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INTERNATIONAL KNOWLEDGE SPILLOVERS AND CLIMATE-FRIENDLY TECHNOLOGIES

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Introduction and summary

The thesis empirically analyzes the role of international knowledge spillovers in climate-friendly technological change. The final goal is to add empirical evidence to the debate on policies and strategies that support the mitigation of climate change.

The development and diffusion of new climate-friendly technologies are necessary to reduce carbon emissions without hindering economic growth (IPCC, 2011; Popp, 2011). The three papers that are included in the dissertation aim at improving our understanding of a crucial element of climate-friendly technological change, i.e. whether and how it arises from innovative activities of other countries. To this aim, the thesis focuses on carbon emissions from energy uses, and considers two groups of new energy-related technologies, i.e. renewable energy (RE) and energy-efficient (EE) technologies. Research questions and motivations of individual papers are illustrated in the following sections, but the main arguments that led me to identify the objectives and structure of dissertation are worth being discussed here.

a) Carbon emissions cannot be curbed if RE and EE shares do not increase significantly. The *diffusion* of RE and EE technologies is necessary to reduce, respectively, carbon intensity (CI, carbon emissions carbon per unit of total primary energy supply), and energy intensity (EI, total primary energy supply per unit of GDP). CI and EI are the two precursors of carbon emissions, given the country GDP. A relevant part of the thesis will thus be devoted to the diffusion of RE and EE technologies.
b) Nevertheless, I am aware that still today *R&D activities* are crucial for the challenge of climate change mitigation. More particularly, R&D activities on RE sources and technologies will continue playing a role in the next years for the following reasons (IPCC, 2011): today most RE sources can provide competitive energy services only in certain favorable locations; some RE technologies have to be modified in order to be integrated successfully in the energy system; finally a few RE technologies are still in the nascent phase. In addition, countries that are followers in the domain of climate-friendly technologies should engage in domestic R&D for absorptive and adaptive purposes (Lanjouw and Mody, 1996; Popp, 2006; Bosetti et al., 2008). As a result, I will also analyze RE development.

c) *Developing countries* are called to play an increasingly relevant role in climate-friendly technological change. While only few developing economies are well positioned in the ranking of climate-friendly innovators (Dechezleprêtre et al., 2011), the diffusion of new climate-friendly technologies over less advanced countries is a priority. Developing countries are already responsible for more than 50% of world carbon emissions and are expected to account for two-thirds of global carbon increase over the next 30 years (IEA, 2011a, b; U.S Energy Information Administration, 2011). The diffusion process will be studied in both developed and developing countries.

d) International technology transfers dominate the sector of climate-friendly technologies, because innovation is concentrated in a few countries, and new high-quality mitigation technologies are developed by a small number of advanced economies (Dechezleprêtre et al., 2011). At the same time, follower countries cannot limit themselves to importing new technologies, they should also engage in domestic R&D activities (see (b)). In order to overcome market, cost and infrastructure barriers to deployment, countries should also engage in the accumulation of operating and installation experience (learning-by-doing: Sagar and van der Zwaan, 2006; Clarke, 2008), an activity which is highly visible and whose benefits can spill over (Nemet, 2012a and 2012b). It thus seems plausible that technological change in RE and EE sectors is accompanied by an intense cross-country transfer of knowledge from R&D and learning. The most tacit elements of technological knowledge can hardly be acquired via market transactions (e.g. technology licensing). They are more likely to be transmitted via *international knowledge spillovers* (IKS; I follow Clarke et al. (2008), who define IKS in a broad way: technological change that arises from innovation activities of other countries, as distinct from domestic R&D, domestic learning-by-doing, domestic intra- and inter-industry spillovers). I thus considered the hypothesis that IKS from both R&D and learning are a key input to climate-friendly technological change as particularly promising.

