Economie Industrielle des Projets MOC-MDP

RAPPORT FINAL

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Executive summary

The purpose of the research project is to undertake an analysis of Kyoto project mechanisms (CDM and JI) from the perspective and with the tools of industrial economics. These mechanisms allow firms to invest in carbon emissions mitigation projects in developing countries, and to obtain as a counterpart carbon credits that can be sold in the carbon markets of industrialized countries. Besides facilitating the reduction of carbon emissions at a lower marginal cost than in industrialized countries, the implementation of CDM and JI projects frequently implies the international transfer of clean technology from developed to developing countries.

Analyzing these mechanisms with the tools of industrial economics makes it possible to highlight the underlying economic motives and mechanisms, with a particular emphasis on their effect on international technology diffusion. For this purpose, we use economic modelling and empirical analysis in the research project. Reflecting these different approaches, this final report is structured in three parts. The first part presents an economic model developed to analyse the effect of Project mechanisms on technology diffusion in developing countries. The second and third parts present descriptive statistics and econometric analyses of a sample of 644 CDM projects, focusing respectively on the measure and drivers of international technology transfers, and on attractiveness of four major developing countries (Brazil, China, India and Mexico) for technology transfers. The studies presented in Parts 2 and 3 have been accepted for publication in *Energy Policy*. The theoretical work presented in Part 1 has been submitted for publication in the *International Economic Review*.

The first Part presents a theoretical study on the dynamics of the diffusion of GHG mitigation technologies in developing countries. We develop a model to evaluate the ability of the Clean Development Mechanism (CDM) to yield the optimal diffusion path in a context where the first adoption of a technology into a developing country entails lower adoption costs for local firms that will adopt subsequently. We show that this pattern create two types of inefficiencies. The first is the standard positive externality problem leading to the underprovision of technology adoption. The second one is a coordination problem. Neither firm wants to adopt first, which delays the introduction of the technology in their country. We show that the CDM does not solve any of these two problems. We consider possible design improvements. Giving a premium to the first adopter solves the externality problem but not the coordination problem. By contrast, bundling the similar projects into a single CDM project at the sector level can yield the first best optimum.

The second Part provides an assessment of the technology transfers that take place through the CDM using our unique data set of 644 registered projects. It provides a detailed description of the transfers (frequency, type, by sector, by host country, etc.). It also includes an econometric analysis of their drivers. We show that more than 40% of CDM projects entail a technology transfer, and that transfer likeliness increases with the size of the projects. The transfer probability is 50% higher in projects implemented in a subsidiary of Annex 1 companies while the presence of an official credit buyer has a lower – albeit positive – impact. The analysis also yields interesting results on how technological capabilities of the host country influence technology diffusion in the CDM.

The third Part presents the results of another econometric work using the same database and a and similar econometric models to explain inter-country differences. We focus on 4 countries gathering about 75% of the CDM projects: Brazil, China, India, and Mexico. 68% of Mexican projects include an international transfer of technology. The rates are respectively 12%, 40% and 59% for India, Brazil and China. Our results show that transfers to Mexico and Brazil are mainly related to the strong involvement of foreign partners and good technological capabilities. Besides a relative advantage with respect to these factors, the higher rate of international transfers in Mexico seems to be due to a sector-composition effect. The involvement of foreign partners is less frequent in India and China, where investment opportunities generated by fast growing economies seem to play a more important role in facilitating international technology transfers through the CDM. International transfers are also related to strong technology capabilities in China. By contrast, the lower rate of international transfer (12%) in India may be due to a better capability to diffuse domestic technologies.

Résumé

L'objectif de ce projet de recherche est d'appliquer les outils de l'économie industrielle à l'analyse des mécanismes de projet du protocole de Kyoto (MDP et MOC). Ces mécanismes permettent à des entreprises d'investir dans des projets de réduction des émissions de gaz à effet de serre dans des pays en développement, en obtenant en contrepartie des crédits carbone pouvant être revendus sur les marchés carbones des pays industrialisés. Les projets MDP/MOC permettent ainsi de réduire les émissions de GES à moindre coût. De plus, leur mise en oeuvre donne lieu à des transferts internationaux de technologies propres depuis les pays industrialisés vers les pays en développement.

Appliquer les outils de l'économie industrielle à ces mécanismes permet d'analyser les incitations et mécanismes en jeu dans ces projets. Cette approche est notamment particulièrement intéressante pour comprendre les effets des mécanismes de diffusion des technologies à travers les mécanismes de projets. A cette fin, nous avons effectué dans ce projet de recherche des travaux modélisation théorique d'une part, et d'analyse économétrique d'autre part. La structure en trois partie du rapport final reflète ces différents travaux. La première partie présente un modèle théorique visant à analyser les effets du MDP sur la diffusion des technologies dans les pays en développement. Les seconde et troisième parties présentent des analyses statistiques et économétriques réalisées à partir d'une base de données de 644 projets MDP construite pour ce projet. Ces deux parties traitent respectivement de la mesure et des déterminants des transferts internationaux de technologies via les projets MDP, et de la capacité de quatre grands pays émergents (Brésil, Chine, Inde, Mexique) à attirer les transferts de technologies. Les études empiriques des parties 2 et 3 ont été acceptées pour publication dans le revue *Energy Policy*. Le modèle théorique présenté dans la partie 1 a été soumis pour publication à la *International Economic Review*.

La première partie présente une étude théorique sur la dynamique de diffusion des technologies économes en GES en direction des pays en développement. Nous développons un modèle visant à évaluer la capacité du Mécanisme de Développement Propre (MDP) à susciter une trajectoire optimale de diffusion internationale des technologies, dans un contexte où la première adoption d'une technologie dans un pays en développement entraîne une baisse du coût d'adoption pour les utilisateurs locaux qui suivront. Nous montrons que cette situation engendre deux formes d'inefficacité. La première correspond au problème classique d'externalité conduisant à une sous-adoption de la technologie. La seconde inefficacité correspond à un problème de coordination. Chaque firme préfèrerait adopter en second pour bénéficier des effets positifs de la première adoption, ce qui engendre des délais inutiles pour l'introduction de la technologie dans leur pays. Nous montrons que le dispositif du MDP n'est pas à même de résoudre ces deux problèmes, et étudions des solutions complémentaires. Attribuer une prime à la firme qui adopte en premier permet de résoudre le problème de l'externalité, mais pas le problème de coordination. En revanche, nous montrons que la réunion de plusieurs projets MDP similaires au sein d'un unique projet au niveau sectoriel serait un moyen d'obtenir une trajectoire de diffusion socialement efficace.

La seconde partie est une étude visant à mesurer le rôle du MDP dans la diffusion internationale des technologies permettant de lutter contre le réchauffement climatique. L'étude comprend une description détaillée des transferts (fréquence, type de technologie, secteur, pays d'origine et de destination). Elle montre que plus de 40% des projets MDP donnent lieu à un transfert de technologies, et que la probabilité de transfert est une fonction croissante de la taille des projets. La probabilité de transfert augmente de 50% lorsque les

projets sont mis en oeuvre par une filiale d'entreprise basée dans un pays de l'Annexe 1. La présence d'un acheteur de crédit parmi les acteurs d'un projet a également un impact positif, quoique moins fort, sur la probabilité de transfert. L'analyse conduit plus généralement à des résultats intéressants sur l'effet des capacités techniques des pays de destinations sur la diffusion de technologie à travers le MDP.

La troisième partie présente les resultats d'une seconde étude économétrique utilisant la même base de données et des modèles économétriques similaire pour analyser les différences entre pays accueillant les projets. L'analyse est focalisée sur quatre pays accueillant au total environ 75% des projest MDP : le Brésil, la Chine, l'Inde et le Mexique. 68% des projets mexicains impliquent un transfert de technologie. Ce taux s'élève respectivement à 12%, 40% et 59% pour l'Inde, le Brésil et la Chine. Nos résultats montrent que les transferts en direction du Brésil et du Mexique sont liés principalement à la forte implication de partenaires étrangers et à de bon niveau de développement technique dans ces pays. Outre un léger avantage au niveau de ces facteurs, le taux plus élevé observé au Mexique semble du à un effet de composition sectorielle. L'implication de partenaires étrangers est moins fréquente en Inde et en Chine. Les opportunités d'investissement générées par une croissance économique rapide semble jouer y un rôle plus important en matière de transferts liés au MDP. En Chine, les transferts sont également liés à de fortes capacités techniques locales. A l'inverse, le taux de transfert plus faible observé en Inde (12%) pourrait être du à une meilleur capacité à diffuser des technologies développées sur place.

Part 1

Kyoto Project Mechanisms and Technology Diffusion: A Theoretical Model

1 Introduction

Due to economic growth, developing countries are expected to overtake industrialized countries as the leading source of Green House Gases (GHG) in the medium or long term. The transfer and diffusion of climate-friendly technologies in these economies is seen as a key means for solving the climate change problem.

Accordingly, technology issues are included in both the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol. The Asia-Pacific Partnership on Clean Development and Climate initiated by the Bush administration in 2005 also places a very strong emphasis on the development and sharing of more efficient energy technologies.

The Clean Development Mechanism (CDM) is considered by many as an important tool to stimulate technology transfer and diffusion. It is an arrangement under the Kyoto Protocol allowing industrialized countries with a greenhouse gas reduction commitment (so-called Annex 1 countries) or firms located in these countries to invest in emission reducing projects in countries that have not made such commitments (or Annex 2 countries). These projects, usually carried out in developing countries, provide a cheaper alternative to costly emission reductions in industrialized countries. The CDM can moreover contribute to technology transfer by financing projects using technologies not available in the host countries.[1] Such transfers have gradually gained in importance in policy debates, and are at the core of on-going talks on the Post-Kyoto regime.

In this paper we develop a model to study whether emissions trading can yield the socially optimal path of technology diffusion. The focus is on the CDM whose specificity lies in the additionality requirement: firms can implement a

[1] It is worth noting that the CDM does not have an explicit technology transfer and diffusion mandate under the Kyoto Protocol. But the CDM is clearly linked to the technological issue in the policy debate (in particular, in post-Kyoto talks).

CDM project only if it would not be profitable without credits. In order to investigate the impact of additionality, we compare the CDM with a traditional Cap and Trade program (C&T, hereafter) where any abatement - whether privately profitable or not - makes emissions credits available.

The model describes n firms located in a host country which initially operate with an old technology. They can adopt a cleaner technology simultaneously or sequentially. The first adoption that occurs is the international technology transfer *per se* since the technology was not previously available in the country. The following adoptions correspond to the diffusion within the host country (sometimes referred to as horizontal diffusion).

Adoption entails a fixed cost. A key assumption of the model is that this cost endogenously decreases once the technology has been introduced in the host country. In reality, this may be so because observing the outcome of the first adoption may reduce the uncertainty on technology benefits for the following adopters. Or the first adopter accumulates learning-by-doing skills which diffuse to potential adopters through various channels (e.g. labor market).

These learning spillovers generate two types of inefficiency. The first is the standard under-provision problem. The leader's propensity to adopt is too low as he does not take into account positive externalities, thereby hindering technology transfer. The second is a coordination problem which results from the dynamic character of the diffusion process. All firms would prefer to follow in order to enjoy a reduced adoption cost. But following requires that one firm take the lead. This is a dynamic version of a "chicken game" where both firms derive a positive benefit from adoption but have conflicting views on who should go first. As a result, one possible outcome is that the first adoption is delayed, although (privately and socially) profitable.

We show that a standard Cap and Trade scheme does not implement the first best diffusion path. One reason is that each adopter receives the same number of credits whatever its adoption rank. Giving an additional premium to the leader is useful as it solves the externality problem and mitigates the coordination problem. However it implements the first best optimum only when the positive externality is low.

We turn next to the CDM. The CDM differs from C&T in that the credit price signal is not uniform across all firms - it is zero for non-additional projects. We show that the welfare impact of the additionality requirement is ambiguous as compared to C&T. Unsurprisingly, it is clearly detrimental when adoption by the leader is not additional, since technology diffusion is too slow in the absence of credits. However, it unambiguously improves welfare when the leader receives credits while the others do not. This is so because it reduces the followers' advantage, thereby mitigating the coordination problem. This result is true whatever the value of the parameters. Our analysis thus provides a strong case for granting CDM credits to non-additional projects that are expected to generate learning spillovers.

The economic literature on Kyoto project mechanims is extremely scant. Michaelowa et al. (2003) evaluate the level of transaction costs that may impede the diffusion of project mechanisms. Millock (2002) studies the cost efficiency effect of technology transfers through bilateral CDM contracts when there is asymmetric information between the investor and the host party. In a recent paper, Dechezlepretre et al. (2008) develop an empirical study of a dataset describing about 600 CDM projects. They show that about 44% of the projects exhibit a transfer. This ratio increases with the project size, and varies across sectors.

Apart from the specific literature on CDM, an important strand of theoretical literature has developed on environmental innovation and policy instruments[2]. This literature has a much broader focus than our work: most papers compare different policy instruments. Moreover, except for Jaffe and Stavins (1995) and Milliman and Prince (1989), they pay little attention to technology diffusion and ignore learning spillovers, which are central in our own analysis. Blackman (1999) surveys the general economic literature on technology diffusion in order to derive lessons for climate policy.

Our paper is also related to a strand of literature on technology diffusion in industrial organization (see Hoppe, 2002, for a good survey). This literature aims to explain why new technologies diffuse only progressively. In most papers the timing of adoption depends on a trade-off between adoption costs that are exogenously decreasing with time, and the competitive advantage of adopting a technology early (Reinganum, 1981; Fudenberg and Tirole, 1985). We depart from this pattern by endogenizing the decrease of the adoption cost, and by undertaking a normative analysis of the optimal path of technology diffusion.

The paper is organized as follows. Section 2 presents a model of technology adoption by n firms, and characterizes the socially optimal technology diffusion path. Section 3 characterizes diffusion patterns under a Cap and Trade scheme. In Section 4 we investigate the CDM and compare it with Cap and Trade. Section 5 concludes.

2 Model and social optimum

In this section we present a simple continuous time model which describes the adoption of a GHG mitigation technology by n symmetric firms under emissions trading.

[2] See for instance Jaffe & Stavins, 1995; Laffont & Tirole, 1996; Requate, 1998; Montero, 2002; Fischer, Parry, & Pizer, 2003.

2.1 Firms' payoffs

At the beginning of the game, firm i derives a market profit π° per time period. When the firm adopts the abatement technology, this profit changes. Let π denote the profit flow after adoption. The technology can increase the profit ($\pi > \pi^\circ$) or decrease it ($\pi \leq \pi^\circ$). For ease of presentation, we maintain throughout that $\pi^\circ = 0$.

Note that technology adoption by a given firm does not affect others' profits. This either means that firms operate in a perfectly competitive market where a change in the production cost of one firm has negligible impacts on other firms' level of output and profit. This assumption rules out strategic market issues which are potentially associated with technology adoption. It greatly simplifies the analysis and allows one to focus sharply on the issue of technology diffusion.[3]

Adoption also reduces GHG emissions. Without loss of generality, we assume that firms emit one unit per period before adoption and zero afterwards. Adopting firms can possibly sell the credits generated by these reductions. The credit market is competitive and the price is s per reduction unit. Adoptions do not modify this price, meaning that adopters represent only a small subset of market participants. Hence, s is exogenous and equal to the marginal cost of a cap on world emissions.[4]

As regards the initial allocation of credits, we consider two rules:

- A Cap and Trade system (C&T, hereafter) whereby each firm initially receives a number of credits corresponding to its pre-adoption emissions[5]. Hence, the firm derives a benefit s per time period after adoption.

[3] Introducing imperfect competition would induce a cumbersome discussion about the potential of CDM to reduce market power in the product market whereas dealing with imperfect competition is not the prime goal of CDM.

[4] The cap may be set jointly in a Kyoto-like agreement. Or it may result from decentralized decisions by individual countries or sub-groups of countries (e.g. the European Union).

[5] Other initial allocation rules would lead to the same results, as outcomes are driven by relative payoffs and welfare changes.

- A CDM-like system whereby each firm receives the same number of credits as under C&T, *but only if adoption is not profitable without credits.* In CDM terminology, the abatement project should be additional.

The main difference between the two scenarios is that under C&T all adopters face the same price signal s whereas the CDM yields a price signal to additional projects only. Analyzing this difference is a key goal of the paper.

