Climate Change Mitigation with Technology Spillovers

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Abstract

We explore the implications of an increase in clean technology spillovers between developed and developing countries. We build a game of abatements in which players are linked with technology spillovers determined by an initial choice of absorptive capacities by developing countries. We show that, within a non-cooperative framework, the response of clean technology investments in developed countries to an increase in cross-country technology spillovers is ambiguous. If the marginal benefits of these additional abatements are not sufficiently high, developed countries have a strategic incentive to decrease investments. Such a strategic response jeopardizes the initial effects of an increase in technology spillovers on climate change mitigation and decreases the incentives for developing countries to enhance their absorptive capacities.

Keywords: climate change; cross-country spillovers; abatements; technology investments.
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1 Introduction

Fostering North-South climate-friendly technology diffusion requires developing countries to enhance their absorptive capacities. An important part of this effort is the result of international agreements, the most important ones being financing mechanisms such as the Clean Development Mechanism (CDM) of the Kyoto Protocol, the Global Environment Facility (GEF), the new Carbon Partnership Facility or the Clean Technology Fund. [1]

Developing countries have indeed been reluctant to unilaterally bear the costs of these technology transfers and therefore have conditioned their participation to climate change mitigation effort upon receiving financial aid from developed countries. In the 2010 Cancun summit, developed countries committed to jointly provide US$ 100 billion per year by 2020 to support the low-carbon transition of developing countries (UNFCCC, 2010).[2] The latest estimates of climate finance show that the aggregate volume of public and private climate finance mobilized by developed countries for developing countries reached US$ 61.8 billion in 2014, up from US$ 52.2 billion in 2013 (OECD, 2015). These financial resources are used to carry out projects in various sectors such as energy, transports, biodiversity, agriculture and water protection. Importantly, these projects encapsulate environmental technology diffusion as they include transfers of know-how, equipment and organizational procedures that are invented in developed countries.[3]

In this paper, we provide an economic rationale for the financing of clean technology absorptive capacities in developing countries by developed countries, beyond any historical considerations suggesting that developed countries are responsible for global warming and therefore should bear most of the costs of the mitigation. We show that an increase in developing countries absorptive capacities may benefit more developed countries for two reasons. First, with larger absorptive capacities, developing countries provide additional abatements on which developed countries free ride. Second, absorptive capacities affect the incentives for developed countries to invest in clean technology. In particular, higher absorptive capacities may deter investment. As a result, without

[1] These initiatives are often combined with more general policies in developing countries (Dechezleprêtre et al., 2008). Changes in absorptive capacities can also be the consequence of changes in environmental regulation (Lanjouw & Mody, 1996; Hilton, 2001; Gallagher, 2006). Other options are openness to trade, foreign direct investment and by strengthening education and skills. See Dutz & Sharma (2012), Popp (2011), World Bank (2010), Dechezleprêtre et al. (2011) and Dechezleprêtre et al. (2013) for discussions.

[2] This objective was reconfirmed in the Paris Agreement of COP 21 in December 2015.

[3] For instance, Popp (2011) discusses evidence on the transfers of climate friendly technologies through projects in the framework of the Clean Development Mechanisms (CDM) of the Kyoto Protocol.

additional transfers developing countries may bear a larger part of the climate change mitigation burden, and even lose from an increase in their absorptive capacities.

We build a 3-stage game in which a developed and a developing country are linked with technology spillovers. We solve it by backward induction. In the last stage, countries non-cooperatively choose their level of abatements. In the second stage, the developed country invests in a technology that reduces the marginal costs of abatements of both countries. In the first stage, the developing country chooses its absorptive capacities that determines the level of technology spillovers between the two countries. A cooperative and a non-cooperative variant of this stage are considered. We choose this timing in order to reflect the influence of technology spillovers on investment in technology, in order to reflect actual negotiations on technology transfers. In practice however, investment in technology and enhancements of absorptive capacities do not follow a unique sequence. When choosing investment in technology, developed countries may also anticipate future technology transfers. For this reason we also study an alternative timing in which investment in technology happens before the enhancement of absorptive capacities.

We start by solving the last two stages of the game. We derive some comparative statics on the impact of the level of spillovers on technology investment, abatements and payoffs. For a given level of technology, an increase in technology spillovers leads to a reallocation of the abatement effort from the developed to the developing country (a variant of the well-known carbon leakage effect). We show that this effect is further exacerbated if the increase in spillovers leads to a decrease in climate-friendly technology investments that the developed country makes in stage 2. This occurs when the marginal benefits of abatements are steep. In particular, this could be the case if there is a well-identified level of abatements around which a catastrophe is avoided, and if the preferences for the public good are such that both countries expect the catastrophic event to be avoided even with limited spillovers. Using these results, we solve the first stage of the game to find the optimal level of absorptive capacities set by the developing country.

We then modify the fist stage to allow for the developed and the developing country to reach an agreement in order to share the gains generated by an increase in a cooperatively chosen level of technology spillovers. In this Nash bargaining process, we assume that both countries have equal power over the negotiations. We show that the developing country may require monetary transfers from the developed country above the cost of enhancing absorptive capacities in order to use clean technologies invented in the latter. As a benchmark, we also solve for the cooperative level of both technology and absorptive capacities.

Both climate-friendly frontier innovations and resulting technology transfers are concentrated in industrialized countries. However, technology diffusion from developed to developing countries is non-negligible and could be scaled-up (Dechezleprêtre et al., 2011). A sensible green growth strategy for developing countries is more about catch-up innovations and diffusion of already-existing technologies than frontier innovations (Dutz and Sharma, 2012).

In this paper, we consider that enhancing absorptive capacities in developing countries requires a combination of specific policies targeted at the environment. Unlike other types of innovation, environmentally friendly technologies suffer from two market failures that should in principle be addressed with two sets of instruments (Jaffe et al., 2005; Popp, 2010). First, innovation policies create incentives for the development of abatement technologies. These include R&D subsidies and funding for research with a specific focus on the environment. Second, environmental regulation ensures the adoption of these technologies by creating a market through the correction of externalities related to pollution. For instance, this can be done relying on market-based instruments such as carbon taxes or Emissions Trading Schemes.

In addition, the adoption of foreign technology can be increased via channels such as trade, foreign direct investment, human capital investments or facilitating global connectivity through the insertion of firms into the global value chain.[4] Again, these policies can be specifically targeted at the absorption of (foreign) clean technologies. For example, Dutz and Sharma (2012) argue that the rapid development of wind energy capacities in China and India was made possible because of licensing agreements with European manufacturers and international mobility of workers, which allowed access to foreign technology.

Our paper relates to several strands of the economic literature. A series of papers have addressed how the presence of technology spillovers could affect the incentives to join a self-enforcing International Environmental Agreement (IEA) (Barrett, 2006; Carraro et al., 2006; De Conink et al., 2008; Hoel & de Zeeuw, 2010). The approach adopted in this paper is different: unlike an IEA in which some of the countries cooperate, we consider a non-cooperative framework. Another line of research has focused on the implications of investments in clean technology in a transboundary

[4]See Dutz & Sharma (2012), Popp (2011), World Bank (2010), Dechezleprêtre et al. (2011) and Dechezleprêtre et al. (2013) for discussions.

pollution control model (Van der Ploeg & de Zeeuw, 1994; Xepapedeas, 1995). Unlike us, these papers consider technology transfers to be fixed and countries to be identical. Our contribution relates more closely to Golombek & Hoel (2004), who show that for a given level of technology spillovers, if a developed country starts caring more about the environment, it will increase both its R&D expenditures and abatements. Depending on the slope of the benefits from aggregate abatements, the developing country may in turn choose to decrease its abatements. Our approach differs in the sense that we take preferences over the environment as given and let the technology spillovers vary.

In our model, the possibility of spillovers decreasing the R&D investment comes from marginally decreasing benefits from abatements. Hence, while building on a setting similar to Beccherle & Tirole (2011) and Schmidt & Strausz (2014), we identify a novel effect because these papers assume linear benefits. This paper also relates to a strand of the industrial organization literature that considers the strategic dimension of investments. In particular, Fudenberg & Tirole (1984) and Bulow et al. (1985) are two independent works that address the role of investments on ex post firms' behaviors in a non-cooperative framework. This paper shows how such strategic considerations apply in a global public good provision game. Finally, we consider international spillovers, as opposed to R&D spillovers between profit maximizing firms in a given country (as for instance in Ulph and Ulph, 2007).

