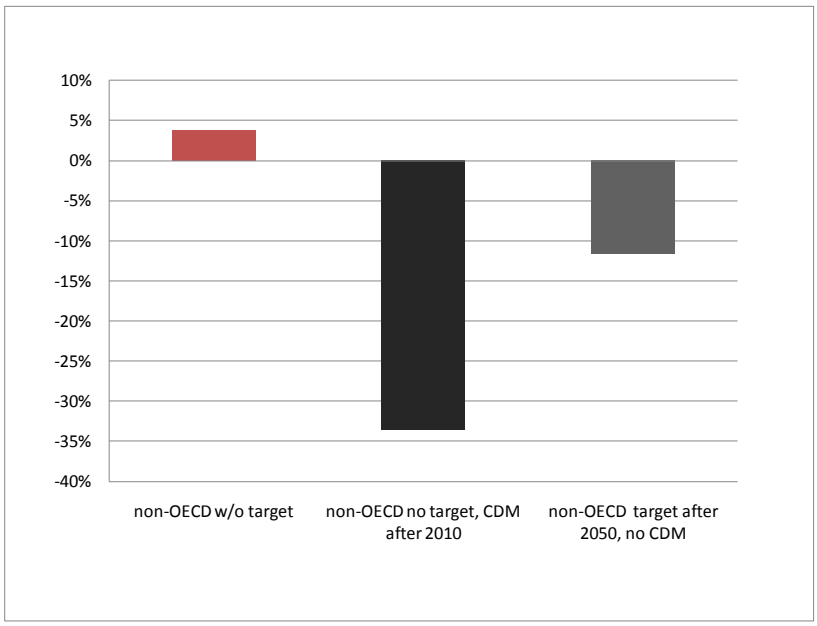
We have argued that very ambitious unilateral climate policies can be counterproductive because countries outside the coalition have the incentive to take advantage of lower energy prices and rely more on fossil-fuel-based energy. Section 4.1 showed that, to avoid boomerang effects, unilateral climate policies should aim at moderate targets. In addition, 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 holds true if non-signatory countries expect never to take any mitigation action. Should developing countries anticipate a future credible commitment, this would allow more ambitious efforts by the OECD group. We explore two cases, the first in which non-OECD do

not have specific emission reduction targets, but take part to the international carbon market[16] through mechanisms such as the Clean Development Mechanisms (CDM). The second case assumes no CDM, but a domestic target that stabilises non-OECD emissions after 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, offsetting leakage. Expectations about future commitments could reverse the sign of carbon leakage (Figure 4, right-most bar), while the left-most bar shows the optimal response under the "never to commit" assumption. The central bar illustrates the optimal reaction of non-OECD when they have the option to join a carbon market after 2010. Any emission reduction compared to baseline would then be remunerated at the price of carbon in place within the coalition. In this case non-signatories have an almost immediate incentive to reduce their emissions in order to sell carbon credits on the international market. As expected, both engagements would motivate a proactive reaction even for a stricter target that would otherwise lead to carbon leakage.

Figure 4: 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

[16] We assumed that in this case non-OECD countries do not increase emissions above baseline levels.



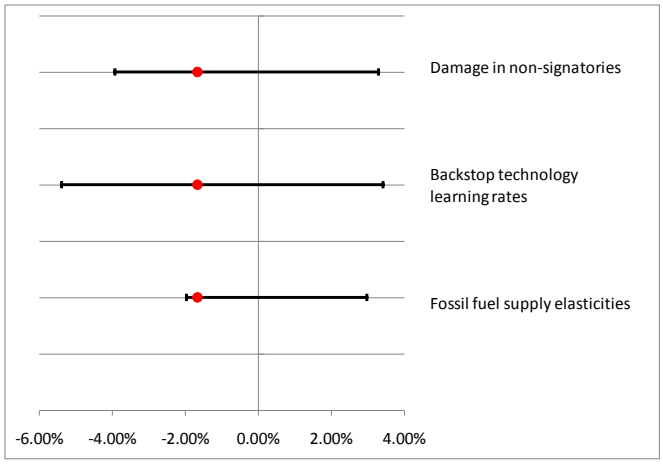
5. Sensitivity to technology diffusion, elasticity of energy markets and climate change damages

The paper shows 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. 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 We test the robustness of our conclusion to alternative assumptions concerning technology cost and climate change damage functions. We start from the key assumptions that have been identified by the literature on carbon leakage. Supply elasticities of fossil fuels play a pivotal role [12,27]. 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 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 to 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. In red the central case and error bars show the plus and minus 20% variations.