Adopting the technology entails a fixed cost. To capture the learning spillovers following the introduction of the technology into the host country, we make the assumption that the adoption cost starts decreasing endogenously after the first adoption. This differs from the assumptions made in most previous models of technology diffusion in which the adoption cost decreases with time for exogenous reasons (see for instance Reinganum,1981; and Fudenberg & Tirole,1985). Formally, c is the cost for the first adopter while a follower bears $ce^{-\lambda d}$ where d is the time passed since the first adoption. When $\lambda < 0$, there is an incentive for the followers to delay adoption in order to benefit from the leader's experience. When $\lambda = 0$, there is no positive externality of adoption.

The technology is competitively supplied at a uniform price which we normalize to zero, meaning that there is no extra cost for the adopters. What we have in mind are generic technologies which are competitively supplied. Empirical studies like that of Dechezlepretre et al. (2008) suggest that real-world CDM projects do not rely on advanced proprietary technologies.

We now express the net present profits. Let T denote the date of the first adoption and v^L the payoff discounted at time T of the first adopter ignoring credit sales/purchases. We have:

$$v^L = -c + \int_0^\infty \pi e^{-rt} dt = \frac{\pi}{r} - c \tag{1}$$

where r is a discount factor per time period which reflects the cost of waiting ($r > 0$). Turning next to followers, they derive zero market profit ($\pi^\circ = 0$) before adoption (between T and $T + d$). After adoption, they derive the market profit π. Their net present payoff excluding credit sales/purchases at time T is thus:

$$v^F(d) \equiv -ce^{-(r+\lambda)d} + \int_d^\infty \pi e^{-rt} dt = e^{-rd}\left(\frac{\pi}{r} - ce^{-\lambda d}\right) \tag{2}$$

2.2 Timing

We consider a dynamic game in continuous time where the n firms decide whether and when they adopt the abatement technology. In doing so, they take into account the other firms' adoption decisions. The game has two stages:

- The first stage determines the date T of the first adoption.
- The second stage starts at time T and concerns the $n - 1$ firms that did not adopt in the first stage. More specifically the follower indexed i selects the adoption time $T + d_i$.

The fact that they act strategically substantially influences the results. Importantly, this does not mean that the n firms operate in the same oligopolistic product market. In our game, the firms interact with other firms that could generate positive spillovers, from which they would benefit. To do so, firms must be similar from a technological point of view. But they are necessarily competitors. The fact that they operate on the same labor market is for instance much more relevant, as one spillover channel is labor mobility. In fact, what we assume is that the space containing the spillovers is sufficiently small for inducing strategic decisions by the potential adopters.

2.3 The socially optimal path of adoption

We now derive what should be the welfare-maximizing adoption path. Consider first the last stage. Our goal is to identify the socially optimal delay d^* after the first adoption. Recall that there is a cap on worldwide emissions so that s is the marginal abatement cost of market participants (the market is competitive). Hence, adopting yields a benefit s per time period which corresponds to the abatement cost avoided by the credit buyers. As adoption occurs at date d, this discounted benefit is equal to $\int_d^\infty se^{-rt} = se^{-rd}/r$. In addition to this, adoption also yields the private benefit $v^F(d)$ so that the socially optimal delay is simply the solution of:

$$\max_d v^F(d) + se^{-rd}/r \tag{3}$$

under the constraint that adopting improves the social benefit of adoption relative to the status quo:

$$v^F(d) + se^{-rd}/r > 0 \tag{4}$$

Note that this social welfare function is highly restrictive. We ignore the impact of new technologies on consumer surpluses through the product market. We also ignore the impact of diffusion on the incentives to innovate. In fact, our welfare analysis is entirely focused on diffusion.

Substituting (2) and solving this program for d yields:

$$\widehat{d} = \begin{cases} \frac{1}{\lambda} \ln \frac{c}{\pi+s} (r+\lambda) \text{ if } c > \frac{\pi+s}{r+\lambda} \\ 0, \text{ otherwise.} \end{cases} \tag{5}$$

Equation (5) essentially says that the higher the cost of adoption and the faster its decrease over time, the less likely followers are to adopt immediately. Should they decide to wait ($\widehat{d} > 0$), the delay $\widehat{d}$ decreases with the profit flow π.

Moving backwards, we consider now the first adoption. Importantly, this adoption generates a positive externality for the followers. Hence, the first adoption is optimal if the social welfare induced by this decision and the $n-1$ subsequent adoptions is less than the welfare without any adoption. Formally, this condition writes

$$v^L + s/r + (n-1)\left[v^F(\widehat{d}) + se^{-r\widehat{d}}/r\right] \geq 0 \tag{6}$$

which simplifies as follows

$$c \leq \beta \frac{\pi + s}{r} \text{ with } \beta \equiv \frac{1 + (n-1)\, e^{-r\widehat{d}}}{1 + (n-1)\, e^{-(r+\lambda)\widehat{d}}} \geq 1. \tag{7}$$

In addition to this, adoption should take place at $T = 0$ because discounting makes any delay socially detrimental once (6) holds true.

We gather these findings in a first proposition:

Proposition 1 *The socially optimal diffusion path is the following:*

1. *If $c \leq \frac{\pi+s}{r+\lambda}$, all firms should adopt simulatenously at $\widehat{T} = 0$.*
2. *If $\frac{\pi+s}{r+\lambda} < c \leq \beta \frac{\pi+s}{r}$ with $\beta = \frac{1+(n-1)e^{-r\widehat{d}}}{1+(n-1)e^{-(r+\lambda)\widehat{d}}}$, a first adoption should occur at $\widehat{T} = 0$ and the $n-1$ following adoptions at $\widehat{T} + \widehat{d}$ where $\widehat{d} = \frac{1}{\lambda} \ln \left(\frac{c}{\pi+s} (r+\lambda) \right) > 0$.*
3. *If $c > \beta \frac{\pi+s}{r}$, no adoption should take place.*

We will maintain throughout the paper that

Assumption: $c \leq \frac{\pi+s}{r+\lambda}$

This means that we exclude the case where there are no learning externalities in the social optimum as all firms adopt simultaneously at $\widehat{T} = 0$. This allows us to focus on the role of learning in the diffusion of technologies.

3 Diffusion under the Cap and Trade scheme

We now investigate whether a C&T scheme implements the social optimum. Given the existence of a positive externality, the answer is expectedly negative as the early adopters neglect learning benefits. However, we will see that the positive externality induces two types of inefficiency in our dynamic setting: the traditional under provision problem and a coordination problem leading to socially-detrimental delays of adoption.

3.1 The second stage

Consider first how followers react once one firm has adopted the technology. Under C&T, the followers derive the benefit s per time period after adoption as emissions fall to zero and the initial allocation of credits amounts to pre-adoption emissions. Hence, the welfare maximization program (3) and the followers' profit maximization program are exactly the same. This is not surprising: as followers' decisions entail zero externality, the decentralized outcome is socially optimal

Denoting $d^*(s)$ as the equilibrium delay contingent on the credit price s, we thus have $d^*(s) = \widehat{d}$.

3.2 The first stage

Moving backward, we consider next the first adoption. We randomize the adoption decision at each time period $[t, t + dt)$ in order to obtain equilibria in mixed strategies. As we will see, this setup allows us to determine endogenous delays of adoption.

Let $x_i dt$ denote the probability that firm $i = 1, .., n$ adopts the technology between t and $t + dt$, provided that the technology has not been adopted yet at time t. Using these notations, a pure strategy consists of a probability which is either $x_i dt = 1$ or $x_i dt = 0$. That is, firm i adopts (or not) in the short time interval $[t, t+dt]$. A mixed strategy is $0 < x_i dt < 1$.

The firm i's expected payoff at any time t is given by the following Bellman equation:

$$V_i(t) = \left[v^L + s/r\right] x_i dt + (1 - x_i dt)\left[1 - \prod_{k \neq i} (1 - x_k dt)\right]\left[v^F(d^*) + se^{-rd^*}/r\right] + \left[\prod_{k=1}^{n} (1 - x_k dt)\right] e^{-rdt} V_i(t + dt) \tag{8}$$

In this expression, the first term $\left[v^L + s/r\right] x_i dt$ is the payoff of firm i if it adopts the technology times the probability of adoption $x_i dt$. The second term

$$(1 - x_i dt)\left[1 - \prod_{k \neq i} (1 - x_k dt)\right]\left[v^F(d^*) + se^{-rd^*}/r\right]$$

is the expected payoff if firm i does not adopt in the time interval - which occurs with a probability $(1 - x_i dt)$ - and if at least one firm $k \neq i$ adopts in the same period - which occurs with a probability $1 - \prod_{k \neq i} (1 - x_k(t))$ -. Finally,

$$\left[\prod_{k=1}^{n} (1 - x_k dt)\right] e^{-rdt} V_i(t + dt)$$

is the payoff when nobody adopts between t and $t + dt$. In this case, firm i derivesV_i in the next period which is discounted.

In the appendix we solve the game for equilibria in pure and mixed strategies. This leads to:

Proposition 2 *Depending on payoffs, we observe different equilibria:*

1. *If $v^L + s/r < 0$ - or equivalently if $c > \frac{\pi+s}{r}$ -, then no firm ever adopts the technology.*
2. *If $v^L + s/r \geq 0$ - or equivalently if $c \leq \frac{\pi+s}{r}-$, there are:*

(a) n equilibria in pure strategies, whereby one firm adopts at $T^* = 0$ *and the others follow at* $T^* + d^*$.

(b) one symmetric equilibrium in mixed strategies in which each firm $i = 1, .., n$ *adopts with a probability*

$$x^*(s) = \frac{rv^L + s}{[n-1]\left[v^F(d^*) - v^L - (s/r)\left(1 - e^{-rd^*}\right)\right]}$$

so that the expected delay until the first adoption is:

$$ET^*(s) = \frac{n-1}{n} \frac{v^F(d^*) - v^L - (s/r)\left(1 - e^{-rd^*}\right)}{rv^L + s} \tag{9}$$

Proof. See Appendix. ■

This proposition is the first key result of the paper. The intuition underlying Case 1 is obvious. No firm ever adopts because adopting first is not profitable ($v^L + s/r < 0$). This is so either because the adoption cost c is high or because the growth adoption benefit $\frac{\pi+s}{r}$ is too low.

The most interesting possibility is Case 2 where we have multiple equilibria. In this case, the adoption cost is sufficiently low for making adoptions profitable. But followers prefer delaying adoption to derive learning benefits.

In this situation we have $v^L + s/r < v^F(d^*) + se^{-rd^*}/r$, meaning that the incentive to preempt is weaker than the incentive to follow. This is the dynamic version of a "chicken game" where all firms are willing to adopt but have conflicting views on who should go first. As usual in chicken games, this creates a coordination problem leading to multiple Nash equilibria.

The economic interpretation of the equilibria in pure strategies (2a) is problematic because all firms have an incentive to free ride on the first adoption, so that no firm wishes to adopt first at $T = 0$. In that case, we can reasonably expect strategic delays in the first adoption. This corresponds to the symmetric equilibrium in mixed strategies (3b) where the expected date of the first adoption $E(T^*)$ is strictly positive. In the rest of the paper, we remain focused on this equilibrium. Note that, given (9), the larger the gap between the leader's total payoff $v^L + s/r$ and the followers' total payoff $v^F(d^*) + se^{-rd^*}/r$, the longer the delay before the first adoption.

3.3 Welfare properties

We are now able to investigate the welfare properties of the C&T regime. To begin with, recall that the followers' decision is optimal as it does not generate any externalities of adoption. Turning next to the leader, Proposition 2 tells us that the first adoption will take place iff

$$v^L + s/r \geq 0 \iff c \leq \frac{\pi + s}{r} \tag{10}$$

Unsurprisingly, the comparison of (10) with the optimality condition (7) shows that the credit price s is not sufficiently high to induce socially optimal decisions by the leader as $\beta \geq 1$. This is the standard result, that positive externalities lead to too few adoptions.

Interestingly, there exists a second inefficiency: Proposition 2 predicts an equilibrium in mixed strategies which involves a delay in the first adoption while the optimal date is $\widehat{T} = 0$.

We summarize these findings in:

Proposition 3 *A C&T scheme does not implement the first best outcome when* $c \leq \beta \frac{\pi+s}{r}$. *More precisely,*

1. *When* $c \leq \frac{\pi+s}{r}$, *the first adoption is delayed while the optimal adoption date is* $\widehat{T} = 0$.

2. When $\frac{\pi+s}{r} < c \leq \beta\frac{\pi+s}{r}$, the first adoption should take place at $\widehat{T} = 0$ but it never occurs.

In summary, the social inefficiency exclusively concerns the leader: diffusion starts either too late or gets stuck. By contrast, the followers make efficient decisions. This suggests that offering a premium for the first adopter could solve the problem.[6] We now consider this policy solution.

3.4 Premium to the leader

We immediately rule out subsidies that would be based on adoption dates. This we do for the sake of realism: in practice, regulators cannot know when it is $T = 0$ - or any other date - as there is no clear beginning of the diffusion process.[7] We focus the analysis on subsidies based on the adoption rank which is more easily observable by the regulator.

Consider a scheme where all firms that adopt first (possibly simultaneously) enjoy the same premium. Let α denote this subsidy. We obtain a new participation constraint $v^L + \alpha \geq 0$ whereas the optimality condition writes $v^L + (n-1)\, v^F(\widehat{d}) \geq 0$. A premium $\widehat{\alpha}$ such that

$$\widehat{\alpha} \equiv (n-1)\, v^F(\widehat{d}) \tag{11}$$

then immediately solves the under-provision problem. This is the classical story where the leader which generates a positive externality should receive a subsidy internalizing the full social benefit of adoption by the $(n-1)$ followers.

Until now, we have ignored the coordination problem. What about the impact of $\widehat{\alpha}$ on the possible delay before the first adoption? From (9), we know

[6] In a totally different setting, this idea has been explored by Rosendahl, 2004, in a case where the policy instrument is a pollution tax.

[7] Or at least, the beginning date is technology- and sector-specific so that regulators cannot know it (or they might be eventually informed ex post which is useless for granting subsidies to leaders).

that the longer the delay, the larger the gap between followers' and leader's payoffs. Therefore, granting the premium $\widehat{\alpha}$ to the leader obviously mitigates the problem as it reduces the payoff difference. Whether it is sufficient to solve it completely depends on the subsidy level, and thus on the size of the externality. More precisely, two cases are possible:

1. If $v^L + \widehat{\alpha} \geq v^F(\widehat{d})$ - which is equivalent to $v^L + (n-2)\, v^F(\widehat{d}) \geq 0$ -, the leader adopts at $T = 0$. However, all firms will do the same thing, as waiting is less profitable than adopting immediately. This is inefficient as followers should wait for a delay $\widehat{d} > 0$.

2. If $v^L + \widehat{\alpha} < v^F(\widehat{d})$, there remains a gap between the leader's and the followers' payoffs, so that $T > 0$. Then, followers make efficient decisions by adopting after a delay $\widehat{d}$.

In order to limit the distortions created by the premium in the first case, one can imagine rewarding a single firm. Once this firm gets the premium, the other ones' best reply is to follow, after an optimal delay $\widehat{d}$. However, being a follower will remain more attractive in the second case, meaning that the second inefficient diffusion path will not be eliminated in equilibrium. We rigorously state these results:

Proposition 4 *1) Granting a premium $\widehat{\alpha} = (n-1)\, v^F(\widehat{d})$ to a firm that adopts first improves welfare as diffusion occurs iff this is socially optimal. Importantly, the premium should be granted to a single firm in the case where several firms want to take the lead.*

2) This exclusive subsidy $\widehat{\alpha}$ implements the first best optimum under C&T except when $v^L + (n-2)\, v^F(\widehat{d}) < 0 \leq v^L + (n-1)\, v^F(\widehat{d})$. In this case, the premium $\widehat{\alpha}$ induces a path where a first firm adopts with a strictly positive delay ($T^* > 0$) whereas the optimal date is $\widehat{T} = 0$.

Proof. See the appendix. ■

The intuition is simple. When first adoption entails a loss ($v^L < 0$) and the social benefit of technology diffusion is so weak that it hinges on the last follower (it would be negative with one less follower), the premium is not large enough to compensate the opportunity cost of moving first. Hence, there remains a positive delay before the first adoption.

4 Diffusion path under the CDM

4.1 Additionality

Contrary to a C&T system, the benefit of the CDM is conditional to an additionality requirement. The additionality requirement means that a firm that adopts a new technology obtains credits only if technology adoption is not profitable without them. Hence adoption by a leader is additional if $v_L \leq 0$. Or equivalently if $\pi/r \leq c$.