We present and solve the general model in Section 2. We introduce the alternative timing in Section 3. We allow for cooperation in the first stage in Section 4. In Section 5, we provide more intuition about our results by solving the game for two analytical functions. We discuss the policy implications of our results and conclude in Section 6.

2 The model

The world is populated by two countries that play a 3-stage game. The two countries are asymmetric in their technology endowment. Country 1 - the developed country - is the only one able to choose to invest in a technology that lowers abatement costs.[5] Country 2 - the developing country - is able to capture the benefit of the investments made by country 1 through technology spillovers.

[5] In practice, this encompasses a number of policies in favor of public and private investment in clean technologies, but we follow the standard specification that a country directly invests in a level of technology.

Country 1 and country 2 have the following payoff functions:

$$\pi_1 = b(a_1 + a_2) - c(a_1, x) - \alpha x \tag{1}$$

$$\pi_2 = b(a_1 + a_2) - c(a_2, \gamma x) - \kappa\gamma \tag{2}$$

where $a_i, i \in \{1,2\}$ is the abatement of country i in the third stage, $b(.)$ and $c(.)$ are the benefit functions of (common) abatements and the cost function of (private) abatements respectively. Clean technology investments made by country 1 in the second stage are represented by x, provided at constant linear cost $\alpha > 0$. The parameter $\gamma \in [0,1]$ accounts for the intensity of technology transfers through technology spillovers between the developed and the developing country.[6] The degree of spillovers is determined by the level of absorptive capacities set by the country 2 in stage 1 at a constant linear cost $\kappa > 0$. We choose this timing in order to study the strategic effects of technology spillovers on developed country's investment in clean technology and ultimately on each country's welfare.

Throughout the rest of the paper, we make the following general assumptions:

$$\begin{gathered} b' = \frac{\partial b}{\partial a} \geq 0\,;\; c' = \frac{\partial c}{\partial a} \geq 0\,;\; \frac{\partial c}{\partial x} \leq 0\,;\; b'' = \frac{\partial^2 b}{(\partial a)^2} < 0 \\ c'' = \frac{\partial^2 c}{(\partial a)^2} > 0\,;\; \frac{\partial^2 c}{\partial a \partial x} \leq 0\,;\; \frac{\partial^2 c}{\partial x^2} \geq 0 \end{gathered} \tag{3}$$

Benefit and cost functions are continuous and twice differentiable, marginal benefits of (global) abatements are decreasing, marginal costs of (private) abatements are increasing and investments lower the abatement costs. Furthermore, investments in clean technology also lower the marginal costs of abatements. Finally, returns on investments in technology and absorptive capacities are diminishing.

We look for subgame perfect Nash equilibria and solve the game by backward induction. Hence, we start with the analysis of the third stage.

[6] We borrow this specification of imperfect spillovers from Spence (1984).

2.1 Third stage

In this stage, country 1 and country 2 decide simultaneously how much abatement to provide. Best responses of each country are given by:

$$a_1(a_2,x,\gamma) = \arg\max_{a_1} b(a_1+a_2) - c(a_1,x) \quad (4)$$

$$a_2(a_1,x,\gamma) = \arg\max_{a_2} b(a_1+a_2) - c(a_2,\gamma x) \quad (5)$$

The choices of abatements are determined by a Nash equilibrium $\{a_1^*(x,\gamma), a_2^*(x,\gamma)\}$, which is characterized by the following conditions:

$$b' = \frac{\partial c(a_1,x)}{\partial a_1} \quad (6)$$

$$b' = \frac{\partial c(a_2,\gamma x)}{\partial a_2} \quad (7)$$

At equilibrium, as abatements are a global public good, equations (6) and (7) imply that $\partial c(a_1,x)/\partial a_1 = \partial c(a_2,\gamma x)/\partial a_2$. As we have $0 \leq \gamma \leq 1$, it must be that:

$$a_1^* \geq a_2^*. \quad (8)$$

This result is the consequence of the fact that players are asymmetric in their abatement costs. The most efficient player (the developed country) provides more abatements than the least efficient one (the developing country).

Lemma 1 *For every x, $\partial a_1^*/\partial\gamma \leq 0$ while $\partial a_2^*/\partial\gamma \geq 0$. However, $\partial(a_1^*+a_2^*)/\partial\gamma \geq 0$.*

Proof. See Mathematical Appendix. ■

The intuition underlying Lemma 1 is that, for a given level of technology investment x, an increase in γ results in the two countries becoming more symmetric. Country 2, which initially provides less abatement (equation (8)), provides more. Conversely, country 1 reduces its abatement provision. Thus, all other things held constant, an increase in γ is also a transfer of abatements from the most to the least efficient country. It generates a *carbon leakage* and the burden of climate change mitigation is redistributed towards country 2. However, the net effect on the sum of abatements is positive. Indeed, an increase in γ also implies a reduction in the overall abatement costs (i.e. abatement costs of country 1 are unchanged but abatement costs of country 2 are reduced). Since it is cheaper to abate, aggregate abatements increase. In the special case of quadratic costs that we further develop in Section 5, $c(a_1,x) = {}^{a_1^2}/_{2x}$ and $c(a_2,\gamma x) = {}^{a_2^2}/_{2\gamma x}$, equations (6) and (7) simplify to

$$b' = \frac{a_1}{x} = \frac{a_2}{\gamma x}. \tag{9}$$

Hence, $a_2^* = \gamma a_1^*$.

2.2 Second stage

In the second stage of the game, country 1 determines the optimal investment x that both countries will use in the third stage. Formally, country 1 faces the following maximization problem:

$$x^* = \arg\max_x \; b(a_1^* + a_2^*) - c(a_1^*,x) - \alpha x. \tag{10}$$

Equilibrium investment x^* is then determined by the first-order condition of this maximization problem, which is given by:

$$b' \frac{\partial a_2^*}{\partial x} - \frac{\partial c}{\partial x} - \alpha = 0. \tag{11}$$

Thus, a characterization of the Nash equilibrium of the subgame composed of the second and the third stages is a set of strategies $\{x^*(\gamma), a_1^*(x,\gamma), a_2^*(x,\gamma)\}$.

Equation (11) shows that country 1 considers the effects of its own investments (in clean technology) on country 2. That is, in the presence of technology spillovers, investment has an *indirect effect* as it changes country 2's ex post abatements. This effect is described by ${}^{\partial a_2^*}/_{\partial x}$ in equation (11).

In general, the sign of this effect is ambiguous, as an increase in technology reduces costs for country 2 but has an higher impact on the costs of country 1. However, in the special case of the quadratic costs $c(a_1,x) = {}^{a_1^2}/_{2x}$ and $c(a_2,\gamma x) = {}^{a_2^2}/_{2\gamma x}$, we can derive the following additional results.

Claim 1 *With quadratic costs of abatement, for $\gamma \in [0,1]$, ${}^{\partial a_1^*}/_{\partial x} \geq 0$ and ${}^{\partial a_2^*}/_{\partial x} \geq 0$. As a result,* ${}^{\partial (a_1^*+a_2^*)}/_{\partial x} \geq 0$.

Proof. See Mathematical Appendix. ■

Corollary 1 *With quadratic costs of abatement, for $\gamma \in [0,1]$, ${}^{\partial a_2^*}/_{\partial x} = \gamma\, {}^{\partial a_1^*}/_{\partial x}$. As a result, ${}^{\partial a_2^*}/_{\partial x} \leq {}^{\partial a_1^*}/_{\partial x}$.*

Proof. See Mathematical Appendix. ■

The response of x^* to a change in γ is crucial to determine final payoffs. Country 2 anticipates this reaction when determining its optimal level γ in stage 1. To help us understand this choice, we now study in more details the strategic interaction between γ and x^*.