Based on these considerations, I targeted my efforts to studying IKS. Depending on the empirical setting I assumed IKS to be embodied in imported products or disembodied, and to arise from R&D or experience. At the same time, it appeared that the role of developing countries should not be overlooked, particularly with respect to the diffusion of new EE technologies, while developed countries can offer a more appropriate empirical test-bed for the development and diffusion of RE technologies, also because they are designing and enforcing appropriate policies to this purpose. Finally, the “disembodied” exchange of information is assumed to be particularly intense between more advanced economies, due to geographical and institutional proximity, i.e. knowledge externalities can occur through the Web, publications, patents, conferences, mobility of employees, students and scientists, and so on. Imports of capital goods are instead deemed the primary channel of technology transfer from developed countries to developing countries, because the latter have weaker and less frequent contacts with technological leaders.

In sum two broad issues are empirically addressed in this thesis: the extent to which international knowledge spillovers determine the development and diffusion of new climate-energy technologies; factors that enable technological knowledge to spill over internationally in these sectors (e.g. geographic proximity, established cross-country connections, or imports of intermediary products). Figure 1 summarizes the general structure of dissertation, i.e. the contributions offered by the three papers to the research on climate-friendly technological change.

Figure 1 – Climate-friendly technological change and dissertation papers

	R&D stage Outputs: climate-friendly innovations	*Diffusion stage* Outputs: climate-friendly investment; CI and EI reduction
Developed countries	Paper 1: Disembodied IKS ↔ RE innovations	Paper 3: Disembodied IKS ↔ RE investment
Developing countries		Paper 2: Embodied IKS ↔ EI and CI reduction

Paper 1 - Cross-country knowledge spillovers in renewable energy technologies

The paper has been prepared with Paola Garrone and Lucia Piscitello, from Politecnico di Milano. A preliminary version was presented at the 34th IAEE international conference (Stockholm, June, 19-23, 2011), and was published in a research volume (Garrone P., Piscitello L., Wang Y., 2011, “The role of cross country knowledge spillovers in energy innovation", in Verbeke A., van Tulder R., Tavares A.T., IBS Role in Building a Better and Stronger Global Economy, Emerald Series Progress in International Business Research, Emerald Group, 327-342).

Research questions. This paper is aimed at analyzing the effect of international knowledge spillovers (IKS) on R&D activities, and conditions that favor the cross-country transmission of technological knowledge in the renewable energy (RE) sector. More particularly two hypotheses have been tested: IKS are a significant input to the production of RE innovations; IKS need connections between countries to arise.

Motivations and background. There are some reasons to focus on the development of new RE technologies, and to analyze – among various potential determinants - the impact of IKS and the relevance of linkages with those countries that lead RE innovation. Firstly, RE technologies harness non-exhaustible, zero-carbon (or low-carbon) energy sources. Their diffusion can thus ensure the reduction of carbon emissions without hindering energy uses (Popp, 2011; IPCC, 2011, p. 40); an additional benefit is a stronger supply security for countries that depend on fuel imports. At the same time, despite the relevance of diffusion phase, R&D activities will continue playing a key role in the next years for reasons that are documented by the IPCC special report on RE sources (IPCC, 2011, pp. 39-40, 103-119 and 137-138). Second, the geography of R&D activities in RE technologies allows us to advance the hypothesis that important knowledge flows are likely to occur between advanced countries. A small number of advanced countries have developed high-quality climate-friendly inventions (Dechezleprêtre et al., 2011; OECD, 2008), but quite a number of followers are relatively activists. R&D activities are distributed over OECD countries more homogeneously in the RE sector than in other technological domains (for instance, biotechnology, ICT, nanotechnology). Adaptive and absorptive R&D investments are needed in order to integrate and to exploit international knowledge (Lanjouw and Mody, 1996; Popp, 2006; Bosetti et al., 2008). Finally, knowledge about technologies is not fully codified and remains tacit and informal in nature (Keller, 2004), also because energy innovation systems are extremely country-specific (Sagar and Holdren, 2002; Sagar and van der Zwaan, 2006; Taylor, 2008). The most tacit elements of technological knowledge can hardly acquired via market transactions; instead they can be transmitted if repeated interactions occur and mutual relations are established (Audretsch, 1998). International knowledge sourcing in the RE sector is thus likely to require established linkages between countries (Perkins and Neumayer 2009, 2012). IKS are likely to be more effective when cross-country connections are stronger.