Similarly, a second adoption after a delay d is additional if $v_F(d) \leq 0$, or $\pi e^{\lambda d}/r \leq c$. As $e^{\lambda d} > 1$, it is obvious that additionality subsists if followers adopt before a threshold delay $d^{\max}$ defined by $c \equiv \pi e^{\lambda d^{\max}}/r$.

To sum up,

Lemma 1 *Adoption is additional for the leader if $\pi/r \leq c$. It is additional for a follower if $d < d^{\max}$ with $d^{\max} = \frac{1}{\lambda}\ln\left(\frac{rc}{\pi}\right)$*

It is then convenient to analyze diffusion separately, when the first adoption is additional ($\pi/r < c$) and when it is not ($\pi/r \geq c$).

4.2 The first adoption is not additional ($\pi/r \geq c$)

This case is extremely simple. When the initial adoption is not additional, the same is obviously true for subsequent ones. This means that all firms face the same price signal as under C&T, except that the price is zero. Accordingly, we just need to substitute $s = 0$ in Proposition 2 to derive the equilibrium diffusion paths. This leads to:

Lemma 2 *If adoption cannot be additional ($c \leq \pi/r$), each firm adopts with the same probability*

$$\tilde{x}dt = \frac{rv^L}{(n-1)\left[v^F(\tilde{d}) - v^L\right]}dt.$$

Once a firm has adopted, the others follow after the delay $\tilde{d} = d^*(0) = \frac{1}{\lambda}\ln\frac{c}{\pi}(r+\lambda)$.

4.3 Additional adoptions ($\pi/r < c$)

Reasoning backwards, we identify first the equilibrium delay $\widetilde{d}$. Assume that a firm has taken the lead (which requires $c < (\pi + s)/r$). Under CDM, followers have two options. They may either decide to get CDM credits by choosing a delay $\widetilde{d} < d^{\max}$. Or they may prefer to give up the credits by choosing a longer delay. Let us consider these two strategies in turn.

In the first case, we know from (5) that the delay would be $\widehat{d} = \frac{1}{\lambda}\ln\left(\frac{c(r+\lambda)}{\pi+s}\right)$ under C&T. However, choosing the optimal delay $\widehat{d}$ under the CDM implies losing additionality when $\widehat{d} > d^{\max}$. Hence, keeping additionality imposes a delay such that:

$$\widetilde{d} = \min\left\{\widehat{d}, d^{\max}\right\}$$

Calculations easily show that $\widehat{d} < d^{\max}$ is equivalent to

$$\frac{\pi + s}{r + \lambda} > \frac{\pi}{r} \Leftrightarrow \frac{\pi}{r} < \frac{s}{\lambda} \tag{12}$$

If this condition is met, the additionality constraint is not binding. The firms can thus select the optimal delay $\widehat{d}$ and get credits. Things are more ambiguous when the condition is not met (e.g. if $\frac{\pi}{r} > \frac{s}{\lambda}$). The followers may then decide either to choose a delay $d^{\max}$ in order to benefit from additionality, or not to implement a CDM project, and rather choose a delay $\widetilde{d} = d^*(0)$ as shown in Lemma 2. They need to compare $v_F(d^{\max}) + \frac{s}{r}e^{-rd^{\max}}$ with $v_F(d^*(0))$. Appropriate substitutions yield:

$$\begin{aligned} v_F(d^{\max}) + \frac{s}{r}e^{-rd^{\max}} &> v_F(d^*(0)) \\ &\Leftrightarrow \\ \frac{\pi}{r} &< \frac{s}{\lambda}\left(\frac{r+\lambda}{r}\right)^{\frac{r+\lambda}{\lambda}} \end{aligned}$$

This is very intuitive: followers shorten their adoption delay to implement a CDM project when the credit price is high and/or post-adoption market profit is low.

We summarize the whole analysis in the following:

Lemma 3 *If adoption can be additional ($c > \pi/r$), and assuming that a leader has adopted the technology (which requires $c < (\pi + s)/r$), the followers select the delay $\tilde{d} > 0$ given by:*

$$\tilde{d} = \begin{cases} \widehat{d} \text{ if } \frac{\pi}{r} < \frac{s}{\lambda} \\ d^{\max} \text{ if } \frac{s}{\lambda}\left(\frac{r+\lambda}{r}\right)^{\frac{r+\lambda}{\lambda}} > \frac{\pi}{r} \geq \frac{s}{\lambda} \\ d^*(0) \text{ if } \frac{\pi}{r} \geq \frac{s}{\lambda}\left(\frac{r+\lambda}{r}\right)^{\frac{r+\lambda}{\lambda}} \end{cases}$$

Note that $d^{\max} < \hat{d} < d^*(0)$: as compared to the socially optimal delay $\hat{d}$, additionality can induce diffusion that is either too slow or too fast, depending on the size of π/r. The welfare effect of additionality seems complex.

We complete the analysis with stage 1. We already know that no firm ever adopts if $c \geq (\pi + s)/r$. When $c < (\pi + s)/r)$, the coordination problem arises. Exploiting similarities with Proposition 2 and the results of Lemma 3, we easily obtain:

Proposition 5 *In the case where adoptions can be additional ($c > \pi/r$), no firm ever adopts if $c > (\pi + s)/r$). Otherwise, each firm adopts with the per-time period probability*

$$\tilde{x}dt = \frac{ru^L}{(n-1)\left[u^F(\tilde{d}) - u^L\right]}dt$$

where u^L and u^F are the leader's and followers' payoffs (including credits). They are given by:

$$\begin{aligned} u^L &= v^L + \frac{s}{r} \\ u^F(\tilde{d}) &= v^F(\tilde{d}) + \frac{s}{r}e^{-r\tilde{d}} \end{aligned}$$

where

$$\tilde{d} = \begin{cases} \hat{d} \text{ if } \frac{\pi}{r} < \frac{s}{\lambda} \text{ (all followers get credits)} \\ d^{\max} \text{ if } \frac{s}{\lambda}\left(\frac{r+\lambda}{r}\right)^{\frac{r+\lambda}{\lambda}} > \frac{\pi}{r} \geq \frac{s}{\lambda} \text{ (all followers get credits)} \\ \hat{d} \text{ if } \frac{\pi}{r} \geq \frac{s}{\lambda}\left(\frac{r+\lambda}{r}\right)^{\frac{r+\lambda}{\lambda}} \text{ (no follower gets credits)} \end{cases}$$

5 Welfare comparison

We are now able to compare the welfare properties of C&T and CDM. To begin with, note that social welfare is obviously zero if no firm ever adopts the technology. This occurs with C&T and CDM under the same condition $c \geq \frac{\pi+s}{r}$, so that both schemes are welfare equivalent in this case.

When $c < \frac{\pi+s}{r}$, diffusion occurs and social welfare consists of the firms' private adoption benefits - v^L and $v^F(d)$ - plus the social benefit corresponding to avoided abatement costs by the credit buyers - s/r and $(s/r)\,e^{-rd}$ for the leader and the followers, respectively. Therefore, social welfare discounted at date $T = 0$ writes

$$W(x,d) = \int_0^\infty nxe^{-nxt}\left[v^L + \frac{s}{r} + (n-1)(v^F(d) + \frac{s}{r}e^{-rd})\right]dt$$

which simplifies as follows

$$W(x,d) = \frac{nx}{r+nx}\left[v^L + (n-1)v^F(d) + (1 + (n-1)e^{-rd})(s/r)\right] \tag{13}$$

We can now use (13) to compute the equilibrium welfare in the different cases.

5.1 C&T

By substituting x^* and d^* given in Proposition 2 in (13) we obtain a very simple expression:

$$W_{C\&T} = n(v^L + \frac{s}{r}) \tag{14}$$

Since $v^L + \frac{s}{r} < v^F(d) + \frac{s}{r}e^{-rd}$, this is obviously less than the first best level which would be

$$\widehat{W} = v^L + \frac{s}{r} + (n-1)\left[v^F(\widehat{d}) + \frac{s}{r}e^{-r\widehat{d}}\right]$$

In fact, welfare under C&T is the same as if all firms adopt immediately and simultaneously. It means that the benefit of the delay between first and second adoption - which amounts to the difference between $v^F(d) + \frac{s}{r}e^{-rd}$ and $v^L + s/r$ for the $n-1$ followers - is entirely dissipated by the delay before the first adoption. In other words, the learning benefits and the coordination cost exactly cancel each other out. This is not that counter-intuitive: the higher the learning benefit, the lower the incentives to take the lead, and thus the longer the delay before the first adoption.

5.2 CDM

Under CDM, Lemma 2 and Proposition 5 give four possible diffusion paths which we consider in turn.

5.2.1 Case 1: $c \leq \pi/r$

In this case, adoptions are not additional and firms receive zero credits. Accordingly, we substitute $\tilde{x}$ and $\tilde{d}$ from Lemma 1 in (13) leading to

$$W_{CDM} = nv^L \left[1 + \frac{1 + (n-1)e^{-rd^*(0)}}{v^L + (n-1)v^F(d^*(0))} \frac{s}{r} \right] \tag{15}$$

Case 2: $\pi/r < c < (\pi + s)/r)$ **and** $\frac{\pi}{r} < \frac{s}{\lambda}$

In this case, all firms obtain credits and $\tilde{d} = \hat{d}$. Hence it is immediate that $W_{CDM} = W_{C\&T}$

Case 3: $\pi/r < c < (\pi + s)/r)$ **and** $\frac{s}{\lambda} \left(\frac{r+\lambda}{r}\right)^{\frac{r+\lambda}{\lambda}} > \frac{\pi}{r} \geq \frac{s}{\lambda}$

In this case, all firms obtain credits as well but they adopt sooner at $\tilde{d} = d^{\max}$. Substituting $\tilde{x}$ and $d^{\max}$ in (13) yields $W_{CDM} = n(v^L + s/r) = W_{C\&T}$.

Case 4: $\pi/r < c < (\pi + s)/r)$ **and** $\frac{\pi}{r} \geq \frac{s}{\lambda} \left(\frac{r+\lambda}{r}\right)^{\frac{r+\lambda}{\lambda}}$

In the latter case, credits are granted only to the leader so that $u^L = v^L + s/r$ and $u^F(\tilde{d}) = v^F(d^*(0))$. Substituting u^L and $u^F(\tilde{d})$ in x^* and then x^* and $d^*(0)$

in (13) leads to

$$W_{CDM} = nu^L \left[1 + \frac{(n-1)e^{-rd^*(0)}}{u^L + (n-1)u^F(d^*(0))} \frac{s}{r} \right] \tag{16}$$

Then, very simple calculations show that:

Proposition 6 *There are two cases where CDM & C&T are not welfare equivalent:*

1. *C&T dominates CDM when adoption by the leader is not additional under CDM so that no firms receive any credits (Case 1).*

2. *The opposite is true when the first adoption is additional whereas the subsequent ones are not. That is, when CDM credits are granted only to the first adopter.*

Proof. By comparing (14), (15), and (16). ■

Let us comment on these results. To begin with, the fact that C&T outperforms CDM when all adoptions are not additional is not surprising. The main reason is that followers having zero credits wait too long to adopt while their response is optimal under C&T ($d^* = \hat{d}$). In addition to this, the second source of inefficiency - the delay before the first adoption - is not significantly affected by the absence of credits as this loss relative to C&T concerns both leaders and followers.

The second result is very interesting. Like the previous case, the followers distort their decision as they have no credits. But the leader now gets credits implying that the gap between payoffs is reduced. Hence, diffusion starts earlier. Proposition 6 shows that the latter effect outweighs the former.

This is quite counter-intuitive. Recall that the original problem is the existence of positive learning externalities generated by the first adopter, whereas followers make efficient decisions if they face the appropriate price signal s. The standard policy solution is thus to subsidize the leader. This is not at all what we do here: the leader derives the same benefit as under C&T. By contrast, the CDM punishes the followers. Proposition 6 says that this solution partly mitigates the externality problem.

These results do not depend on the value of the parameters π, λ, c, or r. Proposition 6 thus allows for robust policy lessons to be derived: credits should be granted to non-additional projects when significant learning spillovers are expected.

Finally, the fact that CDM & C&T perform equally when everybody obtains credits is not that intuitive either. Recall that followers may adopt too early at $d^{\max} < \hat{d}$ to meet the additionality requirement under the CDM. The proposition says that this distortion is welfare neutral. One can understand why, by looking at (14). This equation says that the (optimal) learning benefit is entirely dissipated by the losses due to the initial delay under C&T. The same mechanism works when the followers do not wait for the optimal amount of time under the CDM. This distortion is compensated by a lower initial delay.

6 Conclusion

Kyoto mechanisms like the CDM are often depicted as a powerful lever for the diffusion of environmental technologies in developing countries. In this paper we explore this insight by developing a simple model capturing both the transfer of a technology into a developing country and its horizontal diffusion within the country.

As compared to other emissions trading schemes, the CDM originality is the additionality requirement, whereby credits are granted only to projects which would not be profitable otherwise. As a result, the CDM yields a positive price signal to additional projects only. By contrast, the price is uniform across all firms under other trading schemes (e.g. Cap and Trade, Baseline and Credit).

In order to investigate the role of additionality, we have compared a standard Cap and Trade system and the CDM. In the presence of learning spillovers we have shown that C&T fails to implement the optimal diffusion path for a classical reason: the leading firm - which generates positive externalities - and the followers receive the same number of credits.

By design, the CDM either yields the same number of credits as C&T or zero credits when the project is not additional. Hence, it cannot reward the leader in order to internalize learning benefits as recommended in textbooks. But it can punish the followers. We show that this "punishment" may be useful. In fact, the CDM yields a higher welfare than C&T in the case where the leader receives credits whereas the followers do not. This does not solve the under-provision problem, but it does mitigate coordination costs. The result is not ambiguous. It thus provides a strong case for relaxing the additionality requirement for non-additional projects when significant learning spillovers are expected.

In post-Kyoto talks, whether emitters located in emerging economies like China, India or Brazil should be covered by a CDM-like mechanism featured by additionality or a Cap & Trade scheme is a subject of intense discussion. Our analysis stresses one advantage of the CDM: the additionality requirement can be tailored to speed up technology diffusion as compared to other emissions trading schemes.

Of course, technology policy solutions are also possible. In this regard, we have shown that combining CDM or C&T with adoption subsidies to leading firms is appealing. But the main focus of our analysis was to see whether trading mechanisms *per se* could partly solve the positive externality problem.

7 Appendix

7.1 Proof of Proposition 2

The firm i's expected payoff at any time t is given by (8). Using this equation we derive successively the conditions for the different equilibria to arise.

7.1.1 Case 1: No firm adopts ($x_i dt = 0$, $\forall i = 1, ..., n$)

If the other $(n-1)$ firms do not adopt, the expected payoff of firm i writes

$$V_i = v^L x_i dt + e^{-rdt} \prod_{k=1}^{n} (1 - x_k dt) V_i$$

Since we consider infinitesimal values of dt, we can eliminate all terms in $(dt)^n$, $n > 1$. Noting moreover that $1 - e^{-rdt} \sim rdt$ and $e^{-rdt} \to 1$, the expression can write:

$$V_i = \frac{x_i v^L}{r + x_i} \tag{17}$$

This expression is decreasing in x_i if $v^L < 0$. Hence the equilibrium where no firm adopts exists when $v^L < 0$.

7.1.2 One firm j adopts immediately ($x_j dt = 1$).

In that case the expected payoff of the other firms $i \neq j$ write:

$$V_i = v^F(d^*) + x_i dt \left[v^L - v^F(d^*)\right]$$

Recall that $v^L < v^F(d^*)$ as $d^* = \hat{d} > 0$ by assumption. Hence the best reply for firm $i \neq j$ is clearly $x_i dt = 0$. Knowing this we have to check whether firm j will still play $x_j dt = 1$. From 17 we know that firm j's payoff is $V_j = x_j v^L / (r + x_j)$ and that firm j will play $x_j dt = 1$ only if $v^L > 0$. It follows that there are n equilibrium in which one firm adopts immediately ($x_j dt = 1$) while the others do no adopt ($x_i dt = 0$, $i \neq j$) if $v^F(d^*) > v^L > 0$.