2.3 Increased technology spillovers: comparative statics

In this section, we carry out the analysis of the effects induced by an increase in technology spillovers on abatements and payoffs at equilibrium. Such effects on a_i, $i \in \{1,2\}$ are formally given by:

$$\frac{da_i^*}{d\gamma} = \underbrace{\frac{\partial a_i^*}{\partial \gamma}}_{\text{Direct effect}} + \underbrace{\frac{\partial a_i^*}{\partial x}\frac{\partial x^*}{\partial \gamma}}_{\text{Indirect effect}}. \tag{12}$$

We see that the total effect of an increase in γ on abatements is the sum of two distinct effects. First, the direct effect on abatements described in Lemma 1. Second, the indirect effect through investments x. We must now sign ${}^{\partial x^*}/_{\partial \gamma}$, that is, country 1's investments response to changes in technology spillovers.

Proposition 1 *Equilibrium investments by country 1 increase with technology spillovers whenever the benefits from additional abatements generated by an improved technology are sufficiently high. A necessary and sufficient condition is given by:*

$$b' \frac{\partial^2 a_2^*}{\partial x \partial \gamma} \geq -b'' \frac{\partial a_2^*}{\partial \gamma}\left(\frac{\partial a_1^*}{\partial x} + \frac{\partial a_2^*}{\partial x}\right) \tag{13}$$

Proof. Thanks to assumptions (3) and the implicit function theorem, ${}^{\partial x^*}/_{\partial \gamma}$ has the same sign as ${}^{\partial^2 \pi_1}/_{\partial x \partial \gamma}$. Therefore, we have that:

$$\frac{\partial^2 \pi_1}{\partial x \partial \gamma} = b' \frac{\partial^2 a_2^*}{\partial x \partial \gamma} + b'' \frac{\partial a_2^*}{\partial \gamma}\left(\frac{\partial a_1^*}{\partial x} + \frac{\partial a_2^*}{\partial x}\right) \tag{14}$$

■

The sign of equation (14) is ambiguous which implies that condition (13) might not be fulfilled. The intuition underlying Proposition 1 is as follows. Provided that ${\partial^2 a_2^*}/{\partial x \partial \gamma} \geq 0$, when γ increases, country 2 is more responsive to country 1's investments. As a result, incentives for country 1 to invest increase. This is illustrated by the first term of the right-hand side of equation (14). On the other hand, for a given x, the additional abatements provided by country 2 have a lower marginal value as marginal benefits of abatements are declining. Consequently, incentives for country 1 to invest decrease. This is illustrated by the second term of the right-hand side of equation (14). The sum of these two effects determines the reaction of x to an increase in γ.

Moreover, it is not necessarily the case that ${\partial^2 a_2^*}/{\partial x \partial \gamma} \geq 0$,[7] as the sign of this expression depends on the third-derivatives of the benefit functions for which we make no specific assumptions. If ${\partial^2 a_2^*}/{\partial x \partial \gamma} \leq 0$, it follows directly that ${\partial^2 \pi_1}/{\partial x \partial \gamma} \leq 0$ and country 1 decreases investments x^* as γ increases.

The decline in marginal benefits of abatements is crucial to understand the impact of an increase in cross-country technology spillovers. High absolute values of b'' tend to reduce the impact of γ on the marginal benefit of technology investments in country 1. At a given equilibrium in the subgame composed of the last two stages, if the next abatement has an arbitrarily low value (that is, if b'' is arbitrarily high in absolute value at that point), country 1 will reduce its technology investments as a response to an increase in technology spillovers. The reason is that country 1's investments response will accordingly attenuate or exacerbate the carbon leakage defined in Lemma 1. In the special case of the quadratic costs studied in the examples, $c(a_1, x) = {a_1^2}/{2x}$ and $c(a_1, \gamma x) = {a_2^2}/{2\gamma x}$, and if ${\partial x^*}/{\partial \gamma} \geq 0$, from Lemma 1 and Claim 1, we have:

$$\frac{da_1^*}{d\gamma} = \underbrace{\frac{\partial a_1^*}{\partial \gamma}}_{\leq 0} + \underbrace{\frac{\partial a_1^*}{\partial x}\frac{\partial x^*}{\partial \gamma}}_{\geq 0} \tag{15}$$

and we see that the indirect effect of increased investments limits the direct adverse reaction of country 1's abatements to an increase in technology spillovers. In contrast, by decreasing its investments, country 1 exacerbates carbon leakage. In doing so, country 1 chooses a world with

[7] In the examples we provide, this condition however always holds.

less additional abatement provided by country 2, but with more free riding. To see this, note that:

$$\frac{da_1^*}{d\gamma} - \frac{da_2^*}{d\gamma} = \underbrace{\left(\frac{\partial a_1^*}{\partial \gamma} - \frac{\partial a_2^*}{\partial \gamma}\right)}_{\leq 0} + \underbrace{\left(\frac{\partial a_1^*}{\partial x} - \frac{\partial a_2^*}{\partial x}\right)}_{\geq 0} \frac{\partial x^*}{\partial \gamma} \tag{16}$$

from Lemma 1 and Corollary 1. As γ increases, the difference between country 1 and country 2's abatements decreases even further if ${}^{\partial x^*}/_{\partial \gamma} \leq 0$.

Thus, as cross-country spillovers increase, country 1 observes that country 2 is more able to abate. One would expect rising γ to increase investments in country 1 as they can now increasingly benefit country 2. This is only true if the marginal benefits of these additional abatements are high enough. Otherwise, country 1 takes the increased capability of country 2 as an opportunity to shift the burden of climate change mitigation instead of providing it with further incentives to abate. As its capacity to abate increases, country 2 might be left with a more difficult challenge.

Finally, we can characterize the welfare implications of an increase in cross-county technology spillovers.

Proposition 2 *At equilibrium, an increase in technology spillovers makes country 1 better off. Country 2 is better off with marginally higher technology spillovers if and only if:*

$$\frac{\partial b}{\partial a}\frac{da_1^*}{d\gamma} \geq \frac{\partial c}{\partial \gamma} + \frac{\partial c}{\partial x}\frac{\partial x^*}{\partial \gamma} \tag{17}$$

Proof. See Mathematical Appendix ■

The intuition underlying Proposition 2 is that country 1 is better off with an increase in technology spillovers as it can now free ride on the additional abatements provided by country 2. The effect on the payoff of country 2 is ambiguous. Country 2 observes a direct effect of decreasing abatements of country 1 (the carbon leakage). However, as equation (15) shows, this adverse effect is attenuated if country 1 increases investment in response to an increase in technology spillovers. In this case, country 2 can enjoy a reduction in abatement costs thanks to the additional technology provided by country 1. Thus, the sign of the left-hand side of equation (17) is ambiguous as the sign of ${}^{da_1^*}/_{d\gamma}$ is ambiguous. The first term on the right-hand side is clearly negative, as the direct impact of spillovers is to decrease costs. The sign of the second term is however also ambiguous.

While the effect of a better technology is to decrease the costs ($\partial c/\partial x < 0$), the effect of spillovers can be either to increase or decrease the equilibrium investment in technology (as shown in Proposition 1). This also implies that if country 1 could commit to a certain level of investment in R&D after the enhancement of absorptive capacities take place, country 2 would always be better off when technology spillovers increase. If such a commitment were possible and credible, most of the problems documented in the present paper would be mitigated.

Hoel (1991) and Golombek & Hoel (2004) show that with marginally decreasing benefits from abatements, one country caring more about the environment may induce the other one to abate less in equilibrium. In their paper, an increase in the environmental sensibility of a developed country always increases the investment in technology, as this country directly benefits from the investment for the additional abatements that it provides. Our case is different. Instead of measuring the impact of a change in preferences, we measure the impact of a change in the level of spillovers. If spillovers increase, the developed country has the opportunity to impose more of the climate change mitigation burden on the developing country. As Propositions 1 and 2 show, this might result in lower investment in technology by the developed country, and a net loss for the developing country.