The literature that has addressed international knowledge spillovers in new energy technologies has yielded mixed results. Bosetti et al. (2008) have integrated disembodied international R&D spillovers in a climate-economy model of different regions throughout the world. High-income countries have been shown to reduce their energy R&D investments due to international spillovers, but free-riding does not impair the overall knowledge stock. Braun et al. (2010) and Garrone and Grilli (2010) have not found a significant effect of foreign innovative activities on, respectively, wind and solar innovations and climate-related indicators in OECD countries. By contrast, Verdolini and Galeotti (2011) have shown that international knowledge spillovers foster energy-related innovation, and discovered factors that govern cross-country knowledge transfers. It is worth emphasizing that they referred only to the transmission of codified knowledge as represented by patent citations. Perkins and Neumayer (2009, 2012) have compared different spillover channels, but their analysis concerns the transmission of pollution and carbon efficiency across countries, an outcome that includes but is not limited to the diffusion of technological knowledge.

Methodology. Relying on a knowledge production function à la Griliches-Jaffe, we model country-level innovations in the RE sector as depending on domestic R&D stocks, domestic human capital, and disembodied IKS, after controlling for climate-energy policies. R&D stocks have been measured through an application of perpetual inventory method. The innovation outputs of 18 OECD countries (1990-2006) is represented through counts of patents that have been obtained in one of the RE technological classes, as identified by Johnstone et al. (2010). An innovative IKS indictor is advanced, i.e. one that weighs the R&D stock of other countries with the intensity of cross-country interactions. The latter are proxied by a function of mutual bilateral trade flows, which have been drawn from the UN Comtrade database. It should be underlined that here trade flows are assumed to describe cross-country connections and interactions, and imports of capital goods are used as control variable, in order to control for embodied knowledge spillovers. . In order to check the robustness of results and to assess the role of alternative channels of knowledge transmission, two alternative IKS indicators have been used: the un-weighted sum of international R&D stocks; the sum of international R&D stocks weighted by the reverse of the geographic distance. In addition, estimates have been obtained also after having excluded GDP from regressors (to verify the role of size effects). Estimates have been obtained using a negative binomial model with fixed effects.

Main findings. The ability of advanced economies to develop new RE technologies depends to a great extent on international R&D activities. The effect of IKS is significant, and comparable with the effect of domestic R&D, even though it is smaller. The analysis allows us to identify factors that enable developed countries to build on international technological knowledge and to join the RE innovation arena. International knowledge cannot be sourced by countries that have not established interactions with R&D leaders, whether the geographic distances are limited or not. Policies aimed at strengthening international cooperation on climate-friendly technologies should be encouraged (Bosetti et al. 2008, Bohnstedt et al., 2012; Popp 2011), particularly between countries that have already developed mutual connections.

Paper 2 – International knowledge spillovers and carbon emissions from developing country

The preliminary version of this paper has been presented in the 2012 ZEW Summer Workshop on Trade and the Environment (Centre for European Economic Research, Mannheim, Germany, October 12-16, 2012) and in a FEEM seminar (Fondazione Eni Enrico Mattei, October 25, 2012). It has been prepared with Ian Sue Wing and David Popp, as an outcome of a research visiting period in Boston University.

Research questions. The second paper is aimed at characterizing the climate-friendly technical change in developing countries, arising from North to South technology transfer. It is an attempt to answer the question whether IKS are on net amplifying or attenuating CO_2 emissions from developing countries. More particularly, three hypotheses have been tested: IKS embodied in capital goods trade improve the energy efficiency of recipient countries; IKS embodied in capital goods trade lead to a change of carbon intensity in recipient countries, but no priors are formulated about the effect sign; IKS embodied in capital goods trade can contribute to the increase of labour productivity in recipient countries.