7.1.3 Case 3: all firms play mixed strategies

Consider again the expected payoff of firm i in (8). Since we consider infinitesimal values of dt, we can eliminate all terms in $(dt)^n$, $n > 1$. Noting moreover that $1 - e^{-rdt} \sim rdt$, the expression rewrites:

$$V_i = \frac{x_i v^L + \sum\limits_{k \neq i} x_k v^F(d^*)}{r + \sum\limits_k x_k}$$

If $v^L \geq 0$, the expected profit V_i admits a maximum in x_i. The FOC of firm i's program rewrites into the following equation:

$$\sum_{k \neq i} x_k = \frac{r v^L}{v^F(d^*) - v^L} \tag{18}$$

It is clear from 18 that only one equilibrium is possible, where $x_i^* = x^*$ for all $i = 1, ..., n$. The equilibrium adoption strategy is then:

$$x^* = \frac{r v^L}{[n-1]\left[v^F(d^*) - v^L\right]} \tag{19}$$

The strategy x^* followed by each firm defines a Poisson process of parameter nx^* for the first adoption. This allows us to calculate the expected delay until the first adoption:

$$E(T) = \int\limits_0^\infty t n x^* e^{-nx^* t} dt = \frac{n-1}{n} \frac{v^F(d^*) - v^L}{r v^L} \tag{20}$$

7.2 Proof of Proposition 4

We need to investigate precisely the impact of $\widehat{\alpha}$ when it is exclusively granted to a unique firm. This is not so straightforward as it is not possible to replace v^L by $v^L + \widehat{\alpha}$ in the Bellman equation (8) for all firms as just one obtains the premium. As a result, the first adoption game does not solve according to Proposition 1.

A firm's willingness to accept the premium depends on the difference between its payoff if it adopts at $T = 0$ and its payoff if not. In turn the payoff of refusing the premium depends on whether another firm accepts it.

Assume that another firm would accept the premium and adopt at $T = 0$. Then the best reply of the other firms is to wait a delay d^* before adopting in turn the technology, so that their payoff is $v^F\left(\widehat{d}\right)$. Knowing this, a firm will accept the premium if $v^L + \widehat{\alpha} \geq v^F\left(\widehat{d}\right)$. This condition thus implies that one firm will accept the premium and adopt at time $\widehat{T} = 0$ while the other will follow after a delay $\widehat{d}$.

If, on the other hand, we have $v^L + \widehat{\alpha} < v^F\left(\widehat{d}\right)$, then being a follower (with $\widehat{d} > 0$) is more profitable than accepting the premium. In this case the adoption game corresponds to the Bellman equation (**??**) in which v^L is replaced with $v^L + z\widehat{\alpha}$ where z denotes the firm i's probability to obtain the premium when it decides to adopt the technology. Ruling out pure strategies, the likelihood that two firms or more adopt simultaneously is a term in $(dt)^n < 1$, with $n > 1$. For small time increments, this term becomes negligible ($(dt)^n \sim 0, n > 1$) such that $z \sim 1$. As a result, Proposition 2, point 2c, can apply.

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Part 2

The Clean Development Mechanism and the international diffusion of technologies: an empirical study

1 Introduction

The Clean Development Mechanism (CDM) is one of the most innovative tools of the Kyoto Protocol. It allows industrialized countries which have accepted emissions reduction targets to develop or finance projects that reduce greenhouse gas (GHG) emissions in non-Annex 1 countries[1] in exchange for emission reduction credits. Since reducing GHG emissions in a less-developed country may be cheaper than doing so domestically, it helps Annex 1 countries to achieve their emission reduction target at a lower cost and it contributes to the sustainable development of the host countries (see Ellis et al., 2007, for an up-to-date discussion on the CDM).

While its primary goal is to save abatement costs, the CDM is also considered by many as a key means to boost technology transfer and diffusion. If the technology used in the project is not available in the host country and has to be imported, the project de facto leads to a technology transfer. This technology may consist of “hardware” elements, such as machinery and equipment involved in the production process, and/or “software” elements, including knowledge, skills, and know-how (OECD 2005). Note that the CDM did not have originally an explicit technology transfer requirement in the Kyoto Protocol. This was included later in the 2001 Marrakech Accords

Expecting international technology transfer through CDM projects sounds reasonable. However whether this is true in practice is an empirical question. In this paper, we use a unique dataset describing the 644 CDM projects that have been registered until May 1st, 2007 in order to explore this issue. More precisely, we address two types of questions. The first are descriptive: how often do CDM projects include a transfer of technology from abroad? In which sectors? Which types of technologies are transferred? Which countries are the main recipients? Who are the technology suppliers?

The second set of questions is more analytical. Using regression analysis, we investigate what drives technology transfer in the CDM. This provides insights on questions such as: do the host country’s technological capabilities influence technology transfer? Does the presence of an official credit buyer in the project’s partnership promote transfer? Is a transfer more likely in projects implemented in subsidiaries of companies based in industrialised countries?

[1] Non-Annex 1 countries have also ratified the Kyoto Protocol but do not have any emissions reduction targets. This group has 148 members and is mainly comprised of developing countries. Large GHG emitters such as China, India, Brazil or Mexico belong to this group.

The transfer of environmentally sound technologies in the context of climate change mitigation is the subject of an extensive literature (see for example Worrell et al. 2001; Yang and Nordhaus, 2006). In contrast, only two papers deals with technology transfer through CDM projects using a quantitative approach. Based on a limited sample of 63 registered projects, De Coninck, Haake and van der Linden (2007) show that imported technologies originate mostly from the European Union and that the investments from industrialized countries associated with the CDM are small when compared to total foreign direct investments. Haites, Duan and Seres (2006) work on a larger database gathering 860 projects. They find that technology transfers occur in one third of the projects, accounting for two thirds of the annual emission reductions. Larger projects and projects with foreign participants tend to induce technology transfer.

We depart from these papers in two respects. First, our data set provides a richer description of the countries hosting the CDM projects and of the countries supplying the technologies. It also describes in more details the participants involved in the projects. Second - and this is related to the previous point- a richer set of independent variables allows to run regressions that explain the technology transfer[2]. This gives insights on the design variables of CDM that promote technological transfer, thereby leading to potentially useful policy lessons. More generally, it helps deepening our understanding of the transfer of GHG mitigation technologies, which could be useful in the current debate surrounding post-Kyoto talks.

The article is organized as follows. In section 2, we describe the data set. Section 3 includes the descriptive results on technology transfers. The econometric analysis is carried out in Sections 4 and 5. We investigate what drives the transfer but also the type of transfer (equipment or knowledge). Section 6 concludes.

2 Data issues

Sources

In this section, we describe how we construct the data set. CDM projects that result in real, measurable and long-term climate mitigation benefits in non-Annex 1 countries are registered by the Executive Board of the UNFCCC. Our data describes all the 644 projects that have been registered as

[2] The paper by Haites et al. (2007) also includes a regression. But its explanatory power is weak as independent variables are essentially country and sector dummies.

of May 1st, 2007. These projects amount for 888.5 expected million tons of CO_2-equivalent ($MtCO_2eq$) emissions reductions until the end of 2012.

We use three main information sources to describe these projects: 1) the UNEP Risoe Center CDM Pipeline database[3], 2) the so-called Project Design Documents, and 3) data from international institutions like the World Bank and the World Trade Organization for country-level economic and technological variables.

For every CDM project, the UNEP Risoe Center CDM Pipeline database includes the host country, the type of technology, the estimated amount of the annual emissions reductions, the cumulative emissions reductions to the end of the Kyoto period (31 December 2012) and the countries that will buy the carbon credits generated by the project (if already available). We have also collected the registration date and the name of all parties involved on the UNFCCC website dedicated to CDM projects[4].

The content of the Project Design Documents (PDDs, hereafter) is our main source of information. They are mandatory standardized documents of about 50 pages submitted to the Executive Board by the project developers for registration. In the PDDs, we have collected information about the technology used, whether there is a transfer or not, the type of transfer, the project implementer (name, business sector and name of parent company) and every foreign partner involved (name, location). We have also retrieved information on the role of the projects partners: whether they are credit buyers, consulting companies, PDD consultant or equipment suppliers.

Host country characteristics, including information on GDP, trade or FDI flows have been obtained from the World Bank's World Development Indicators 2006[5]. We have completed this information with economic performance indicators from the Earth Trends database of the World Resource Institute[6]. To proxy the technological capability of a country to import and use advanced technology, we have used the composite index Arco developed by Archibugi and Coco (2004).

Information on technology transfers

Given our questions, it is worth describing carefully how we encode information on technological transfers. To begin with, we define technology transfer as the import of a technology from abroad.

[3] The database is available at http://cdmpipeline.org/
[4] http://cdm.unfccc.int/Projects/index.html,
[5] Available online at http://devdata.worldbank.org/wdi2006
[6] http://earthtrends.wri.org/

We consider two forms of technology transfer. The first one is referred to as a *knowledge transfer* and takes place if the local project developer benefits from the transfer of knowledge, know-how, information or technical assistance from a foreign partner. The second form is referred to as an *equipment transfer*. It consists in importing equipments, such as wind turbines or gas burners, from a supplier located in a foreign country. Of course, a project can involve both a transfer of equipment and a transfer of knowledge.

We get this information from the PDDs. In these documents, the technology to be employed in the project activity is described in section A.4.3. The Guidelines for completing the PDD available from UNFCCC indicate that ”this section should include a description of how environmentally safe and sound technology, and know-how to be used, is transferred to the host Party(ies).” Yet, this is not a compulsory requirement and no section is specifically devoted to technology transfer. Indeed, claims of technology transfer can often be found in others sections such as “Description of the project activity” (A.2) or “Barrier analysis” (B.4). Section G (“Stakeholders comments”) sometimes contains interesting information on equipment suppliers. Further information on the technology employed may also be displayed in the annex. In order to get relevant information, we have read carefully all the PDDs.[7]

In order to illustrate how we have proceeded in practice, consider two examples. Project #247 involves a *knowledge transfer*. It consists in replacing fossil fuel with biomass in the production of cement at Lafarge Malayan Cement Company in Malaysia. The technology to process and use local biomass has been developed by Lafarge Malayan Cement’s parent company, Blue Circle Industries. Their research centre is based in Europe. The PDD makes it clear that “knowledge and expertise have been actively transferred in the development of the project by European expert deployment in Malaysia.” Training of local staff and engineers has been provided by experts from Blue Circle as well as from Lafarge Europe (Blue Circle’s parent company).

Project #839 is an example of *equipment transfer*. It aims at generating electricity from biogas at a landfill in Talia, Israel. The PDD informs us that “the high temperature flare, blower, gas analyzer, industrial computer are all imported from Europe” but does not give any further information on the equipment supplier’s involvement beyond the sale. Technology suppliers certainly transfer some

[7] For efficiency purposes, we first searched the PDDs for the words “technology”, “transfer”, “equipment”, “supplier”, “import”, “manufacturer” and “training”. If no information on technology transfer could be found through this search, the PDD was read.

knowledge, at least in the form of an instructions leaflet. Hence an equipment transfer should be seen as a transfer of technology that comes with the minimum possible transfer of knowledge.

How reliable is this information? There are several potential problems we have tried to mitigate. In some PDDs, a transfer of technology sometimes refers to the simple adoption of a new technology. If the technology provider is clearly located within the country, the project does not involve any international technology transfer, and consequently does not appear as such in our database.

Another difficulty concerns specifically the import of equipment. From a general point of view, the import of goods does not always entail a technology transfer. For instance, importing a DVD player produced in China in the U.S. does not. The same is true for CDM projects. They might include the imports of generic devices. In this regards, we have considered that the import of equipment is associated with a technology transfer as soon as the PDD claims it is so.

It remains that PDD editors have an incentive to overstate the existence of technology transfer as it helps project registration. Accordingly, type I errors are unlikely while type II errors could be frequent even if any claim of technology transfer should be justified in the PDD[8]. Therefore, descriptive statistics on the percentage of technology transfer are probably less reliable than other figures.[9] This is a usual difficulty with this type of studies. But, one can realistically assume that this bias is randomly distributed in the population of PDD writers. Therefore, this problem probably does not damage our econometric results.

[8] A type I error consists in wrongly describing a project as not involving any technology transfer. Conversely, a type I error occurs when a project is wrongly described as not involving any technology transfer.

[9] Haites et al. (2006) find that 33% of the projects involve transfer, compared to 43% in our data set. One possible reason is that the datasets are slightly different. Another is the procedure that has been used in both papers for encoding tech transfer. We read the whole PDDs whereas Haites et al. (2006) have only searched for the word “technology”.

3 Descriptive statistics on technology transfers

In this section we provide a detailed description of technology transfers occurring in CDM projects.

Frequency and nature of technology transfers

Table 1 shows that 279 projects out of 644 involve technology transfer. They represent 43% of the number of projects and 84% of the expected annual CO_2 emissions reductions. Projects with transfer are thus larger on average than those without transfer. This discrepancy is partly explained by the fact that all 11 HFC-destruction projects, representing more than 56 million tons of annual CO_2eq reductions, involve transfers.

In Table 1, we see that transfers limited to the import of equipments are much less frequent than the transfer of knowledge only (9% of the projects against 19%). The transfer of both equipment and knowledge is observed in 19% of the projects. This illustrates the key role of technical skills in the diffusion of carbon mitigation technologies.

Table 1 – *Nature of technology transfer involved in the CDM projects*

Nature of technology transfer	Number of projects	% of projects	% of annual emission reductions	Average reduction per project (ktCO_2eq/yr)
Transfer	279	43 %	84 %	403
Equipment	57	9 %	6 %	133
Knowledge	101	15 %	14 %	185
Equipment + Knowledge	121	19 %	64 %	714
No transfer	365	57 %	16 %	59
Total	644	100%	100 %	208

Transfer by type of technology

Using the 21 technology categories established by the UNEP Risoe Center CDM pipeline, Table 2 shows that the number of projects and the transfer likeliness vary greatly across types of technology.

Table 2 – *Technology transfer by type of technology*

Type of technology	Number of projects	Percentage of projects involving technology transfer	Share of transfers that include equipment	Average project size (annual $ktCO_2eq$)
Biomass energy	141	19%	81%	56
Hydro power	112	22%	68%	50
Biogas recovery in agriculture (breeding farms)	104	70%	10%	43
Wind power	80	63%	96%	84
Energy efficiency measures in industry	65	25%	75%	112
Landfill gas recovery	51	80%	80%	279
Fossil fuel switch	14	43%	100%	34
Biogas recovery (other)	14	29%	75%	45
Reduction of the share of clinker in cement production	14	7%	0%	144
HFC decomposition	13	100%	92%	4612
Energy efficiency / supply side	7	14%	0%	33
N_2O destruction	6	100%	83%	3141
Geothermal power	5	40%	50%	293
Solar power	4	100%	100%	11
Recovery of fugitive gas	3	100%	33%	621
Power generation from coal mine methane	3	67%	100%	462
Energy efficiency measures in households (insulation)	3	67%	100%	14
Energy efficiency measures in the services sector	2	100%	100%	8
Tidal power	1	100%	100%	315
Reforestation	1	0%	–	26
Transport	1	0%	–	247

All projects aiming at the destruction of HFC-23 entail a transfer. HFC-23 is a byproduct of HCFC-22, a widely used ozone-friendly refrigerant. The global warming potential of HFC gases is 12,000 times higher than that of carbon dioxide (IPCC 2001). Projects mitigating HFC thus generate very large amounts of CERs and are extremely profitable. A few companies located in Europe and in Japan have developed technologies to destroy HFC. They are key partners in any HFC decomposition CDM project. Projects avoiding the emission of nitrous oxide (N_2O) in the chemicals industry and recovering methane (CH_4) in landfills and farms also exhibit a very high transfer rate.

In the energy sector, equipment for solar and wind power generation are usually imported from Annex 1 countries. More precisely, about 60% of wind power projects import turbines which are of higher capacity than locally produced ones. This is not surprising as local companies like Goldwind in China and Suzlon in India only produce small-capacity turbines. This explains why projects using imported turbines have an average total capacity of 53 MW in comparison with 28 MW for projects using local devices.

A large share of projects recovering biogas in breeding farms also involves technology transfer. The purpose of this type of project is to mitigate and recover biogas resulting from the decomposition process of animal effluents. Each project includes the installation of covered lagoons and a combustion system that destroys the captured biogas. Albeit the technologies are not very elaborate, knowledge transfer is frequent because these projects are mainly initiated by developers located in Annex 1 countries like AgCert. This Irish company provides farmers with turnkey solutions, including training sessions on how to operate the technology. The offered service includes specification and design of the complete technology solution, identification of appropriate technology providers, supervision of the project installation, farm staff training and ongoing monitoring.

Conversely, technology transfers are limited in certain areas. Power generation using hydro power or biomass is an example. Biomass power plants are similar to fossil-fuel fired power plants and use a very common technology. So do hydro power plants: most projects are located in Brazil, India and China, which have been mastering hydro power technology for decades.