2.4 First stage

In the first stage, the developing country 2 chooses the level of its absorptive capacities before technology investment by the developed country 1. As the developed country makes all its technology available, absorptive capacities are equal to the level of spillovers γ. There is a positive marginal cost κ to enhance absorptive capacities. The equilibrium level of absorptive capacities in the first stage directly follows from Proposition 2, by comparing the (possibly negative) marginal impact of increased spillovers on the payoffs of country 2 and the marginal cost of enhancing absorptive capacities.

Proposition 3 *The subgame perfect level of absorptive capacities is given by γ^*, and solves*

$$\kappa = \frac{\partial b}{\partial a}\frac{da_1^*}{d\gamma} - \frac{\partial c}{\partial \gamma} + \frac{\partial c}{\partial x}\frac{\partial x^*}{\partial \gamma}, \tag{18}$$

if there exists an interior solution $\gamma \in (0,1)$ to the first stage maximization problem of the developing country 2. Else, $\gamma^* = 0$ if $\kappa > \frac{\partial b}{\partial a}\frac{da_1^*}{d\gamma} - \frac{\partial c}{\partial \gamma} + \frac{\partial c}{\partial x}\frac{\partial x^*}{\partial \gamma}$, $\forall \gamma \in (0,1)$ and $\gamma^* = 1$ if $\kappa < \frac{\partial b}{\partial a}\frac{da_1^*}{d\gamma} - \frac{\partial c}{\partial \gamma} + \frac{\partial c}{\partial x}\frac{\partial x^*}{\partial \gamma}$, $\forall \gamma \in (0,1)$.

Proof. The proof follows directly from condition (17). If there exists an interior solution the developing country enhances its absorptive capacities up to the point where its marginal benefit (the right-hand side of equation (18)) equates the marginal cost κ. ■

This proposition shows that the reason for which a developing country does not enhance absorptive capacities is not necessarily that the cost κ is too high, but that the strategic consequences are not always positive. Hence, trying to design monetary transfers between developed and developing countries based on κ alone might misestimate the total costs, that include the possibly adverse effect from the strategic behaviour of the developed country.

3 Alternative timing

Consider now an alternative timing, where technology is chosen first and enhancement of absorptive capacities afterwards. In the third stage, country 1 and country 2 decide simultaneously how much abatement to provide. As before, the equilibrium level of abatements in this last stage is characterized by $b' = \frac{\partial c(a_1,x)}{\partial a_1} = \frac{\partial c(a_2,\gamma x)}{\partial a_2}$.

In the second stage, the developing country 2 chooses the level of its absorptive capacities given the technology investment by the developed country 1. The subgame perfect level of absorptive capacities is given by γ^*, and solves

$$\kappa = \frac{\partial b}{\partial a}\frac{da_1^*}{d\gamma} - \frac{\partial c}{\partial \gamma}, \tag{19}$$

if there exists an interior solution $\gamma \in (0,1)$ to the second stage maximization problem of the developing country 2. Else, $\gamma^* = 0$ if $\kappa > \frac{\partial b}{\partial a}\frac{da_1^*}{d\gamma} - \frac{\partial c}{\partial \gamma} + \frac{\partial c}{\partial x}\frac{\partial x^*}{\partial \gamma}$, $\forall \gamma \in (0,1)$ and $\gamma^* = 1$ if $\kappa < \frac{\partial b}{\partial a}\frac{da_1^*}{d\gamma} - \frac{\partial c}{\partial \gamma} + \frac{\partial c}{\partial x}\frac{\partial x^*}{\partial \gamma}$, $\forall \gamma \in (0,1)$.

If there exists an interior solution the developing country enhances its absorptive capacities up to the point where its marginal benefit (the right-hand side of equation (19)) equates the marginal cost κ.

In this timing, the enhancement of absorptive capacities is not influenced anymore by the anticipated level of technology offered by the developed country 1. The first element of the right-hand side of (19) is negative (higher spillovers decrease the abatement of country 1), while the second is positive (higher spillovers decrease the costs). As compared to the timing outlined in Section 2, there are fewer incentives to invest for the developing country, unless the impact of higher spillovers was to decrease investment in technology by the developed country.

In the first stage, country 1 determines the optimal investment x that both countries will use in the third stage. It is the solution to the first-order condition of this country's maximization problem, which is given by:

$$b'(\frac{\partial a_2^*}{\partial x} + \frac{\partial a_2^*}{\partial \gamma}\frac{\partial \gamma}{\partial x}) - \frac{\partial c}{\partial x} - \alpha = 0 \tag{20}$$

The difference with the previous timing is that this time the developed country 1 anticipates the impact of its investment on the enhancement of absorptive capacities of the developing country in period 2. The strategic effect can be disentangled in two parts. First, the developed country may be reluctant to invest in technology if it expects the developing country to react by choosing a low γ. Second the developed country may invest more to compensate for the fact that the developing country will not enhance its absorptive capacities. We come back to this timing in the simulations in Section 5.

4 Nash bargaining over absorptive capacities

As discussed in the introduction, joint implementation of technology transfers is largely promoted by international institutions. It is therefore natural to think of enhancement of absorptive capacities as being the result of a cooperation between developed and developing countries in the first stage. We assume that countries need to reach an agreement in order to share the gains generated by an increase in technology spillovers. This case is therefore in deliberate contrast to the one presented in the previous Section, where absorptive capacities enhancement was chosen unilaterally by the developing country. We model this process as a Nash bargaining that takes place among countries in the first stage in order to decide on the level of technology spillovers to be implemented and the associated monetary transfers $T(\gamma)$ so that (4) and (5) become

$$\pi_1 = b(a_1 + a_2) - c(a_1, x) - \alpha x - T(\gamma) \tag{21}$$

$$\pi_2 = b(a_1 + a_2) - c(a_2, \gamma x) - \kappa\gamma + T(\gamma) \tag{22}$$

As we allow for all possible monetary transfers, spillovers are chosen cooperatively in order to maximize joint surplus in the first period, solving by backward induction for the impact of γ on x^* and a^*. Using (21) and (22), if there exists an interior solution, the cooperative level of spillovers $\hat{\gamma}$ solves

$$\kappa = \frac{\partial b}{\partial a}\left(\frac{da_1^*}{d\gamma} + \frac{\partial a_2^*}{\partial\gamma}\right) - \frac{\partial c}{\partial\gamma} + \frac{\partial c}{\partial x}\frac{\partial x^*}{\partial\gamma}. \tag{23}$$

Comparing (23) and (18), it is straightforward that $\hat{\gamma} \geq \gamma^*$, as when the level of absorptive capacities is decided cooperatively the benefits on the developed country 1 are internalized. As in Proposition 2, corner solutions $\hat{\gamma} \in \{0, 1\}$ exist if no value of γ satisfies (23). We define bargaining over technology spillovers as follows:

The outcome of a Nash bargaining over the gains generated by an increase in technology spillovers is a pair $(\hat{\gamma}, T)$, with $\hat{\gamma}$ defined in (23) if it is not a corner solution, and T the (possibly negative) monetary transfers from the developed to the developing country. As any technology spillover is the consequence of an agreement between countries, we assume the disagreement point to be $\gamma = 0$. We assume the bargaining power of developed and developing countries to be $(1-\beta)$ and β respectively. [8]

Proposition 4 *Under Nash bargaining over the level of absorptive capacities, a level of spillovers $\hat{\gamma}$ is implemented with a monetary transfer T that solves,*

$$T(\hat{\gamma}) = \beta \int_0^{\hat{\gamma}} \frac{\partial b}{\partial a}\frac{\partial a_2^*}{\partial\gamma} d\gamma - (1-\beta) \int_0^{\hat{\gamma}} \left(\frac{\partial b}{\partial a}\frac{da_1^*}{d\gamma} - \frac{\partial c}{\partial x}\frac{\partial x^*}{\partial\gamma} - \frac{\partial c}{\partial\gamma} - \frac{\partial\kappa}{\partial\gamma}\right) d\gamma. \tag{24}$$

Proof. See mathematical appendix. ■

[8] For a Nash bargaining solution to be implementable, the enhancement of absorptive capacities must be contractible. Else, the developing country could perfectly accept a transfer T to increase spillovers and not improve absorptive capacities if it decreases its surplus.