Motivations and background. The second paper adds empirical evidence to the knowledge basis on international transfer of climate-friendly technologies that are embodied in capital goods trade (machinery and equipment), focusing on developing countries. We employ a simple empirical approach which allows us to statistically isolate the offsetting effects of spillover on developing countries' emissions through the growth channel and energy-saving channel. On the one hand, spillovers can be considered to increase the productivity of recipient countries. In turn, productivity increases have long been known to be the key driver of output growth (Islam, 2004). On the other hand, spillovers are recognized to contribute to the improvements of energy efficiency, which is thought to exert the most important influence on long run emissions (Sue Wing, 2008; Popp et al., 2009). Understanding how these forces are likely to play out in developing economies is challenging because of the paucity of direct observations of technical change there (Johnstone et al., 2010, Garrone et al., 2011).

This paper differs from the first paper in the following aspects (see also the introduction). Firstly, it focuses on 56 developing countries, rather than on developed countries. Developing countries are crucial in the effort of mitigating emissions of greenhouse gases, as they are big emitters now and also in the future. Secondly, the second paper focuses on the diffusion of new technologies rather than on the R&D process, because it seems plausible that the vast majority of R&D investment and technology development take place in industrialized economies, while poor nations acquire technology from them (Dechezleprêtre et al., 2011). Hence, in order to gain a better insight it is necessary to investigate the relationship between measures of international technology diffusion and the precursors of CO_2 emissions in developing economies. Thirdly, in this paper IKS are mediated through technology transfer embodied in north-south trade of equipment and machinery, while the first paper models the disembodied technology spillovers that can occur by means different from the exchange of goods. There is evidence that that the use of new equipment in the manufacturing and industrial sectors is an important source of technological progress and of economic growth (Jaffe et al., 2005). There are two kinds of embodied spillovers. The first one is related to final goods imports, which suggest a reverse engineering process that leads to the exploration of ideas and know-how embedded in the commodities. The second one is associated with the trade of intermediary inputs, which could contribute to input-bias technical change (Carraro and De Cian, 2012).

Empirical evidence on the effects of international technology transfers on developing countries' climate performances is relatively scarce. Applying panel data techniques, Hübler and Keller (2010) investigate the impacts of foreign direct investment on energy intensity of a panel of developing countries, and they don't find significant effects of international technology transfer. Kretschmer et al. (2010) examine the effects of foreign aid on energy intensity and carbon intensity in a panel of 80 developing countries over the period 1973-2005. Applying dynamic panel data techniques and LSDVC estimations, they find that aid inflows tend to be effective in reducing the energy intensity of recipient countries while the carbon intensity is hardly affected by total aid.

Methodology. We consider energy intensity of GDP, carbon intensity of energy use and GDP per labour as dependent climate-related variables. The sample includes 56 developing countries over the 1972-2009 period. The IKS embodied in equipment and machinery imports from 24 developed countries are tested as the core determinant. Other factors, such as sector industrial shares (transportation, agriculture, service and industry sector), education attainments and domestic physical capital stocks are controlled for. The total amount of knowledge that can spill over is assumed to depend on the technological gap between the developing country and its trading partners, and on the imports intensity. In other words, the key IKS variable weighs the imports of machinery and equipment from individual developed countries with the technological gap between the developing country and the trading partner (as measured by the ratio between the total factor productivities). The underlying assumption, relying on the theory of backward advantages of countries, is that more backward countries have a larger stock of foreign technology to borrow from and a larger potential for international knowledge spillovers (Gerschenkron, 1962; Falvey et al., 2007). The bilateral imports data have been drawn from the OECD International Trade by Commodity Statistics (ITCS) Revision 2. Estimates have been obtained using a Within-Group estimator. Finally, in order to assess the implications of our econometric results, we subtracted the estimated contributions of IKS to each of the so called Kaya components (i.e. three components of carbon emissions: scale effect, composition or energy-saving effect, technique or fuel substitution effect; Raupach et al., 2007). In other words, we used the estimation results to generate counterfactual emissions series for each of our 56 developing countries and establish how much higher or lower emissions of developing country would be if there were no spillovers.