Table 3 gives an aggregate view of these results by sector. Excepting the chemicals sector with HFC and N_2O destruction projects, the industrial sector surprisingly does not yield many technology transfers. The situation is different for the energy sector with a technology transfer rate of 39%.

Table 3 – *Technology transfer by sector*

Sector	Number of projects	Percentage of projects involving technology transfer	% of equipment transfer in projects with transfer
Waste	51	80%	80%
Agriculture (incl. reforestation)	105	70%	10%
Energy	264	39%	87%
Industry	223	27%	79%
Transport	1	0%	–

Transfer by mitigation mechanism

Table 4 distinguishes different mitigation mechanisms. Transfers largely concern end-of-pipe technologies that remove gaseous pollutants from effluent streams at the end of the production process. The "new units" category describes the setting up of new production units with reduced GHG emissions. It gathers biomass-fired and hydro power plants that essentially use local technology as well as wind farms that often benefit from technology transfer. In contrast, projects that modify existing production processes involve far less transfers. Input switch refers to projects involving a change of production inputs (e.g., biomass instead of coal in a power plant).

Table 4 – *Technology transfer by mitigation mechanism*

Mechanism	Number of projects	% of technology transfer
End-of-pipe	205	69%
New unit	286	36%
Input switch	39	33%
Change in the production process	111	20%

Technology transfer by host country

CDM projects are located in 44 non-Annex 1 countries, but Brazil, China, India and Mexico host 73% of them. 35 % of the projects are located in India alone. 24 countries host 3 projects or less and among these, 12 countries host only 1 project.

Table 5 shows technology transfers in the main host countries. They appear very heterogeneous in their capability to attract technology transfers.

Table 5 – *Technology transfer for selected host countries*

Country	Number of projects	% of technology transfer
India	225	12%
Brazil	99	40%
Mexico	78	68%
China	71	59%
Chile	17	35%
Malaysia	15	87%
South Korea	13	77%
Honduras	10	30%

Technology suppliers

Among the 154 projects that explicitly mention the origin of the imported equipment, 71% originate from a European supplier. Within Europe, the main exporting countries are Germany, Spain and Denmark, which accounted for 45% of the exported machinery. Non European suppliers are mainly located in the USA (19%) and Japan (10%).

This means that the money spent by Annex 1 countries to finance CDM projects – through the purchase of carbon credits– is only marginally used to buy machinery from countries that have not ratified the Kyoto Protocol. Does it mean that each country subsidizes its own technologies through the Clean Development Mechanism? This argument has been widely used by CDM opponents. A closer look at our data invalidates this assertion: an Annex 1 country hosts both the credit buyer and the equipment supplier in only 2% of the projects.

Table 6 reports the main countries of origin and of destination by technology. Spain mainly exports wind turbines manufactured by Gamesa Eolica. Other wind turbines exporters include Vestas from Denmark and Enercon from Germany. The French company Vichem is the main technology provider for HFC decomposition projects. Technologies for N_2O destruction are provided by Japanese companies or by UHDE (a ThyssenKrupp company).

Table 6 – *Main countries of origin and of destination by type of technology*

Type of technology	Main countries of origin	Main countries of destination
Biomass energy	Belgium, Denmark, Japan	Malaysia, India, Brazil, Indonesia
Wind power	Denmark, Germany, Spain, USA	China, India, Brazil, Mexico
Landfill gas	Italy, UK, France, USA, Ireland, Netherlands	Brazil, Mexico, Argentina, Chile, China
HFC decomposition	France, Germany, Japan	China, India
Hydro power	France, Germany, UK, Spain	Ecuador, Panama, Honduras, South Korea, Mongolia
Agriculture	Ireland, Canada, UK	Mexico, Brazil, Philippines, Ecuador
Energy efficiency in industry	Japan, Italy, USA	India, China, Malaysia
N_2O destruction	Germany, Japan, France	South Korea

Partnerships

Initially, it was thought that CDM could be initiated by companies from Annex 1 countries to cut emissions at a lower cost through technological partnerships that would also benefit developing countries. An example in line with these expectations is Project # 526. The Heidelberg group - a German cement company - has developed this project to cut carbon emissions in its Indonesian subsidiary, Indocement. The project aims at producing a new type of blended cement which reduces CO_2 emissions reductions. It has benefited from research and development activities conducted in Europe by Heidelberg Cement.

However, if we look at the data, a limited number of projects follow a similar pattern. Only 8% are implemented in subsidiaries of companies located in an Annex 1 country. Among these projects, only 21 parent companies offered technical assistance to their local subsidiary. This means that in total, less than 5% of all CDM projects involve a transfer from an Annex 1 country company to its subsidiary. Instead, the CDM business has generated unexpected forms of technological partnership. Companies such as AgCert, EcoSecurities, Carbon Resource Management, Agrinergy or Carbon Asset Services Sweden are now key players in this area. They manage the whole CDM project cycle, from PDD writing to credit sale. Their diversified portfolio of CDM projects allows to minimize risk and to exploit economies of scale in administrative tasks. Some of them directly transfer the technology to local project developers. For example, AgCert transfers know-how in Animal Waste Management Systems to livestock farms in Brazil and Mexico. Others simply help local firms finding technology suppliers and assessing their technologies.

As shown by Table 7, nearly 50% of the credit buyers are CDM projects developers. Carbon traders - either banks like ABN AMRO or companies involved in commodity trading like Nuon Energy or EDF Trading - are not very active on the primary market, although the Noble group has created a dedicated subsidiary, Noble Carbon Credits. Private companies also frequently buy credits.

Table 7 – *Types of credit buyer*

Type of credit purchaser	Number of projects (percentage)
CDM projects developer	179 (47%)
Carbon trader (mostly banks)	18 (4.7%)
Private company	96 (25.1%)
Private fund	5 (1.3%)
Government fund	45 (11.8%)
Public-private fund	9 (2.4%)
World Bank fund	29 (7.6%)
TOTAL	381 (100%)
Note: a project may have more than one credit buyer involved.	

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4 The determinants of technology transfers: an econometric analysis

In the previous section, we have presented statistics describing technology transfers through the CDM. They give a detailed view on these issues but do not help us to understand what drives the transfer. For instance, we know from Table 5 that 69% of the Chinese projects involve a transfer while the percentage is only 12% in India. Why is it so? Is it because the technological capability of India is less than that of China? Or is it due to sector composition effect – Indian projects may take place in economic sectors where a transfer is less likely? Is it due to project characteristics? For instance, is it because Chinese projects are implemented more frequently in subsidiaries of Annex 1 companies, assuming that this type of partnership increases the likeliness of transfer?

Understanding the rationale underlying the technology transfer through CDM projects is necessary to derive policy implications and, more generally, to give more general insights on the diffusion of GHG mitigation technologies. In this section, we rely on econometric analysis to do so.

The econometric model

Let *TECH_TRANSFER* denote a binary variable equal to 1 if a project involves a technology transfer (regardless of the nature of this transfer) and 0 otherwise. To examine the relationship between *TECH_TRANSFER* and a set of explanatory variables, the following logit equation is estimated:

$$\Pr(TECH\_TRANSFER = 1) = \frac{e^{\Omega}}{1 + e^{\Omega}}$$

with:

$$\begin{aligned}\Omega = {} & \alpha_0 + \alpha_1(LOGSIZE) + \alpha_2(CREDIT\_BUYER) + \alpha_3(SUBSIDIARY) \\ & + \alpha_4(SIMILAR\_PROJECTS) + \alpha_5(TRADE) + \alpha_6(FDI\_INFLOWS) \\ & + \alpha_7(GDP\_GROWTH) + \alpha_8(TECH\_CAPACITY) \\ & + \alpha_9(LOG\_POPULATION) + \alpha_{10}(GDP\_PERCAPITA) + \alpha_i SECTOR_i + \alpha_j COUNTRY_j + \varepsilon\end{aligned}$$

α_i is a vector of coefficients to be estimated and ε is a random term identically independently distributed following a Gumbel extreme distribution.

We now discuss in depth the different explanatory variables. LOGSIZE[10] is the log of the project size, as measured by its annual emissions reduction. The underlying hypothesis is that CDM projects entail transaction costs that are fixed and that are likely to be higher when some technology transfer is involved (Maskus, 2004). Such transaction costs are an impediment to small projects. Assumedly, the larger a project, the higher its probability to involve technology transfer.

CREDIT_BUYER is a dummy variable indicating the participation of one or more credit buyers in the project. Before the project developer can sell the credits, the UNFCCC must first certify, issue and register the emission reduction and this administrative process takes time. Selling credits through a forward contract can be of great help. It reduces the risk surrounding the investments by adding a guaranteed revenue stream. Most credit buyers are not pure financial actors as shown in Table 7.[11] One can assume that they also give advice and bring expertise that may ease technology transfer.

[10] Using the logarithm of the size ensures that the few very large HFC projects do not have a disproportionate influence on the results

[11] Only 18 credit buyers are banks.

SUBSIDIARY is a dummy variable indicating whether the project is implemented in the subsidiary of a company located in an Annex 1 country. In this case, the local project developer can probably benefit from the expertise or from the technology of the parent company (Jahn *et alii* 2004).

The number of other CDM projects using the same technology within the host country is described by the variable SIMILAR_PROJECTS. We see this variable as a proxy for the local availability of the technology in the country. Accordingly, the higher the number of similar projects, the lower the probability of transfer.

We also include country variables. In this regard, there is empirical evidence in the general economic literature that international trade and Foreign Direct Investments (FDI) promote the transfer of technology across countries (Coe, Helpman, and Hoffmaister 1997). Accordingly, we use the variable TRADE which is the ratio of the sum of exports and imports of merchandise on GDP and FDI_INFLOWS which is the level of incoming FDI in the host country.

As richer and larger countries are likely to have more technologies already available locally, we include the country size (LOG_POPULATION) and the per capita GDP (GDP_PERCAPITA) as control variables. In order to take into account the possible influence of economic dynamism, we also use GDP_GROWTH which is the average annual rate of GDP growth from 2000 to 2004.

Furthermore, empirical evidence indicates that the adoption of a new technology is strongly associated with human capital, supporting infrastructure and research and development activities (Blackman 1997). In order to measure this technological capability (TECH_CAPABILITY), we use the ArCo technology index developed by Archibugi and Coco (2004). This composite indicator captures three aspects determining technological capabilities: the creation of technology (number of patents and number of scientific articles), the technological infrastructures (internet penetration, telephone penetration and electricity consumption) and the development of human skills (percentage of tertiary science and engineering enrolment, mean years of schooling and literacy rate).

TECH_CAPABILITY may have contrasted effects on technology transfers. On the one hand, the influence may be positive as the establishment of a new technology in a country may require technical competencies and a skilled workforce. On the other hand, high technological capabilities mean that many technologies are already available locally, thereby reducing the probability of transfers through CDM projects. These antagonistic effects may have different weights across sectors. This leads us to estimate two variants of the model:

- In Model A, we simply use the index TECH_CAPABILITY, thereby assuming that the effect of technological capability does not vary across sectors.
- In Model B, the variable TECH_CAPABILITY interacts with 11 sector dummies allowing differentiated effects across sectors. We use AGRICULTURE, ENERGY, WASTE[12] and 8 other dummies describing industrial sectors.

Finally, $SECTOR_i$ and $COUNTRY_i$ are vectors of sector dummies and country dummies, respectively. They control for sector- and country-specific characteristics that are not captured by the other variables.

Table 8 yields precise definitions, summary statistics and the expected signs of the coefficients.

Table 8 – *Definition of variables and summary statistics*

Variable	Definition	Number of obs.	Mean	Standard deviation	Expected impact
LOGSIZE	Log of the size of the project (expected annual reductions in $ktCO_2eq$).	644	3.716	1.532	+
CREDIT_BUYER	= 1 if the project has one or more credit buyer, 0 otherwise	644	0.607	0.489	+
SUBSIDIARY	= 1 if the project developer is the subsidiary of a company from an Annex 1 country, 0 otherwise	644	0.171	0.377	+
SIMILAR_PROJECTS	= log (N) where N is the number of projects already using the same type of technology within the host country	644	1.959	1.386	–
GDP_GROWTH	Average annual growth of GDP from 2000 to 2004	644	4.688	2.560	+
TRADE	Sum of exports and imports of merchandise divided by the value of GDP. Average for 2000-2004	644	25.62	17.06	+
FDI_INFLOWS	Sum of net inflows of FDI divided by GDP. Average for 2000-2004	644	2.374	1.534	+
TECH_CAPABILITY	Index of technological capability * 100 (source: Archibugi and Coco 2004)	644	30.05	8.80	?
GDP_PERCAPITA	GDP per capita 2004	644	3779	3871	–
LOG_POPULATION	Log of total population in million (2004)	644	5.38	1.80	–

[12] We have excluded the transport sector which only concerns one project.

Results

Empirical results are displayed in Table 9. The overall quality of the estimations is reasonably good. The McFadden pseudo R-squared is around 0.35-0.4 depending on the model. The model correctly predicts 80 % of the observations and the results are robust across the two specifications (models A and B).

We now interpret the influence of the different variables. To begin with, technology transfer positively depends on the size of the project (LOGSIZE). This is in line with the expectation that larger projects are better able to exploit economies of scale in technology transfer.

Having a credit buyer also increases the likelihood that the project involves technology transfer. But calculations show that the marginal effect of CREDIT_BUYER is low: a project with a credit buyer has only a 16% higher probability of involving a technology transfer.

Being the subsidiary of a company from an Annex 1 country clearly favors the transfer of technology. The coefficient is highly significant in all specifications and much larger than that of CREDIT_BUYER. In marginal terms, the transfer likeliness of a project located in the subsidiary of an Annex 1 company is 50% higher. This confirms the conjecture that pre-existing capital links strongly promote the import of a new technology.

As expected, the probability of technology transfer decreases with the number of projects using the same type of technology in the country (SIMILAR_PROJECTS).

Turning next to country variables, we confirm that, all other things being equal, the openness of the economy positively influences transfer probability. In contrast, the share of FDI inflows in GDP does not have any significant impact. This is not that surprising as capital links are already captured by the variable SUBSIDIARY.

Results on technological capabilities are very interesting. First, Model A tells us that the technological capability has a positive overall effect on technology transfer. However, introducing the possibility of differentiated effects across sectors (Model B) modifies this statement. In fact, TECH_CAPABILITY has a positive influence only in the energy sector and in the chemicals industry. The effect is strongly negative in agriculture and not significant in most industry sectors and in waste management.

Recall the two antagonistic effects of technological capabilities. One the one hand, they promote transfer as local implementers have skills to use the technology. On the other hand, high technological capabilities increase the local availability of technologies. Our results suggest that the latter effect dominates the former in agriculture while the opposite is true in the energy sector and in the chemicals industry. The interpretation is that technologies transferred in the agriculture sector are not very elaborate, implying that they might be introduced without high technical skills. In contrast with this, wind turbines, solar panels in the energy sector or abatement devices in the chemicals industry would require technically qualified manpower to be built and operated. In the other sectors in which coefficients are not significant, the two effects might compensate each other.

In order to compare the size of the effects of different explanatory variables, we draw Figure 1 using model B's results. Using the same metric, each bar measures the impacts of the variable on an average CDM project.

Figure 1 is based on the following calculation. Let $\overline{x_i}$ be the average value of the variable x_i in the data set and let β_i denote the value of its coefficient. Then, the product $\beta_i \overline{x_i}$ represents the average impact of x_i on the linear predictor Ω. Calculating the value of $\beta_i \overline{x_i}$ for every variable allows to compare the average weight of each variable on the decision to transfer technology. Figure 1 represents these weights.

This representation shows that, among project variables, the size of the project and the number of similar projects within the host country have the most important impact on technology transfer.

CREDIT_BUYER and SUBSIDIARY have similar effects but for different reasons. SUBSIDIARY increase the transfer probability by 50% but only 8% of the projects are implemented in subsidiaries of Annex 1 companies. CREDIT_BUYER has a weaker marginal effect (+16%) but credit buyers participate in 61% of the projects.