As for the previous results, the equilibrium transfers depend on the curvature of the benefit curve. Equation (24) can be disentangled in two parts. First, the direct effect of spillovers: provided that β is sufficiently high, an increase in γ increases the monetary transfer T simply because the surplus increases more for the developed country 1. However, for a given level of technology x, marginal transfers are decreasing with γ, as benefits from abatements are also marginally decreasing. Second, the indirect effect: an increase in γ affects the investment in technology. For this second effect, an increase in x acts as a substitute for monetary transfers, because it allows country 2 to receive a higher share of the total surplus before any transfer. Thus, as the marginal benefit curve is decreasing when abatements increase, the impact of γ on investment in technology decreases with γ.

The bargaining over γ only aims at providing a rationale for the actual monetary transfers described in the introduction. To see how efficient this bargaining is, one could also consider a more cooperative solution in which both x and γ are jointly chosen by country 1 and 2. The outcome of this negotiation is characterized by

$$(\hat{x},\hat{\gamma}) = \arg\max_{x,\gamma} 2b(a_1^* + a_2^*) - c(a_1^*, x) - c(a_2^*, \gamma x) - \alpha x - \kappa\gamma. \tag{25}$$

It is possible to show (see also the simulations in the next section) that, while it always increases aggregate welfare, cooperation on both γ and x may lead to a lower level of absorptive capacities than cooperation on γ only. The reason is that, when countries bargain on γ alone, a high level of spillovers can be used in order to provide incentives for higher investment in technology, something that is not be necessary if technology is also chosen cooperatively.

Similarly, it is possible to solve the model for a bargaining over all variables of interest,

$$(\hat{x},\hat{\gamma},\hat{a}_1,\hat{a}_2) = \arg\max_{x,\gamma,a_1,a_2} 2b(a_1^* + a_2^*) - c(a_1^*, x) - c(a_2^*, \gamma x) - \alpha x - \kappa\gamma. \tag{26}$$

Again, more cooperation always increases aggregate welfare. However, full cooperation may also yield lower investment both in x and γ. It is because the cooperative investment in technology and spillovers in the absence of cooperation on abatements can be used as a way to provide incentives for future abatements.

In the next section, we illustrate the results in Propositions 3 and 4 with cost and benefit functions that lead to the different strategic effects studied in Propositions 1 and 2. We use the (numerical) solutions characterized by equations (25) (denoted as "bargaining over x and γ") and (26) (denoted as "fully cooperative") as a benchmark to compare the non-cooperative and semi-cooperative scenarios found above.

5 Simulations

In this section, we use analytical payoff functions in order to illustrate the main intuitions of the paper. To simplify the computations, we assume that in the case of Nash bargaining both countries have equal bargaining power. Therefore, equation (24) rewrites

$$T(\hat{\gamma}) = \frac{1}{2}\int_0^{\hat{\gamma}} [\frac{\partial b}{\partial a}(\frac{\partial a_2}{\partial \gamma} - \frac{da_1}{d\gamma}) + \frac{\partial c}{\partial x}\frac{\partial x^*}{\partial \gamma} + \frac{\partial c}{\partial \gamma} + \frac{\partial \kappa}{\partial \gamma}]d\gamma. \tag{27}$$

[INSERT FIGURES 1 and 2 about here]

We use two different benefit functions (see Figures 1 and 2):

$$b_l = -\frac{(2-a_1-a_2)^2}{2} \tag{28}$$

$$b_h = -(2-a_1-a_2)^2 \tag{29}$$

The first one, b_l, represents a case where marginal benefits from abatements decrease slowly, so that technology and absorptive capacities act as complements. Hence, the abatements of country 1 are relatively inelastic to those of country 2 and higher spillovers induce higher investment in technology. The second, b_h, represents a case where marginal benefits decrease quickly, so that technology and spillovers act as substitutes, the abatements of country 1 are relatively elastic to those of country 2 and higher investment in absorptive capacities induce lower investment in technology. In the terms of equation (13), we see that for a given b', $-b''$ is higher with benefit function b_h.

Cost functions for country 1 and country 2 are respectively given by:

$$c_1 = \frac{a_1^2}{2x} \tag{30}$$

$$c_2 = \frac{a_2^2}{2\gamma x} \tag{31}$$

where $a_i \geq 0$ is the level of abatement of country $i \in \{1,2\}$, and $x \geq 0$ is the level of investment chosen by country 1. We also assume the marginal cost of investment in technology to be $\alpha = 1$.

[INSERT FIGURES 3, 4 and 5 about here]

Figure 3 plots the respective equilibrium payoffs and technology levels when the two countries have b_l as a benefit function.[9] In this example, the equilibrium level of technology x increases for most values of γ. The marginal impact of spillovers on payoffs and the bargaining solutions are plotted in Figure 4. The initial increase in technology benefits country 2 more than the marginal cost of enhancing absorptive technologies, so that for low values of γ, $d\pi_2^* > \kappa$ and $\gamma^* \approx 0.29$ has an interior solution. The bargained level has also an interior solution $\hat{\gamma} \approx 0.63$.

In the alternative timing described in Section 3, the second stage absorptive capacities is $\gamma = 0$, for all values of x. As technology and spillovers are complement, this timing also induces the lowest investment in technology (Figure 3).

Figure 5 shows the result of the bargaining over both x and γ. The optimal level of spillovers is given by the intersection of κ and $d\pi_1^* + d\pi_2^*$. The difference with Figure 4 is that is that the payoffs now capture the reaction of the optimal x described in (25). As compared to both the non-cooperative bargaining and the bargaining over γ only, the investment in technology is higher. The optimal level of spillovers is however lower than the result of the bargaining over γ only. The reason is again the complementarity between technology and spillovers. When bargaining is over γ only, a socially too high γ is used as a commitment to induce a level of x that is closer to the optimal one.

We report the equilibrium values of x and γ under no cooperation, for the bargaining over γ only, and for the bargaining over both x and γ in Table 1. We also report these values for the fully

[9] The equilibrium abatements in the second stage are given by $a_1^* = \frac{2x}{1+(1+\gamma)x}$ and $a_2^* = \gamma \frac{2x}{1+(1+\gamma)x}$. The equilibrium level of absorptive capacities in the first stage is the solution to $x^* = \arg\max_x - \frac{(2-a_1^*-a_2^*)^2}{2} - \frac{(a_1^*)^2}{2x} - x$.

cooperative game. Following the same logic, we observe that, while a is higher, a full cooperation (including abatements) leads to values of both x and γ that are lower compared to a bargaining over x and γ only. In the latter case, x and γ are used to induce higher a_1 and a_2, something that is not necessary when abatements are chosen cooperatively. Unsurprisingly, aggregate welfare is always higher when there is more cooperation.

[INSERT Table 1 about here]

[INSERT FIGURES 6, 7 and 8 about here]

Figure 6 plots the equilibrium payoffs and technology levels when the two countries have b_h as a benefit function.[10] In this case, spillovers decrease the level of technology for all values of γ. The marginal impact of spillovers on payoffs and the bargaining solutions are plotted in Figure 7. Both effects identified in Proposition 4 go in the same direction. The initial increase in technology spillovers provokes a decrease in technology investments, which makes country 2 worse-off, so that there is no value of κ such that γ^* has an interior solution. The bargained level has an interior solution $\hat{\gamma} \approx 0.77$, with transfers $T(\hat{\gamma})$ higher than the cost of enhancing absorptive capacities $\kappa\hat{\gamma}$.

In the alternative timing, country 2 would again choose not to enhance at all its absorptive capacities $\gamma = 0$ for all x. Therefore, the first period level of investment x would be the same as in the timing described in Section 2. This is a case where spillovers and technology are substitutes: the developed country 1 compensates for the lower absorptive capacities of country 2.

As for the previous function, we compare in Figure 8 the above result to the one of the bargaining on x and γ. We see that both the bargained levels of spillovers γ and of technology x are slightly higher than the ones resulting from a bargaining over γ only. The reason is that, because of the higher slope of b', over-investing in absorptive capacities to convince the developed country 1 to invest more in technology has little impact. The fully cooperative levels of x and γ are however slightly lower than the result of a bargaining over γ and x only, for reasons similar to the previous example. We report the values of x and γ in the different cases in Table 2.