Main findings. The main results indicate that spillovers embodied in capital goods trade result in an increase of CO_2 emissions in developing countries (baseline: no spillovers occur). In particular, IKS are found to significantly improve energy efficiency of the destination countries, i.e. to lower carbon emissions due to the energy saving bias of technology spillovers. By contrast, the results show that on the sample average IKS have positive – rather than negative - effects on carbon intensity, i.e. they lead to higher carbon emissions per energy unit. Finally, as expected, IKS have positive effects on labour productivity, and through the growth effect they increase carbon emissions. In sum, the emission-increasing influences of IKS due to a higher labour productivity significantly outweigh the emission-reducing influences of technology transfer due to higher energy efficiency.

Paper 3 – The diffusion of renewable energy technologies: R&D, learning and cross-country spillovers

Research questions. The third paper empirically analyzes the role of domestic knowledge and IKS in the diffusion of RE technologies in advanced economies. It builds on a seminal study of Popp et al. (2011), which investigated the determinants of RE investment in OECD countries, and demonstrated that the world technological knowledge have a small yet positive effect on the decision to increase the installed capacity of individual technologies. They focused on knowledge from R&D activities, and did not distinguish domestic from international knowledge. This paper is intended to answer two additional questions: whether IKS from R&D activities have a significant effect on RE investment; whether domestic experience and IKS from experience (i.e. so called international knowledge spillovers) have a significant effect on RE investment (i.e. whether countries learn from the deployment and diffusion experience cumulated by other countries). The analysis has been conducted on photovoltaic (PV) and wind (W) investment.

Motivations and background. This paper has some overlapping with the first one, since both address IKS, RE technologies and developed countries. However, there are also differences. This paper explores the determinants of RE diffusion rather than innovation. Moreover, I assume that the investment process can be spurred by knowledge from innovative activities (i.e. scientific principles, methods and techniques), but differently from the first paper and Popp et al. (2011) I argue that knowledge from practical experience with RE investment and operation can be even more critical for the efficiency and quality of investment process (Taylor, 2008; Nemet, 2012b). Knowledge from experience encompasses a broad set of intangible resources: operating and installation competences, management skills, commercial abilities. More particularly, (i) the deployment phase, i.e. early trials to introduce a new energy technology into the market, face high market, cost and infrastructural barriers, but experience or learning, i.e. a repeated, practical use of the technology, can reduce them (Sagar and van der Zwaan, 2006; Clarke et al., 2008); (ii) learning-by-doing is experienced not only by technology suppliers and research centers, but also by installers and customers, if knowledge flows between different players are not hindered by transaction costs (Taylor, 2008). In this respect, my key research question is whether countries can learn only from domestic experience, or instead whether knowledge born from experience can spill across countries. In some respects, spillovers from experience, both domestic and international, are likely to be great, because “in contrast to laboratory and R&D settings, new technologies in real commercial use cannot be hidden from competitors firms” (Nemet, 2012b). On the other hand, knowledge from experience can be more tacit than knowledge from R&D. Its transmission is less likely to occur “in the void”, and cross-country connections are likely to be necessary.