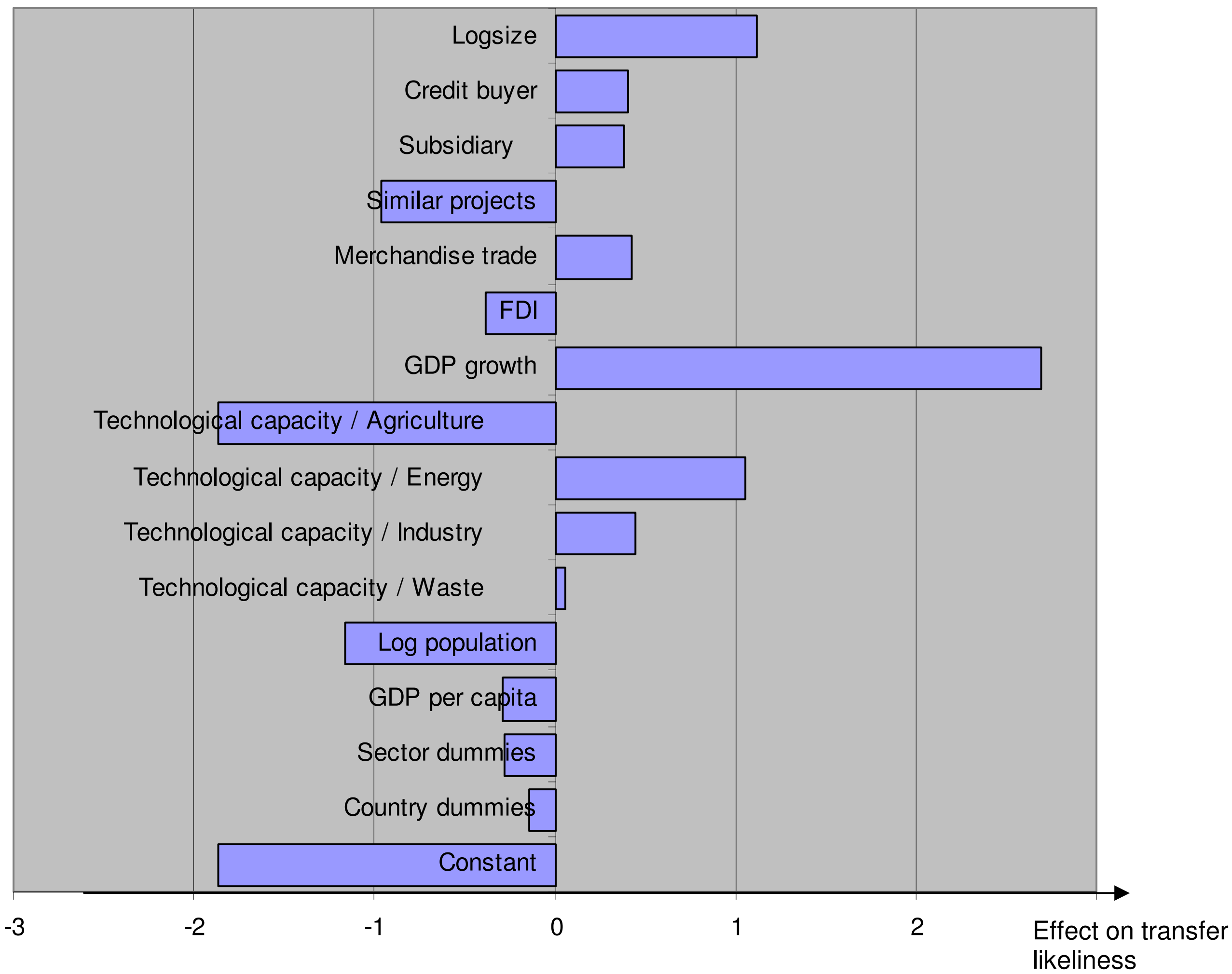
At the country level, GDP growth exerts a stronger influence than economic openness. The technological capability has a strong effect - either negative in agriculture or positive in the energy sector. We also find that the overall impact of project-level variables is smaller than that of country-level variables. This result is very important and suggests that the incentives to transfer technology given specifically by the CDM are low compared to usual economic and infrastructure-related incentives.

Table 9 – Regression results of models explaining *TECH_TRANSFER*

Dependant variables	**Model A**	**Model B**
LOGSIZE	0.2792 *** (0.0842)	0.2590 *** (0.0929)
CREDIT BUYER	0.5122 ** (0.2504)	0.6282 *** (0.2635)
SUBSIDIARY	2.3508 *** (0.3578)	2.2463 *** (0.3621)
SIMILAR_PROJECTS	-0.4192 *** (0.1204)	-0.2782 ** (0.1310)
TRADE	0.0104 * (0.0056)	0.0103 * (0.0060)
FDI_INFLOWS	-0.2587 * (0.1368)	-0.1045 (0.1452)
GDP_GROWTH	0.6153 *** (0.2219)	0.5124 ** (0.2184)
TECH_CAPABILITY	0.0686 * (0.0395)	
TECH_CAPABILITY * AGRICULTURE		-0.3474 ** (0.1730)
TECH_CAPABILITY * ENERGY		0.0825 * (0.0471)
TECH_CAPABILITY * WASTE		0.0134 (0.0508)
TECH_CAPABILITY * CHEMICALS		0.1088 ** (0.0522)
TECH_CAPABILITY * CEMENT		0.0428 (0.0485)
TECH_CAPABILITY * FOOD		0.0497 (0.0475)
TECH_CAPABILITY * IRON & STEEL		0.0392 (0.0542)
TECH_CAPABILITY * PAPER		0.0089 (0.0617)
TECH_CAPABILITY * TEXTILE		0.0538 (0.0690)
TECH_CAPABILITY * WOOD		0.0209 (0.0576)
TECH_CAPABILITY * OTHER INDUSTRY		0.0553 (0.0574)
GDP_PERCAPITA	-0.0001 (0.0001)	-0.0001 (0.0001)
LOG_POPULATION	-0.2546 (0.2645)	-0.1614 (0.2643)
$SECTOR_i$	-	-
$COUNTRY_i$	-	-
# observations	643	643
Pseudo-R2	0.3568	0.3861
Percent correct prediction	80.1 %	79.9 %

Notes: Standard error in parentheses; * denotes significance at 10% level, ** denotes significance at 5% level, and *** denotes significance at 1% level.

Figure 1 – Comparative impacts of the independent variables in a representative project



5 Explaining the type of transfer

In this section, we concentrate on the projects involving a technology transfer and we seek to identify what drives the type of transfer project developers engage in: the transfer of equipment or the transfer of knowledge.

Let *HARD_TRANSFER* denote the binary variable that indicates whether or not the technology transfer concerns equipments. A straightforward solution would be to estimate a standard logit model on the sub-sample of projects involving transfers. But results would be biased because this sub-sample is not random. In technical terms, there is a so-called sample selection bias. The reason is that unobserved factors may influence both the probability of transfer – and thus the probability for a project to belong to the sub-sample – and the type of transfer.

A solution to this problem has been suggested by Heckman (1976). This is a two-step estimation procedure. In a first stage, the probability that a project leads to technology transfer is estimated. This is the sample selection equation. This allows recovering a selection hazard index which is included as a regressor to estimate the type of transfer in the second stage (for more details on the Heckman model, see for instance Greene, 2003).

We have implemented the Heckman procedure and Table 10 reports the results of the second stage. In comparison with the previous models, we have excluded some dependent variables, either because there was no reason to assume they would influence the type of transfer (for example, GDP_GROWTH) or because they were not significant.

Results show interesting patterns. First of all, the probability that the transfer concerns equipment decreases with the number of projects using the same type of technology in the country (SIMILAR_PROJECTS). A possible interpretation is the following. A developer who needs a technology has two options: either to buy it locally or to import it. In the economic literature, the first refers to *horizontal diffusion* while the second refers to *vertical diffusion*. Our results suggest that *horizontal diffusion* dominates when the technology is equipment.

As regards technological capabilities, Models C and D show that the pro-transfer effect dominates for equipment in the energy and the waste management sectors. The agriculture is still specific confirming that the equipments used in agricultural projects do not require significant technological skills.

Table 10 – *Estimation results of the Heckman model's for HARD_TRANSFER*

Dependant variables	C	D
LOGSIZE	0.0132 (0.0638)	0.0021 (0.0667)
SIMILAR_PROJECTS	-0.3108 *** (0.0982)	-0.2417** (0.1136)
TRADE	0.0030 (0.0028)	0.0031 (0.0030)
TECH_CAPABILITY	0.0227 ** 0.0114	
TECH_CAPABILITY * AGRICULTURE		-0.9387 * (0.5051)
TECH_CAPABILITY * ENERGY		0.0427 ** (0.0197)
TECH_CAPABILITY * INDUSTRY		-0.0018 (0.0142)
TECH_CAPABILITY * WASTE		0.0510 * (0.0283)
$SECTOR_i$	-	-
$COUNTRY_i$	-	-
Uncensored observations	279	279
Standard error in parentheses; * denotes significance at 10% level, ** denotes significance at 5% level, and *** denotes significance at 1% level.		

5 Conclusion

This paper focuses on transfers of GHG mitigation technologies induced by the Clean Development Mechanism. We have examined technology transfers in the 644 CDM projects registered until May 2007.

From a descriptive point of view, the data shows that technology transfers take place in more than 40% of the CDM projects. Very few projects involve the transfer of equipment only. Instead, projects often include the transfer of knowledge and operating skills, allowing project implementers to appropriate the technology.

Technology transfer mainly concern two areas. The first one is the end-of-pipe destruction of non-CO_2 greenhouse gas with high global warming potentials, such as HFCs, CH_4 and N_2O. This concerns the chemicals industry, the agricultural sector and the waste management sector. The second one is wind power. Other projects, such as electricity production from biomass or energy efficiency measures in the industry sector, mainly rely on local technologies. Moreover, Mexican and Chinese projects more frequently attract technology transfers while European countries are the main technology suppliers.

We have also developed econometric models in order to characterize the factors underlying these patterns. They show that there are economies of scale in technology transfer: all other things being equal, transfers in large projects – in terms of emissions reductions – are more likely. Furthermore, the probability of transfer is 50% higher when the project is developed in a subsidiary of Annex 1 companies. Having an official credit buyer in the project also exerts a positive influence on transfer likeliness, albeit much smaller (+16%).

As regards the host countries' features, the most interesting econometric results deal with technological capabilities. In theory, this factor has ambiguous effects. On the one hand, high capabilities may be necessary to adopt a new technology. On the other hand, high capabilities imply that many technologies are already available locally, thereby reducing transfer likeliness. Our estimations show that the first effect strongly dominates in the energy sector and in the chemicals industry. By contrast, the second effect is stronger for agricultural projects. This suggests that the agricultural technologies transferred in these projects tend to be simple.

What are the policy implications? First, these results suggest policy lessons on CDM design. Encouraging large projects – or project bundling – allows to exploit increasing returns in technology transfer. Promoting projects in subsidiaries of Annex 1 companies could also be of great use to foster technology transfer. In practice, one could imagine different ways of providing incentives for companies to do so (e.g., additional credits, simplified administrative procedures). To a lesser extent, credit buyers, which are generally not pure financial actors, can also play a positive role.

Our analysis may also give lessons on general measures. In particular, the study suggests that programs of technological capacity building would be particularly profitable in the energy sector and in the chemicals industry.

Last, let us pinpoint some limits of this exercise. First, the data describes projects registered during a very short period of time (about 2 years). This prevents using this information to characterize the dynamic aspects of diffusion. Second, the data does not allow investigating the diffusion of technology within host countries, which may be as important as international transfers. Other methodological weaknesses are the lack of sector-specific variables in comparison with project design variables and country-specific variables and the fact that information on technology transfer may be biased as it is self reported by the project developers in the PDD.

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Part 3

Technology transfer by CDM projects: a comparison of Brazil, China, India and Mexico

1. Introduction

The success of post-Kyoto climate policies will crucially hinge on the involvement of fast growing emerging countries such as China, India or Brazil. Such involvement however raises difficult policy issues that largely shape the current climate negotiations. To reduce the greenhouse gas (GHG) intensity of their growth paths, emerging countries would have to implement environmentally friendly technologies on a massive scale. Thus far, most of these technologies have been developed and used in developed countries. To catch up, developing countries must either develop the technology by their own means, or acquire it abroad – two costly options. Against this background, enhanced action on technology development and transfer was marked as one of the objectives the December 2007 Bali road map, and discussions have started in the Expert Group on Technology Transfer to find effective and acceptable mechanisms to fulfil this goal.

The Clean Development Mechanism (CDM) of the Kyoto protocol was a first attempt to address these challenges. CDM allows industrialized countries which have accepted emissions reduction targets to develop or finance projects that reduce GHG emissions in non-Annex 1 countries in exchange for emission reduction credits. Since reducing GHG emissions in a less-developed country may be cheaper than doing so domestically, it helps Annex 1 countries to achieve their emission reduction target at a lower cost. Besides saving abatement costs, the goal of the CDM is to promote sustainable development in non-Annex 1 countries (for a review on this aspect of the CDM, see Olsen, 2007). It is also considered by many as a key means to boost technology transfer and diffusion. Projects may in particular lead to international transfer if the technology used in the project is not available in the host country and has to be imported. Although international transfers are not necessarily better than the replication of domestic technology (the latter being in some cases more appropriate to match local conditions), it is of course important to analyze whether the CDM is effective in this respect. We aim to do so in this paper by comparing international technology transfers induced by the CDM in four emerging countries – namely China, India, Brazil and Mexico – which are also the main recipients of CDM projects.

The transfer of GHG mitigation technologies to developing countries is the subject of an extensive general literature (for example, Blackman, 1999; Yang, 1999; IPCC, 2000; Yang and Nordhaus 2006). Numerous case studies of successful technology transfers have also been conducted in order to assess the drivers for and barriers to technology adoption (for instance, OCDE/IEA 2001; Kathuria 2002; Ockwell et al. 2008). Ockwell et al. The literature on technology transfers through CDM is more recent but it is growing fast. A good review can be found in Scheider et al. (2008), with a detailed analysis of the CDM contribution to the alleviation of various barriers to technology transfer. Several papers use a quantitative approach. Based on a sample of 63 registered projects, De Coninck, Haake and van der Linden (2007) show that imported technologies originate mostly from the European Union and that the investments from industrialized countries associated with the CDM are small when compared to total foreign direct investments. Seres et al. (2007)[13] and Dechezleprêtre et al. (2008) analyze technology transfers respectively in 2293 projects in the CDM pipeline and 644 registered projects. They find transfers in respectively 39% and 43% of these projects (accounting for 64% and 84% of emission reduction claims). Using regression analysis, both papers find that larger projects and projects with foreign participants involve more technology transfer. Dechezleprêtre et al. (2008) consider other variables such as the technology capabilities of recipient countries, and whether project developers are subsidiaries of Western companies, both of which have significant positive effects on transfers.

As compared to these papers, our originality is to compare different countries and to seek to identify what explains their differences. We follow the econometric approach used in Dechezleprêtre et al. (2008). We use the same data and similar econometric models to explain inter-country differences. The four countries we focus on – Brazil, China, India, and Mexico – gather about 75% of the CDM projects. We seek to highlight and to explain the national specificities of technology diffusion by the CDM, such as differences in the percentage of projects where a technology is imported from abroad. Although our main focus is on international transfers of technology, we also take into account and discuss country differences as regards the diffusion of purely domestic technology.

The remainder of this article is organized as follows. In section 2 we describe the data. Then we give descriptive statistics by country on the frequency of transfer, on the types of technology involved, etc. In Section 4, we present an econometric model which is used in Section 5 to explain inter-country differences with respect to technology transfer. We conclude in Section 6.

2. Data issues

2.1 Sources

Our data describe all the 644 projects registered as of May 1st, 2007. These projects account for an expected 888.5 million tons of CO_2-equivalent ($MtCO_2eq$) emissions reductions by the end of 2012.

We use three main information sources to describe these projects: 1) the UNEP Risoe Center CDM Pipeline database[14], 2) the Project Design Documents, and 3) data from international institutions such as the World Bank and the World Trade Organization for country-level economic and technological variables.

For every CDM project, the UNEP Risoe Center CDM Pipeline database includes the host country, the type of technology, the estimated amount of the annual emissions reductions, the cumulative emissions reductions to the end of the Kyoto period (31 December 2012) and the countries that will

[13] In an extension of Haites et al. (2006).
[14] The database is available at http://cdmpipeline.org/

buy the carbon credits generated by the project (if already available). We have also collected the registration dates of each project and the name of every country involved, on the UNFCCC website dedicated to CDM projects[15].

The content of the Project Design Documents (PDD) is our main source of information. They are mandatory standardized documents of about 50 pages submitted to the Executive Board by the project developers for registration. In the PDDs, we have collected information about the technology used, whether there is a transfer or not, the type of transfer, the project implementer (name, business sector and name of parent company) and every foreign partner involved (name, location). We have also retrieved information on the role of the project partners: are they credit buyers, consulting companies, PDD consultants or equipment suppliers?