[INSERT Table 2 about here]

[10] The equilibrium abatements in the second stage are given by $a_1^* = \frac{4x}{1+(1+\gamma)2x}$ and $a_2^* = \gamma\frac{4x}{1+(1+\gamma)2x}$. The equilibrium level of absorptive capacities in the first stage is the solution to $x^* = \arg\max_x -(2-a_1^*-a_2^*)^2 - \frac{(a_1^*)^2}{2x} - x$.

6 Discussion and conclusion

In most recent climate negotiations, an important topic is the transfer of technologies from developed to developing countries. Within a non-cooperative framework, we show that the strategic response of technology investments in developed countries can jeopardise the effect of an increase in technology spillovers on climate change mitigation.

The most problematic case corresponds to steep marginal benefit curves. In that case, an enhancement in absorptive capacities may decrease investment in technology. Partial cooperation over technology transfers may thus induce a lower technology investment than the fully non-cooperative one. Bargaining over the surplus of cooperation therefore implies monetary transfers from developed to developing countries, on top of the transfers of technology. Similar strategic incentives arise if we consider the symmetric problem of developed countries investing in technology taking into account future technology transfers, that we develop in our alternative timing. If the marginal benefits from additional abatements are steep, investment in technology may decrease incentives to invest in absorptive capacities. If one were to consider international agreements not on technology transfers, but on investment in technology by developed countries, such incentives would also have to be taken into account. A developed country would have to be compensated not only for the cost of higher investments, but also for the possible decrease in absorptive capacities induced by a higher investment in technology.

These adverse effects are attenuated if investment in climate sound technology increases with technology spillovers. This type of response limits the carbon leakage induced by an improvement in developing countries' absorptive capacities and thus alleviates the potential negative effect on developing countries' welfare. It is therefore crucial to understand whether an increase in technology spillovers leads to a rise in clean technology investments. Predicting technological adjustment in developed countries requires estimating the curvature of their benefit function, a tricky and difficult empirical work. This may be done through surveys on the (marginal) willingness-to-pay for CO2 abatements, but the incentives for truthful reporting would obviously be low. These predictions also depend on two particular elements. First, the scientific results on the expected costs of temperature increases. In particular, as the consensus of climate experts moves towards the idea of tipping points, we can expect the marginal benefits of abatements to have a very steep slope around these thresholds. Second, how countries actually value these (future) benefits. Part of it is the discount factor applied on future losses. Another one is the value of life under ambiguity aversion (Treich, 2010).

Quite unsurprisingly, we find that more cooperation is always better. One reason is that it allows achieving higher levels of aggregate abatements. A second one is that simultaneous cooperation on several dimensions allows choosing the most efficient level of investment. When only one or two dimensions are chosen cooperatively, the level of investment also reflects strategic considerations. Because negotiations are currently made on technology transfers (and subsequent agreements being enforced on these), understanding the incentives they create is crucial.

Another implication of this paper is that even if socially desirable, technology transfers may be difficult to implement in practice when the benefits of such a process are not clearly determined. Before cutting a deal, countries must identify the actual gains of each player. If technology investments in developed countries positively respond to an increase in cross-country spillovers, additional monetary transfers are low and technology transfers could even be bought at a strictly positive price by developing countries. However, if the adverse carbon leakage effect is not sufficiently attenuated by technology investment response, developed countries will disproportionately gain from a rise in spillovers and the latter should come with substantial monetary transfers to developing countries. Without sufficient (symmetric) information on the shape of the benefit curve, countries may be reluctant to accept a deal if they fear to be worse off or more generally, to be exploited by receiving only a small share of the increased aggregate welfare generated by a rise in technology spillovers. Additionally, developed countries may fear to be ripped off by paying for technology transfers to countries that have little interest in implementing them.

The finding that monetary transfers resulting from a bargaining over the additional joint surplus from cooperation could go in both directions is in line with Buob and Stephan (2013). They find that developed countries should finance adaptation in poor countries to the extent that they benefit from it. Both papers point that developed countries have weak incentives to provide funding in a non-cooperative framework, which highlights the importance of a compelling international agreement. As of today, it is still not clear what provisions of the Paris agreement are legally binding and the latter might fail to provide incentives strong enough for countries to deliver on their promises.

Finally, unlike the idea that developed countries make double efforts by abating and providing technology, this model shows that providing clean technologies is good for rich countries. While this is true for a country as an entity, it clearly raises an issue regarding incentives for firms to innovate without substantial research subsidies. In particular, firms in developed countries should have incentives to make frontier innovations trickling down to developing countries. Such innovation policies include funding for research with a focus on the environment to the extent that such R&D is the interest of the country as a whole.

7 Figures and tables

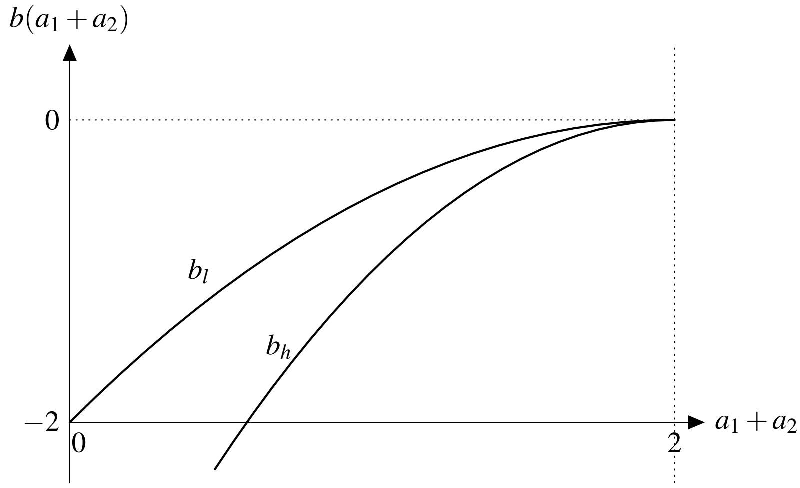

Figure 1: Two examples on the impact of technology spillovers (benefit functions)

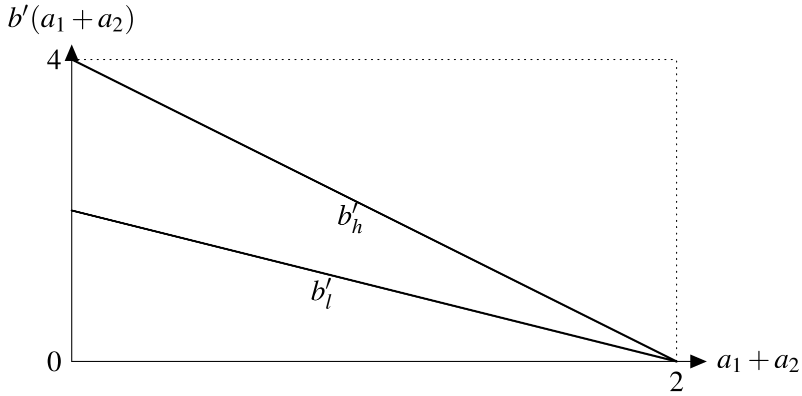

Figure 2: Two examples on the impact of technology spillovers (marginal benefit)

Table 1: Results with benefit curve b_l

	x	γ	a_1	a_2	a	$\pi_1 + \pi_2$
No bargaining	.47	.14	.61	.08	.69	-2.69
Bargaining on γ	.50	.87	.52	.47	.99	-2.50
Bargaining on x and γ	.86	.73	.69	.51	1.20	-2.35
Fully cooperative	.80	.61	.76	.61	1.34	-2.26