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 [12]). 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 convex path of fossil fuel prices leads to an

asymmetric effect. 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.

6. 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 happening and developed economies have made spoken agreements on long-term common targets several times. However, they also share the common fear that, given unilateral action, the response of non-signatories could erode their mitigation action.

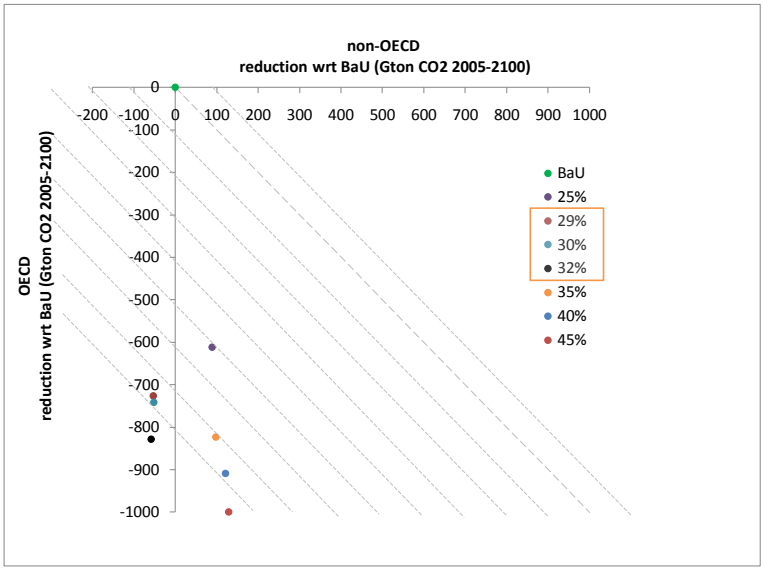
This paper illustrates how an ensemble of factors drives the response of non-participatory countries: the perception of climate change damages, fossil fuel prices, and the efficacy of technology and knowledge transfers. Free-riding incentives and carbon leakage induce non-members to increase emissions compared to their baseline behaviour. However, if innovations

and technology advancements achieved within the coalition extend to non-signatories, emissions can be reduced. 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. Cost-benefit considerations would lead the OECD coalition to follow an abatement path entailing 2050 emissions 30-35% below 2005 levels. It is interesting to note that optimal short-run emissions are in line with the Annex I's Copenhagen conditional pledges. Our study show that these pledges, often criticised for being too mild, have a very important implication: the reaction of non-OECD is proactive. Because international knowledge spillovers and technology transfers counterbalance the energy market effect, non-OECD countries switch to cleaner technologies although not because part of the agreement, reducing their emissions compared to baseline.

Figure 6 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 $\geq$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 6: OECD and non-OECD emission strategies on each axis. The projection on the y-axis of each scenario represents the global emission cut. The box highlights the targets that lead to negative carbon leakage



Of course these are simulations results and should be taken with caution and a grain of salt. Nonetheless, the qualitative insights bear some relevant insight for the current debate on climate negotiations. Indeed, 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 targets are moderate, near-term cooperation between technologically advanced countries could trigger a virtuous behaviour in non-signatory countries as well.

These results imply that effective policies to address carbon leakage should promote the international transfer of technologies rather than threaten border adjustment measures that might

actually shut down important channels of diffusion, such as trade and FDI, and should not be used as a scapegoat for inaction. The international transmission of innovation to non-signatory countries also reduces the risk of carbon leakage, suggesting that policies aiming at adjusting the regimes of intellectual property rights accordingly can play a very important role. For example, green tags that help to signal green ideas and entitle them to a fast track evaluation process could better serve the purpose of innovation diffusion..

Given that developing countries, on the basis of ethical motivations, condition their decision to cooperate on the mitigation effort undertaken by industrialised countries, the OECD represents the appropriate starting coalition, to be followed by a subsequent enlargement of the coalition in the mid, longer-term future. By looking at a two-phase negotiation set-up, we show that moderate future, but credible commitments by developing countries significantly mitigates the risk of carbon leakage associated with more ambitious targets in the OECD.

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