Host country characteristics, including information on GDP, trade or FDI flows have been obtained from the World Bank's World Development Indicators 2006[16]. We have completed this information with economic performance indicators from the Earth Trends database of the World Resource Institute[17]. To proxy the technological capability of a country to import and use advanced technology, we have used the composite index Arco developed by Archibugi and Coco (2004).

2.2 Information on technology transfers

We define technology transfer as the import of a technology from abroad. It is important to keep in mind that this definition does not encompass all forms of technology diffusion. CDM projects may also entail technology transfers within a country, e.g; from an urban to a rural area. Unfortunately such intra-country transfers are difficult to track in PDDs, and therefore they do not lend themselves easily to statistical analysis. By contrast, international transfers can be identified and make it possible to carry out more ambitious analysis. They are also of prime interest for us since they relate directly to international negotiations on technology transfers.

The technology that is transferred may take various forms. *Knowledge transfers* take place if the local project developer benefits from the transfer of knowledge, know-how, information or technical assistance from a foreign partner. By contrast, an *equipment transfer* consists in importing equipment, such as wind turbines or gas burners, from a supplier located in a foreign country. Of course, a project can involve both a transfer of equipment and a transfer of knowledge.

We find information on transfers in the PDDs. In principle, the technology to be employed in the project activity is described in section A.4.3[18]. But this is not a compulsory requirement, and no section is specifically devoted to technology transfer. Indeed, claims of technology transfer can often be found in other[s] sections such as "Description of the project activity" (A.2) or "Barrier analysis" (B.4). Section G ("Stakeholders' comments") sometimes contains interesting information on equipment suppliers. Further information on the technology employed may also be displayed in the annex. In order to get

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[15] http://cdm.unfccc.int/Projects/index.html
[16] Available online at http://devdata.worldbank.org/wdi2006
[17] http://earthtrends.wri.org/
[18] The Guidelines for completing the PDD available from UNFCCC indicate that "this section should include a description of how environmentally safe and sound technology, and know-how to be used, is transferred to the host Party(ies)."

relevant information, we have read carefully all the PDDs[19]. More details and examples can be found in Dechezleprêtre et al. (2008).

How reliable is this information? There are several potential problems which we have tried to mitigate. In some PDDs, a transfer of technology may refer to the simple adoption of a new technology. If the technology provider is clearly located within the country, the project involves no international transfer; consequently our database records no international transfer for that project in that country.

Another difficulty concerns specifically the import of equipment. From a general point of view, the import of goods does not always entail a technology transfer. For instance, importing a DVD player made in China into the U.S. does not. The same is true for CDM projects which might include the import of generic devices. In this regard, we have considered that the import of equipment is associated with a technology transfer as soon as the PDD claims that it is.

It remains that PDD editors have an incentive to overstate the existence of technology transfer as it helps project registration. Accordingly, type I errors are unlikely while type II errors could be frequent even if any claim of technology transfer should be justified in the PDD[20]. Therefore, descriptive statistics regarding technology transfer percentages are probably less reliable than other figures.[21] This is a usual difficulty with this type of study. But one can realistically assume that this bias is randomly distributed over the PDD-writing population. Therefore, this problem probably does not damage our econometric results.

3. Descriptive statistics by country

In this section, we describe the international technology transfers occurring in CDM projects in Brazil, China, India and Mexico. As shown in Table 1, the share of projects involving such transfers varies greatly across countries. 68% of projects set up in Mexico involve an international technology transfer, but only 12% of projects located in India.

In most cases international transfers are not limited to the import of equipment. The transfer of both equipment and knowledge is observed in 42% of Chinese projects and 46% of Indian projects. Transfers of knowledge alone are very frequent in Brazil (23%) and in Mexico (68%). This is mainly due to the high number of projects taking place in the agricultural sector in these two countries.

[19] For efficiency purposes, we first searched the PDDs for the words “technology”, “transfer”, “equipment”, “supplier”, “import”, “manufacturer” and “training”. If no information on technology transfer could be found through this search, we then read through the entire PDD.

[20] A type I error consists of wrongly describing a project as not involving any technology transfer. Conversely, a type II error occurs when a project is wrongly described as involving a technology transfer (when it does not).

[21] Haites et al. (2006) find that 33% of the projects involve transfer, compared to 43% in our data set. One possible reason is that the datasets are slightly different. Another is the procedure used in both papers for encoding technology transfer. We read the entire PDDs whereas Haites et al. (2006) only searched for the word “technology”.

Table 1 – *International technology transfer by host country*

Country	Total number of projects [N]	Number of projects involving technology transfer			Percentage of technology transfer
		Equipment only [E]	Knowledge only [K]	Equipment + Knowledge [B]	[(E+K+B)/N]
India	225	10	5	13	12%
Brazil	99	8	23	9	40%
Mexico	78	4	45	4	68%
China	71	11	1	30	59%
Total	473	33	74	56	34%

Table 2 gives additional information on the projects. In average, Chinese projects are much larger. This is essentially due to the presence of 7 huge projects of HFC-23 destruction. The percentage of projects which are located in the subsidiary of Annex 1 countries' companies is interesting as one might expect more transfers in these projects. In this regard, China and India sharply differ from Brazil and Mexico, where such projects are much more frequent. Finally, the presence of a foreign credit buyer may also facilitate transfer. They are involved in most projects in China and Mexico, but only in 36% of the Indian projects.

Table 2 – *Project characteristics by host country*

Variables	China	India	Brazil	Mexico
Average size (ktCO_2eq/year)	816.7	85.2	160.0	76.5
Median size (ktCO_2eq/year)	110	26	42	17
Projects implemented in a subsidiary of annex I company	0%	3%	28%	56%
Projects with a foreign credit buyer	89%	36%	52%	97%

We now give more specific information on the types of technology that are transferred in each country.

3.1 Brazil

CDM projects in Brazil belong to two main types: renewable energy production and biogas recovery in breeding farms and landfills (see table 3). Renewable energy projects mostly consist of hydro power and biomass energy production. The latter are usually set up in sugar mills where bagasse - a residue from sugarcane processing – is used as a feedstock for cogeneration of heat and electricity. These power plants rely on direct-fired systems that are very similar to usual fossil-fuel fired power plants.

Thus there is no need to import technologies. Hydropower is also common in Brazil as it supplies more than 80% of electricity in this country. A few wind energy projects use turbines supplied by Enercon, Germany.

The second most popular type of CDM projects in Brazil is biogas recovery. They generally entail technology transfer. In particular, projects in breeding farms mitigating biogas resulting from the decomposition process of animal effluents present interesting channels of technology diffusion. 85% of these projects benefit from technology transfers from AgCert. This Irish consulting company provides farmers with turnkey solutions, including training sessions on how to operate the technology. It also operates in Mexico as will see below.

However, in terms of emission reductions, the most important projects concern landfill gas capture and N_2O destruction. Projects in landfills mainly use foreign technology. In particular, several projects set up in subsidiaries of French companies Veolia Environnement and Suez benefited from internal transfers of know-how.

As for the N_2O destruction project, there is only one huge project in a chemical facility producing adipic acid. It amounts for nearly 6 million tons of annual CO_2eq reductions, i.e. 38% of the annual reductions in Brazil by CDM projects. The plant is owned by Rhodia and the Brazilian facility benefits from transfers of know-how from the facility of Chalampé located in France.

Table 3 – *Main project types and international technology transfers in Brazil*

Type of technology	Number of projects	Percentage of projects involving intern. technology transfer	Average project size (annual ktCO_2eq)	Total annual reductions (ktCO_2eq)
Biomass energy	34	9%	51	1747
Biogas recovery in agriculture (breeding farms)	20	90%	74	1477
Hydro power	19	11%	45	852
Landfill gas recovery	13	85%	402	5225
N_2O destruction	1	100%	5961	5961
Wind power	4	75%	42	169
Energy efficiency (industry)	2	0%	47	93
Fossil fuel switch	5	20%	20	99
Fugitive gas recovery	1	100%	220	220

3.2 China

China also implements many renewable energy projects as shown in Table 4. The country can rely on local technologies for hydro power and biomass energy projects but depends upon imported turbines for wind power projects. The main suppliers of wind turbines are Gamesa Eolica (Spain) with 12 projects and Vestas (Denmark) with 8 projects. Notably, 55% of the wind projects registered in April 2007 use turbines manufactured by the local firm Goldwind. Imported turbines have higher capacities on average than locally produced turbines (1.11 MW against 750 kW).

China is the leading country for HFC-23 destruction projects. These 7 projects represent 80% of the annual reductions in China and they always entail a technology transfer. The French company Vichem provides the HFC destruction technology of 4 out of 7 projects. The rest is supplied by Japanese corporations.

As landfill gas capture and flaring is new in China, local CDM developers have frequently cooperated with foreign suppliers such as Waste Management New Zealand or Energi Gruppend Jylland Denmark. This leads to an 85% rate of technology transfer in this area.

Table 4 – *Main project types and international technology transfers in China*

Type of technology	Number of projects	Percentage of projects involving intern. technology transfer	Average project size (annual $ktCO_2eq$)	Total annual reductions ($ktCO_2eq$)
Wind power	34	74%	112	3807
Hydro power	13	0%	104	1349
HFC decomposition	7	100%	6743	47200
Biomass energy	5	20%	160	802
Methane destruction	3	66%	462	1387
Energy efficiency (industry)	3	66%	804	2413
Landfill gas recovery	4	100%	163	652
N_2O destruction	1	100%	350	350
Reforestation	1	0%	26	26

3.3 India

India is the main host country for CDM projects but as mentioned above, international technology transfer is very limited. However this does not imply that there is no technology diffusion. As in China, biomass energy and hydro power projects rely on local technologies (see Table 5). But, contrary to China, most wind power projects use equipment produced by local manufacturers (mainly Suzlon and Enercon India).

Energy efficiency measures in industry - power generation from waste heat recovery or reduction of steam consumption - are usually designed locally. However, technology partnerships have been set up in a few projects. For example, Technovacuum Russia has supplied a technology aiming at reducing steam consumption in a petroleum refinery and Giammarco-Vetrcoke Italy has implemented a solution to reduce energy consumption at an ammonia plant. The technology used in the three HFC destruction projects also comes from Europe (Ineos UK, SGL Acotec and Caloric Anlagenbau Germany).

Interestingly, the unique solar power project in India has been developed through a partnership between a German physicist Wolfgang Scheffler – who has invented the so-called Scheffler reflectors for solar cooking - and Indian institutions.

Table 5 – *Main project types and international technology transfers in India*

Type of technology	Number of projects	Percentage of projects involving intern. technology transfer	Average project size (annual $ktCO_2eq$)	Total annual reductions ($ktCO_2eq$)
Biomass energy	78	8%	38	2926
Energy efficiency (industry)	54	17%	85	4595
Hydro power	30	0%	34	1030
Wind power	26	23%	29	763
Reduction of the share of clinker in cement production	13	0%	119	1544
Biogas (other)	7	0%	32	224
HFC decomposition	3	100%	2589	7766
Fossil fuel switch	4	25%	43	171
Energy efficiency (services)	1	100%	3	3
Energy efficiency (supply side)	6	0%	6	38
Solar power	1	100%	1	1

3.5 Mexico

Mexico is very specific: almost 90% of CDM projects concern biogas recovery in breeding farms (Table 6). AgCert – the Irish company previously evoked for Brazil – has initiated 41 projects involving technology transfers through training of local staff. Granjas Carroll Mexico - the largest commercial pig producer in Mexico - has developed 24 projects with the help of the EcoSecurities (though no technology transfer is claimed in this case). The CDM has clearly enhanced the diffusion of biogas mitigation among Mexican pork producers.

Among the other Mexican projects with technology transfer, there is one large HFC project, which yields more annual emission reductions than the 69 biogas recovery projects altogether, and three wind power projects using turbines supplied by Gamesa Eolica. Two landfill gas projects have been developed through a partnership between EcoMethane and technology providers from UK, Biogas Technology Ltd and ENER*G.

Table 6 – *Main project types and international technology transfers in Mexico*

Type of technology	Number of projects	Percentage of projects involving intern. technology transfer	Average project size (annual $ktCO_2eq$)	Total annual reductions ($ktCO_2eq$)
Biogas recovery in agriculture (breeding farms)	69	65%	31	2146
HFC decomposition	1	100%	2155	2155
Hydro power	2	50%	43	87
Landfill gas	2	100%	186	373
Wind power	3	100%	400	1201
Biogas (other)	1	100%	4	4

4. Econometric model

In the previous section, we have presented statistics describing inter-country differences in international technology transfers by CDM. These statistics do not help us to understand what drives these differences. For instance, 59% of the Chinese projects involve an international transfer while the percentage is only 12% in India. Why is it so? Is it because the technological capability of India is less than that of China or, by contrast, because India can rely on local technology? Is it due to sector composition effect – Indian projects may take place in economic sectors where a transfer is less likely? Is it due to project characteristics? In this section, we present an econometric model which we will use in the next section to answer these questions. Econometric analysis allows us to determine the specific effect of each variable on the likelihood that a project involves international technology transfer, all other factors being held constant.The model is very close to the models presented in Dechezleprêtre et al. (2008).

4.1 Model specification

Let *TECH_TRANSFER* denote a binary variable equal to 1 if a project involves a technology transfer (regardless of the nature of this transfer), and to 0 otherwise. To examine the relationship between *TECH_TRANSFER* and a set of explanatory variables, the following logit equation is estimated:

$$\Pr(TECH\_TRANSFER = 1) = \frac{e^{\Omega}}{1+e^{\Omega}} \qquad (1)$$

with:

$$\begin{aligned}\Omega = {} & \alpha_0 + \alpha_1(LOGSIZE) + \alpha_2(CREDIT\_BUYER) + \alpha_3(SUBSIDIARY) \\ & +\alpha_4(SIMILAR\_PROJECTS) + \alpha_5(TRADE) + \alpha_6(FDI\_INFLOWS) \\ & +\alpha_6(GDP\_GROWTH) + \alpha_7(LOG\_POPULATION) + \alpha_8(GDP\_PERCAPITA) \\ & +\alpha_9(CARBON\_INTENSITY) + \alpha_{10}\left(TECH\_CAPACITY\right) \\ & +\alpha_n\left(SECTOR_n\right) + \alpha_o\left(COUNTRY\right)_o + \varepsilon\end{aligned}$$

α_i is a vector of coefficients to be estimated and ε is a random term identically independently distributed following a Gumbel extreme distribution. We use a set of regression variables at the project and country levels that are likely to influence the probability that a CDM project involves some international transfer of technology.

According to Schneider et al. (2008), technology transfers through CDM projects are hindered by four types of barriers pertaining respectively to their commercial viability; the lack of information on the existence and functioning of the CDM, or on available technologies; a lack of access to capital; and the institutional framework in the host country. Following their analysis, we identify three variables at the project level that may help to alleviate the first three barriers.

We use the log of the project size (LOGSIZE), as measured by its annual emissions reduction, as an indicator of the commercial viability of CDM projects.[22] As a general rule, the CDM registration process entails large transaction costs that are fixed and therefore represent a strong impediment to small scale projects (Michaelowa et al., 2003). Similarly, upfront investment costs are higher when technology is imported from industrialized countries (Schneider et al., 2008). This is especially true when the technology is at an early commercialization stage, which it is often the case with environmentally sound technologies (Wilkins, 2002). Consequently, we can expect projects involving technology transfer to be more viable if they are large.

The two other project variables relate to the access to information and capital. SUBSIDIARY is a dummy variable indicating whether the project is implemented in the subsidiary of a company located in an Annex 1 country. The involvement of a parent company can facilitate technology transfers in many ways. It may help manage the CDM registration, provide expertise at the technology level, or provide an easier access to capital.

Financial barriers can also be alleviated thanks to the participation of one or more credit buyers that are not parent companies but rather carbon founds. Before the project developer can sell the credits, the UNFCCC must first certify, issue and register the emission reduction and this administrative process takes time. Selling credits through a forward contract can be of great help. It reduces the risk surrounding the investments by adding a guaranteed revenue stream. One can assume that credit buyers also give advice and bring expertise that may ease technology transfer. We therefore define CREDIT_BUYER as a dummy variable indicating the participation of one or more credit buyers in the project, and expect a positive effect of this variable on the probability of international transfer.

The remaining variables characterize the capability of the host country to attract international technology transfers. We include the country size (LOG_POPULATION), the per capita GDP (GDP_PERCAPITA) and the carbon intensity of the economy (CO2_INTENSITY) as usual control variables[23]. Although they are likely to affect positively the number of opportunities to undertake CDM projects, it is not obvious how they could influence the probability that those projects involve international technology transfers. By contrast, we can expect the variable GDP_GROWTH to have a positive impact on such transfers. Indeed a fast growth hinges on sustained investments which offer more opportunities for implementing new technologies through CDM projects.