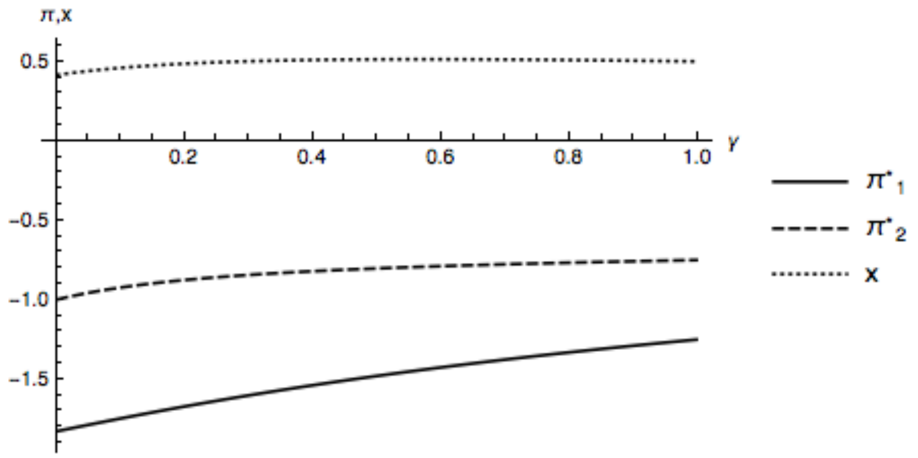

Figure 3: Equilibrium payoffs and technology investment, case 1

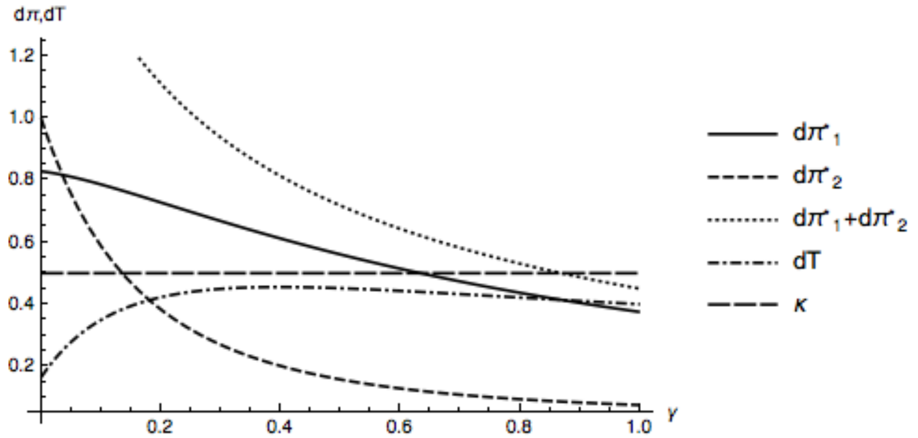

Figure 4: Equilibrium transfers when spillovers increase investment in technology

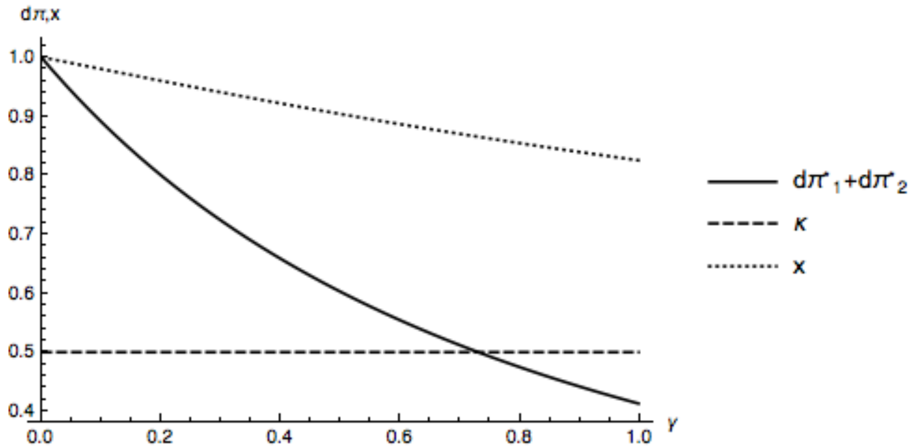

Figure 5: "Complete" bargaining over both x and γ

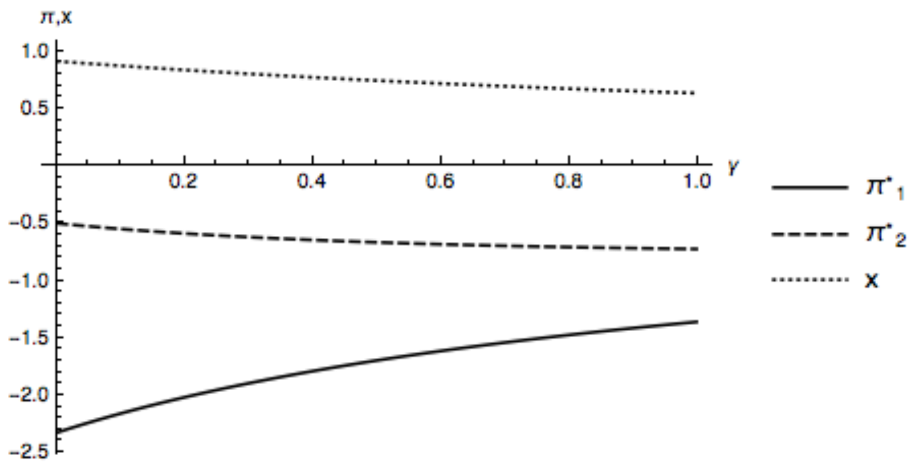

Figure 6: Equilibrium payoffs and technology investment, case 2

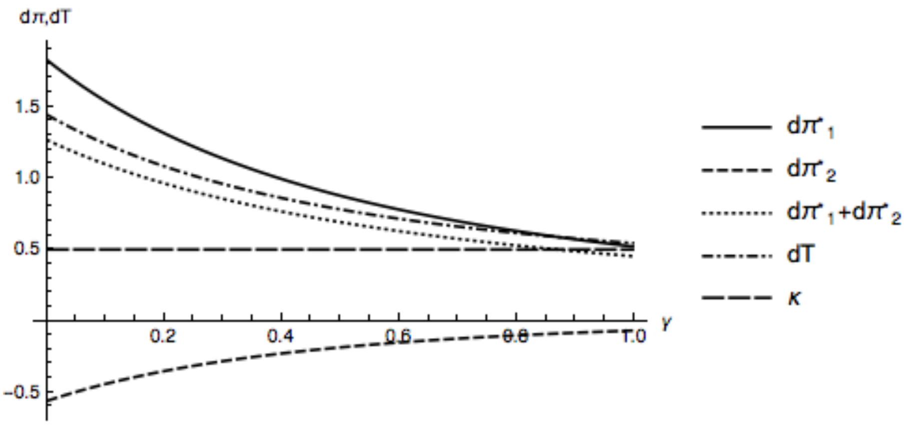

Figure 7: Equilibrium transfers when spillovers decrease investment in technology

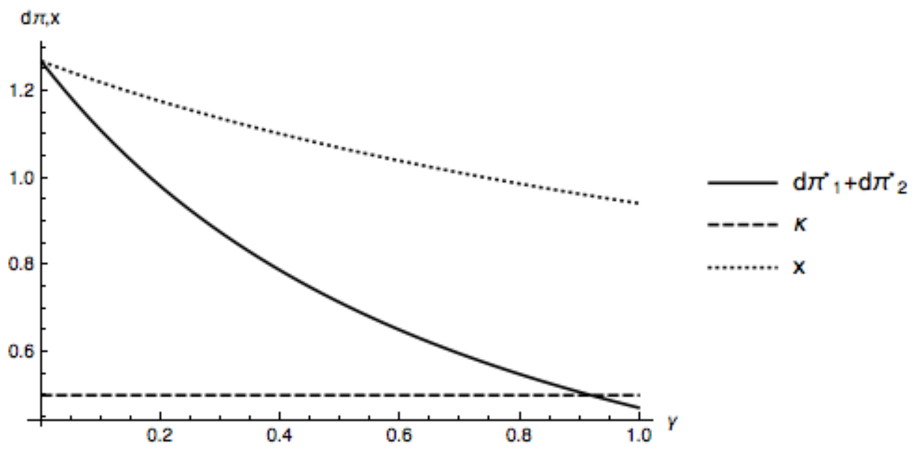

Figure 8: "Complete" bargaining over both x and γ

Table 2: Results with benefit curve b_h

	x	γ	a_1	a_2	a	$\pi_1 + \pi_2$
No bargaining	.91	0	1.29	0	1.29	-2.84
Bargaining on γ	.66	.87	.76	.66	1.42	-2.58
Bargaining on x and γ	.96	.92	.82	.75	1.57	-2.46
Fully cooperative	.91	.82	.95	.78	1.73	-2.37

A Mathematical Appendix

A.1 Proof of Lemma 1

In this proof, we analyze the second stage subgame. From equations (6) and (7), we can derive the slopes of the best-responses $a_1(a_2, x, \gamma)$ and $a_2(a_1, x, \gamma)$:

$$\frac{da_1}{da_2} = \frac{da_2}{da_1} = \frac{-b''}{(b'' - c'')} \in (-1, 0) \tag{32}$$

As a result, the game has a unique and stable equilibrium.