Popp et al. (2011) investigate the effects of knowledge from R&D on investments in wind, solar photovoltaic, geothermal and electricity from biomass and waste across 26 OECD countries from 1991 to 2004. They find that technological advances, as represented by the world stock of patents in relevant technological classes, have positive effects on investment, but the magnitude of this effect is small. Nemet (2012b) analyzed that operating performance of a sample of California wind power plants (44 quarters, 1985-1995). Operators are shown to learn from own operating experience, albeit with diminishing returns; spillovers from external experience have also a significant positive impact. Due to collinearity problems, spillover estimates are not conclusive on the nature of learning spillovers, whether they are cross-country or inter-firm.

In addition to supply-side factors like R&D and learning, demand-side and institutional determinants are also at the origin of RE diffusion. Theoretical literature suggests that regulation is the principal driver of the adoption of RE technologies, as private firms do not have incentives to adopt more costly technologies that reduce emissions while do not bring additional cost savings to the firms (Gan et al., 2007; Popp, 2010). Focusing on the development of RE technologies, Johnstone et al. (2010) used patent data to show that RE policies lead to increased innovation in RE technologies in 25 OECD countries. However Popp et al. (2011) demonstrated that the ratification of Kyoto Protocol spurs the diffusion only for certain RE technologies; individual policies – e.g. feed-in tariffs or renewable certificates – are found not to have a significant autonomous role. The diffusion of RE technologies also depends on socio-economic, technological and institutional factors, other than regulation. From the point of view of a country, the deployment and diffusion of RE technologies are mainly driven by the increasingly serious environmental and energy security concerns arising from the finity of fossil fuel based sources. From the point of view of customers, the deployment of RE technologies depends largely on the motivation of the public and eventually the change of values that concern the appreciation of the environment. In this respect, Popp et al. (2011) found that countries with large hydropower and nuclear power installed capacity are less likely to invest in RE technologies.

Methodology. The sample consists of 18 industrialized countries, over the 1990-2006 period. I define our dependent variable as the investment in RE energy, and proxy it through yearly additions of RE power capacity per person, similarly to Popp et al. (2011). More particularly, I have built photovoltaic (PV) and wind (W) investment panels. In some respects, I follow quite closely the model specification used by Popp et al. (2011), by including the following explaining variables: energy dependency, hydroelectric and nuclear electricity shares, carbon emissions per person, electricity consumption growth rate, and a set of climate-energy policies; the country size and per capita income are controlled for. In order to test the two hypotheses, the model of Popp et al. (2011) is then modified and augmented. A first model addresses the role of knowledge from R&D in PV and W investment, with a split of the stock of knowledge from innovative activities into two variables (see the first paper): domestic R&D stocks; IKS, as measured by international R&D stocks. Another model addresses the role of learning in PV and W investment. It includes technology-specific installed capacity at home, as a proxy of domestic knowledge from experience, and technology-specific installed capacity in other countries, as a proxy of IKS from experience. Since returns from experience may be diminishing, domestic learning and cross-country learning spillovers (i.e. IKS from experience) are included through linear and quadratic terms (Nemet, 2012b). The IKS indicator is constructed by the same rationale as in the first paper, i.e. by taking into account cross-country connections. Accordingly, IKS weighs the installed capacity stock of other countries with the intensity of cross-country interactions. Estimates have been obtained using Generalized Least Squares for panel data, as in Popp et al. (2011).
Main findings. Preliminary results indicate that countries learn from domestic experience in installations, i.e. domestic installed capacity is a relevant factor that has positive effect on the diffusion of PV and W technologies. IKS, both related to R&D and related to experience, are found not to have a significant impact on the diffusion of wind technologies. Solar PV technologies, instead, are shown to spread more intensely when IKS from R&D activities are larger. Moreover, investments in hydropower are shown to serve as a substitute for wind technologies. Quota obligations are the only policy that is found to have positive effect on the diffusion of new RE technologies.