Empirical evidence indicates that the adoption of a new technology is strongly associated with human capital, supporting infrastructure and research and development activities (Blackman 1997). In order to measure this technological capability (TECH_CAPABILITY), we use the ArCo technology index

[22] Using the logarithm of the size ensures that the few very large HFC projects do not have a disproportionate influence on the results.

[23] Per capita GDP and population are similarly used as control variables in previous works (see for instance Haites et al., 2006 and Seres, 2007). We added the carbon intensity of the economy as a control variable following several requests to do so by readers of previous versions of this work. As could be expected, we find no significant effect of this control variable.

developed by Archibugi and Coco (2004). This composite indicator captures three aspects determining technological capabilities: the creation of technology (number of patents and number of scientific articles), the technological infrastructures (internet penetration, telephone penetration and electricity consumption) and the development of human skills (percentage of tertiary science and engineering enrolment, mean years of schooling and literacy rate). It must be noticed that the technological capability, although favoring international technology transfers at a macroeconomic level, may also imply that the technology required for CDM projects are available locally. To take this possibility into account, we add as a country variable the number of other CDM projects using the same technology within the host country (SIMILAR_PROJECTS). Of course we can expect that international technology transfers are less likely when similar projects are carried out in the same country.

There is also strong empirical evidence that international trade and Foreign Direct Investments (FDI) promote the transfer of technology across countries (Coe et al. 1997). A country openness to global trade can indeed alleviate barriers pertaining to access to information and to technology. It may also denote a favorable institutional environment. Accordingly, we use the variable TRADE which is the ratio of the sum of exports and imports of merchandise on GDP and FDI_INFLOWS which is the level of incoming FDI in the host country.

Finally, SECTORi and COUNTRYi are vectors of sector dummies and country dummies, respectively. They control for sector- and country-specific characteristics that are not captured by the other variables.

4.2 Estimation results

Results are displayed in Table 7. The overall quality of the estimation is reasonably good. The McFadden pseudo R-squared is 0.36 and the model correctly predicts 80% of the observed outcomes. The coefficients exhibit the expected signs.

We will be very quick on the comments of these results as this was the prime goal of the companion paper (Dechezlepretre et al., 2008). Technology transfer increases with the size of the project (LOGSIZE). The participation of one or more credit buyers in the project (CREDIT_BUYER variable) also increases the likelihood that the project involves technology transfer. Marginal calculations show that a project with a credit buyer has a 16% higher probability of involving a technology transfer.

Being the subsidiary of a company from an Annex 1 country (as indicated by the dummy variable SUBSIDIARY) clearly favors the transfer of technology. The coefficient is highly significant and much larger than that of CREDIT_BUYER. In marginal terms, the transfer likeliness of a project located in the subsidiary of an Annex 1 company is 50% higher.

Turning next to country variables, it is worth noting that the average annual rate of GDP growth from 2000 to 2004 (GDP_GROWTH) has a very high impact on the likeliness of technology transfer: one additional percentage point of average GDP growth raises transfer likeliness by 19%. The variables LOG_POPULATION , GDP_PERCAPITA and CO2_INTENSITY have no significant effects in the regression.

As expected, trade openness (TRADE) reinforces the likelihood of technology transfer. In contrast, the share of FDI inflows in GDP has a negative impact on transfer. This may be due to the fact that capital links are already captured by the variable SUBSIDIARY. National technological capabilities (TECH_CAPABILITY) have a positive and significant impact on transfer likeliness, while the number of other CDM projects using the same technology within the host country (SIMILAR_PROJECTS) lowers the probability of transfer.

Table 7 – Regression results of model explaining *TECH_TRANSFER*

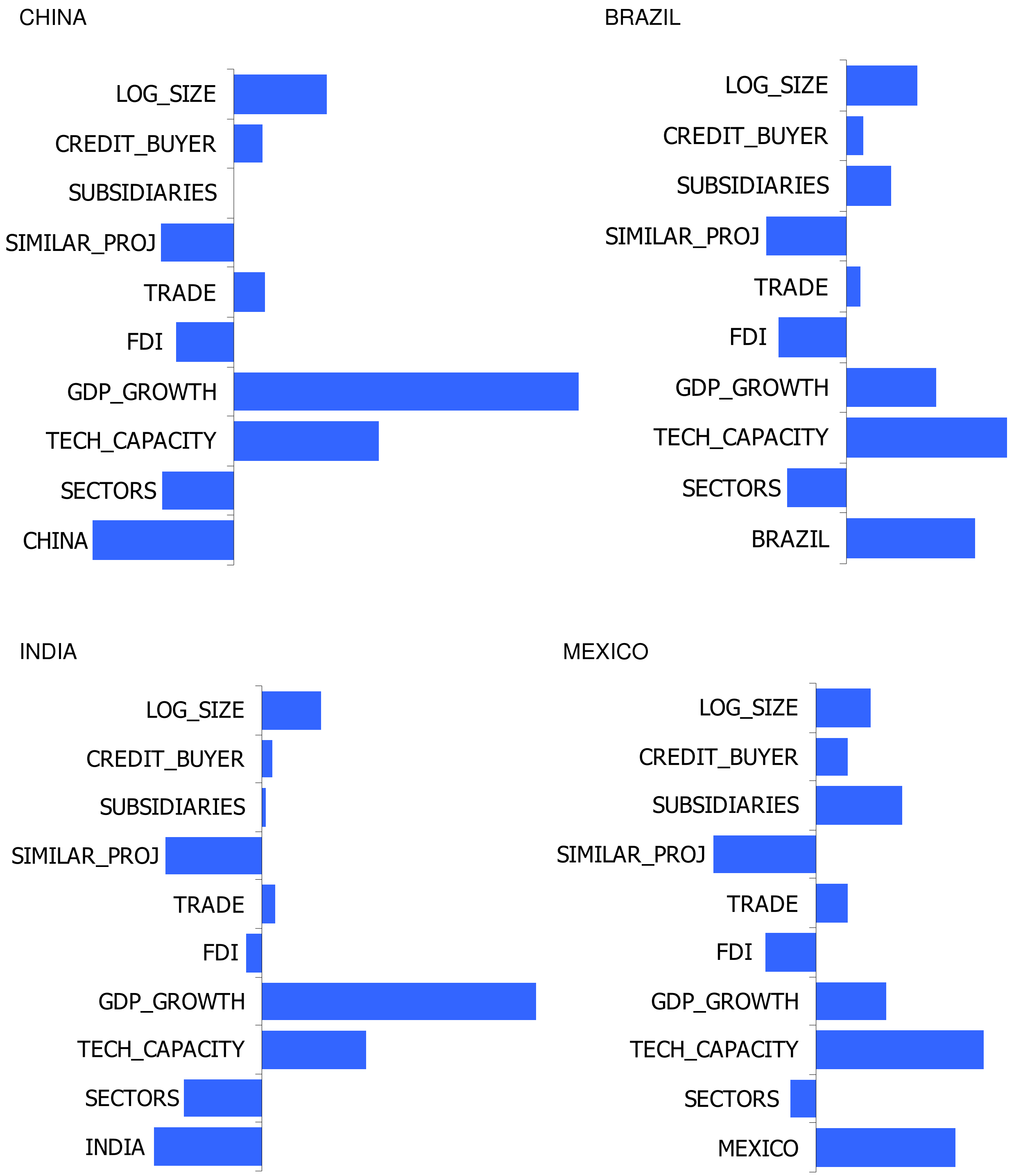
Dependant variables	**Coefficients**
LOGSIZE	0.2806*** (0.0843)
CREDIT_BUYER	0.5050** (0.2509)
SUBSIDIARY	2.3511*** (0.3579)
SIMILAR_PROJECTS	-0.4103*** (0.1206)
TRADE	0.0090* (0.0057)
FDI_INFLOWS	-0.2674* (0.1363)
GDP_GROWTH	0.6882*** (0.2225)
GDP_PERCAPITA	-0.0001 (0.0001)
LOG_POPULATION	-0.2566 (0.2641)
CARBON_INTENSITY	0.0002 (0.0003)
TECH_CAPABILITY	0.0722* (0.0400)
$SECTOR_i$	—
$COUNTRY_i$	—
Nb of observations	643
Pseudo-R2	0.36
Percentage of correct predictions	79.8 %

Notes: Standard errors in parentheses; * denotes significance at 10% level, ** denotes significance at 5% level, and *** denotes significance at 1% level.

5. Country comparison

In this section, we use the econometric model presented in section 2 in order to analyze the impact of the explanatory variables on the overall rate of technology transfer in the different host countries. The discussion about the sign of the coefficients does not yield information about the size of the effects of the explanatory variables. In order to compare these effects across countries, we draw Figure 1 using the model's results. Figure 1 is based on the following calculation. Let $\overline{x}_i$ be the average value of the variable x_i in a sample of projects and let β_i denote the value of its coefficient. Then, the product $\beta_i \overline{x}_i$ represents the average impact of x_i on the linear predictor Ω of Equation (1). Calculating the value of $\beta_i \overline{x}_i$ for every variable allows setting the average weight of each variable against the decision to transfer technology. Figure 1 represents these weights for the different countries. Using the same metric, each bar measures the impact of the variable on an average CDM project in each country. Finally, we only represent statistically significant variables.

Figure 1 – Comparative impacts of the explanatory variables for the different countries



Let us use Figure 1 to compare the different countries. Consider first the effect of the project variables in Figure 1. The stronger impact of PROJECT_SIZE in China is clearly due to its large HFC projects. The two other variables, namely CREDIT_BUYER and SUBSIDIARY, denote important differences in countries' capacities to attract foreign partnerships. China and Mexico have clearly benefited from the involvement of foreign credit buyers. The advantage of Mexico is even stronger as regards foreign subsidiaries, for which Brazil is also well positioned. In contrast, India performs poorly with respect to both variables.

Turning next to country variables, the strong effect of GDP_GROWTH clearly indicates that international technology transfers are more likely in fast growing economies. Although all countries have substantial growth rates, the very fast economic growth in India and in China seem to be decisive factors in their abilities to generate projects involving technology transfers.

International technology transfers are also strongly correlated to national technology capabilities (TECH_CAPACITY). Beside a small lag in the case of India, all countries benefit in equal proportions from attractive technological capabilities. One must however balance this effect with the impact of the variable SIMILAR_PROJECTS which denotes the number of other CDM projects using the same technology within the host country. Local availability of technologies has comparable negative impacts on the likelihood of technology transfers in each country. It mitigates the positive effect of TECH-CAPACITY, without suppressing it entirely. Again, the net impact is the lowest in India, which suggest that India has been particularly successful in relying on domestic technology capabilities to diffuse carbon mitigation technology through the CDM.

Sector dummies are interesting in that they reflect the sector-composition effect. Figure 1 suggests that inter-country differences are not that much influenced by this. The exception is Mexico. One possible explanation is that this country gets very specialized in biogas recovery in breeding farms which frequently entail technology transfer.

Finally, the country dummies – BRAZIL, CHINA, INDIA and MEXICO – capture factors that are not taken into account by the other country-level variables (TRADE, FDI, GDP_GROWTH and TECH_CAPACITY). They may reflect administrative peculiarities - difference in intellectual property regimes, etc.- which are not described in the database. Figure 1 shows that these unobserved factors play a strong role in explaining country differences. Although, by nature, these effects are difficult to interpret, it is likely that the national policies with respect to CDM play an important role. China has for instance been slow in setting up a Designated National Authority (DNA) to help setting up CDM projects. In contrast, Mexico and Brazil seem to benefit of more proactive policies vis-à-vis CDM projects[24].

We can now complete the discussion by relating these results with each country's performance in terms of technology transfers. Comparing the countries in Figure 1 suggests two different types of country profiles, namely Mexico and Brazil on the one hand, and China and India on the other hand.

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[24] Remember that every host country must give its approval to CDM projects through its DNA. Interestingly, the Brazilian Designated National Authority (DNA) is hosted by the Ministry of Science & Technology, while in the great majority of cases, the DNA is hosted by the Ministry of Environment or by some national environmental protection agency.

The relative success of Mexico (where the transfer rate is 68%) in attracting foreign technology when compared to other countries is mainly due a sector-composition effect (in particular, there are many projects of biogas recovery in breeding farms, a sector where transfers prevails) combined with good technological capabilities and a strong involvement of parent companies in Mexican subsidiaries. Brazil has a similar profile but in lesser proportions. The effect of GDP_GROWTH is slightly stronger than in Mexico, while the positive impact of sector composition, foreign subsidiaries and technological capabilities is weaker.

The profiles of India and China are quite different. Indeed neither of them has experienced a strong involvement of foreign partners. The transfer rate of 59% in China is mostly explained by the dynamism of its economy (GDP_GROWTH), combined with good technological capabilities. In comparison with China, the lower rate of international technology transfers (12%) in India can be explained by a (relative) smaller advantage in terms of growth rates and technological capabilities, but also by a stronger propensity to rely on domestic capabilities to diffuse technology through the CDM.

5. Conclusion

We have described the international transfers of GHG mitigation technologies induced by the Clean Development Mechanism in Brazil, China, India and Mexico using a dataset including 644 CDM projects registered until May 2007.

Our analysis shows very large differences across countries. The percentage of projects where an international technology transfer takes place ranges from 12% in India to 68% in Mexico. Moreover, very different technologies are concerned. In Brazil and Mexico, projects recovering biogas in breeding farms represent an important share of the overall transfer. In China, Mexico and Brazil, the import of wind turbines is widespread whereas India mainly relies on local suppliers. Nevertheless, some technologies are imported whatever the country. This is true for HFC or N_2O destruction technologies used in very large projects in the chemical industry. This is also the case of landfill gas capture and flaring.

Note that a high transfer rate does not mean that the country performs better than others. Consider the example of Indian wind power projects. India would seem to perform badly in this area since transfer frequency is low (23%) as compared to others (between 75% and 100%). But it is so because India is in fact more advanced in this area and has leading domestic producers like Suzlon.

We also develop an econometric analysis to investigate what drives these transfers. Our results highlight various patterns of technology diffusion. Transfers to Mexico (68% of CDM project) and Brazil (40%) are related to the same factors, namely the strong involvement of foreign partners and good technological capabilities. The high Mexican rate seems to be due to a relative advantage against Brazil with respect to these factors. Mexico moreover benefits from a sector-composition effect: many Mexican projects concern biogas recovery in breeding farms, a sector where transfers prevail.

The pattern of technology diffusion is quite different in China (59%) and India (12%). The involvement of foreign partners is less frequent, and international transfers seem rather related to the investment opportunities generated by fast growing economies. Our results suggest that technological capabilities may play different roles in both countries. Strong technology capabilities are positively correlated with international transfers in China. By contrast, the technology capabilities of India seem to be rather geared towards the replication of CDM projects involving domestic technologies only.

What are the policy lessons of this analysis? Excluding macro variables like GDP growth, the results stress the importance of project partnerships: promoting projects in subsidiaries of Annex 1 countries' companies and involving a credit buyer in the project clearly alleviate barriers to international transfers. Our results also highlight the importance of capacity building as a means to accelerate technology diffusion. A strong technology capability facilitates the import of foreign technology, but it is also a source of domestic technologies to be diffused locally. Depending on which aspect is emphasized, it may thus be leveraged for very different patterns of technology diffusion.

Appendix ***Projects and technology transfers by type of technology***

Type of technology	Total number of projects (and projects involving transfer)							
	Brazil		China		India		Mexico	
	Total	w/ TT	Total	w/ TT	Total	w/ TT	Total	w/ TT
Biogas recovery (other)					7	0	1	1
Biogas recovery in agriculture (breeding farms)	20	18					69	45
Biomass energy	34	3	5	1	78	6		
Energy efficiency / supply side					6	0		
Energy efficiency measures in industry	2	0	3	2	54	9		
Energy efficiency measures in the services sector					1	1		
Fossil fuel switch	5	1			4	1		
HFC decomposition			7	7	3	3	1	1
Hydro power	19	2	13	0	30	0	2	1
Landfill gas recovery	13	11	4	4	2	1	2	2
N_2O destruction	1	1	1	1				
Power generation from coal mine methane			3	2				
Recovery of fugitive gas	1	1						
Reduction of the share of clinker in cement production					13	0		
Reforestation			1	0				
Solar power					1	1		
Wind power	4	3	34	25	26	6	3	3
TOTAL	99		71		225		78	

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