Next, if we assume that x is held constant, then we have that:

$$\frac{\partial^2 \pi_2}{\partial a_2 \partial \gamma} = -\frac{\partial^2 c}{\partial a_2 \partial \gamma} \geq 0 \tag{33}$$

It follows that π_2 displays increasing differences in (a_2, γ).

An increase in γ induces a positive shift in player 2's best response $a_2(a_1, x, \gamma)$. As the best responses $a_1(a_2, x, \gamma)$ and $a_2(a_1, x, \gamma)$ both have a slope belonging to $(-1, 0)$, the subsequent decrease in a_1^* is less than proportional to the increase in a_2^*. As a result, we have that $(a_1^* + a_2^*)$ must increase with γ. It follows that $\partial a_2^*/\partial \gamma \geq 0$ and $\partial a_1^*/\partial \gamma \leq 0$ and $\partial (a_1^* + a_2^*)/\partial \gamma \geq 0$.

A.2 Proof of Claim 1

Thanks to the Implicit Function Theorem, we have that

$$\begin{pmatrix} \frac{\partial a_1^*}{\partial x} \\ \frac{\partial a_2^*}{\partial x} \end{pmatrix} = -\frac{1}{(\frac{1}{\gamma x} + \frac{1}{x})b'' - \frac{1}{\gamma x}\frac{1}{x}} \begin{pmatrix} b'' - \frac{1}{\gamma x} & -b'' \\ -b'' & b'' - \frac{1}{x} \end{pmatrix} \begin{pmatrix} -\frac{a_1^*}{x^2} \\ -\frac{a_2^*}{\gamma x^2} \end{pmatrix} \tag{34}$$

As a result, we have:

$$\frac{\partial a_1^*}{\partial x} = \frac{-\frac{a_1^*}{x^2}\frac{1}{\gamma x}}{(\frac{1}{\gamma x} + \frac{1}{x})b'' - \frac{1}{\gamma x}\frac{1}{x}} \geq 0 \tag{35}$$

$$\frac{\partial a_2^*}{\partial x} = \frac{-\frac{a_2^*}{\gamma x^2}\frac{1}{x}}{(\frac{1}{\gamma x} + \frac{1}{x})b'' - \frac{1}{\gamma x}\frac{1}{x}} \geq 0 \tag{36}$$

A.3 Proof of Corollary 1

From equation (8), we know that $a_2^* = \gamma a_1^*$. Replacing this value in equation (36) in the proof of Lemma 1, it follows directly that

$$\frac{\partial a_2^*}{\partial x} = \gamma \frac{\partial a_1^*}{\partial x} \leq \frac{\partial a_1^*}{\partial x} \tag{37}$$

for $\gamma \in [0,1]$.

A.4 Proof of Proposition 2

For an increase in γ, the total effect on payoff of country 1 is given by:

$$\begin{aligned}\frac{d\pi_1}{d\gamma} &= \frac{\partial b}{\partial a}\frac{da_1^*}{d\gamma} + \frac{\partial b}{\partial a}\frac{da_2^*}{d\gamma} - \frac{\partial c}{\partial a_1}\frac{da_1^*}{d\gamma} - \frac{\partial c}{\partial x}\frac{\partial x_1^*}{\partial \gamma} - \alpha\frac{\partial x_1^*}{\partial \gamma}\\ &= \frac{\partial b}{\partial a}\left(\frac{\partial a_2^*}{\partial x}\frac{\partial x^*}{\partial \gamma} + \frac{\partial a_2^*}{\partial \gamma}\right) - \frac{\partial c}{\partial x}\frac{\partial x^*}{\partial \gamma} - \alpha\frac{\partial x^*}{\partial \gamma}\\ &= \frac{\partial b}{\partial a}\frac{\partial a_2^*}{\partial \gamma} + \left(\frac{\partial b}{\partial a}\frac{\partial a_2^*}{\partial x} - \frac{\partial c}{\partial x} - \alpha\right)\frac{\partial x^*}{\partial \gamma}\\ &= \frac{\partial b}{\partial a}\frac{\partial a_2^*}{\partial \gamma}\end{aligned} \tag{38}$$

as at equilibrium, $\left(\frac{\partial b}{\partial a}\frac{\partial a_2^*}{\partial x} - \frac{\partial c}{\partial x} - \alpha\right) = 0$ (see condition (11)). The sign of equation (38) is clearly positive as $\partial b/\partial a \geq 0$ by assumption and $\partial a_2^*/\partial \gamma \geq 0$ thanks to Lemma 1.

For an increase in γ, the total effect on payoff of country 2 is given by:

$$\begin{aligned}\frac{d\pi_2}{d\gamma} &= \frac{\partial b}{\partial a}\frac{da_1^*}{d\gamma} + \frac{\partial b}{\partial a}\frac{da_2^*}{d\gamma} - \frac{\partial c}{\partial a_2}\frac{da_2^*}{d\gamma} - \frac{\partial c}{\partial x}\frac{\partial x^*}{\partial \gamma} - \frac{\partial c}{\partial \gamma}\\ &= \frac{\partial b}{\partial a}\frac{da_1^*}{d\gamma} - \frac{\partial c}{\partial x}\frac{\partial x^*}{\partial \gamma} - \frac{\partial c}{\partial \gamma}\end{aligned} \tag{39}$$

thanks to the envelop theorem. We have $\partial b/\partial a > 0$, $\partial c/\partial x < 0$ and $\partial c/\partial \gamma < 0$ by assumption. However, we have that $\partial x^*/\partial \gamma$ and $da_1^*/d\gamma$ are ambiguous by Proposition 1. It follows that the sign of equation (39) is ambiguous.

A.5 Proof of Proposition 4

A Nash bargaining with bargaining power β to the developing country 2 implies a transfer from country 1 to country 2 equal to the difference between a share β of the additional surplus generated by the technology spillovers and the additional surplus obtained by country 2. As we assume spillovers are the consequence of an agreement, the disagreement point corresponds to the payoffs if $\gamma = 0$. This is, using (38) and (39) and adding the enhancement of absorptive capacities κ,

$$\begin{aligned} T(\gamma) &= \beta[(\pi_1(\hat{\gamma}) - \pi_1(\gamma = 0)) + (\pi_2(\hat{\gamma}) - \pi_2(\gamma = 0))] - (\pi_2(\hat{\gamma}) - \pi_2(\gamma = 0)) \\ &= \beta \int_0^{\hat{\gamma}} (\frac{d\pi_1}{d\gamma} + \frac{d\pi_2}{d\gamma}) d\gamma - \int_0^{\hat{\gamma}} \frac{d\pi_2}{d\gamma} d\gamma \\ &= \beta \int_0^{\hat{\gamma}} \frac{\partial b}{\partial a} \frac{\partial a_2^*}{\partial \gamma} d\gamma - (1-\beta) \int_0^{\hat{\gamma}} (\frac{\partial b}{\partial a} \frac{da_1^*}{d\gamma} - \frac{\partial c}{\partial x} \frac{\partial x^*}{\partial \gamma} - \frac{\partial c}{\partial \gamma} - \frac{\partial \kappa}{\partial \gamma}) d\gamma. \end{aligned} \tag{40}$$

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