Cross-country Knowledge Spillovers in Renewable Energy Technologies

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Abstract

International knowledge flows are likely to accompany the spread of renewable energy technologies, because high-value innovations are developed by few countries but technology transfer to other countries requires absorptive and adaptive R&D. This paper focuses on international knowledge spillovers, and tests two hypotheses: they are a significant input to the production of renewable energy innovations; they need connections between countries to arise. Relying on a knowledge production function, we model the innovation activities of 18 OECD countries throughout the 1990-2006 period. Our findings indicate that, after controlling for climate-energy policies, international knowledge spillovers contribute significantly to renewable energy innovations, and their effect is comparable in magnitude to effects of domestic R&D and human capital. Additionally, the stronger the linkages between countries, the more likely spillovers are of occurring.

Keywords

Renewable energies, Innovation, International knowledge spillovers, Cross-country linkages

1. Introduction

The main objective of the paper is to provide empirical evidence on the relationship between international knowledge spillovers and the production of RE innovations by advanced countries. The paper also analyzes the role of cross-country connections in international knowledge transmission.

A better understanding of technological change in the renewable energy (RE) sector is a currently crucial challenge.[1] An extensive diffusion of technologies that harness non-exhaustible, zero-carbon (or low-carbon) energy sources in a cost-effective manner is necessary to reduce carbon emissions without hindering energy uses, and to alleviate the supply security problems of many countries (Popp 2011; Arvizu et al., 2011, p. 40). Demand-pull and "interface" policies are increasingly recognized to be relevant instruments to increase RE shares (Fischer and Newell, 2008; Taylor, 2008; Nemet 2009; Popp, 2011).[2] At the same time, innovative activities will continue playing a role in the next years for reasons that are documented by the IPCC special report on RE sources (Arvizu et al., 2011, pp. 39-40, 103-119 and 137-138): today most RE sources provide competitive energy services only in certain geographical contexts; some RE technologies have to be modified in order to be integrated successfully in the energy system; finally a few RE technologies are still in the nascent phase.

The balance between international and domestic knowledge sourcing in RE technological change is an open question. Innovation in RE technologies and other climate-related sectors is concentrated in few countries, and new high-quality mitigation technologies are developed by a small number of advanced economies (Dechezleprêtre et al., 2011; OECD, 2008; Section 2). As a consequence, most countries are likely to exploit new technologies that have been developed by other countries, but follower countries cannot limit themselves to importing new technologies, they should also engage in absorptive and adaptive R&D (Lanjouw and Mody, 1996; Popp, 2006; Bosetti et al., 2008; Sections 2 and 3). Our descriptive analysis confirms that despite the clear leadership of few economies,

[1] For the purposes of this paper, technological change and innovation are used as synonyms, and mean a change in current technologies, i.e. in devices and methods that are currently used to transform resources and to produce services. Technological knowledge, or knowledge, refers to ideas, methods, know-how, and experience that support technological change. See Clarke et al. (2008) for fundamental definitions.

[2] Demand-pull policies raise the revenues of environment-friendly innovators (e.g. feed-in tariffs, renewable energy obligations, or tax credits reserved to renewable energy investments), while technology-push policies reduce the costs that environment-friendly innovators have to bear (e.g. public energy R&D, or tax credits for energy R&D) (Nemet, 2009). Interface policies support technology deployment and learning by using, by reducing the transaction costs that arise between technology suppliers and users (Taylor, 2008).

innovation activities are more homogeneously distributed over OECD countries in the RE sector than in other technological domains (for instance, biotechnology, ICT, nanotechnology; see Section 2).

It thus seems plausible that technological change in the RE sector is accompanied by an intense transfer of knowledge between countries. In this paper, we follow Clarke et al. (2008), and define international knowledge spillovers as technological change that arises from innovation activities of other countries, as distinct from domestic R&D, learning-by-doing, intra- and inter-industry spillovers.

Although the role of cross-country knowledge spillovers has been widely investigated and tested in literature (Bransttetter, 1998), empirical evidence on the role played by international knowledge spillovers in environmental and climate innovation and, even more, on the channels that allow knowledge to spread over borders is still scarce and mixed (Section 3). Braun et al. (2010) and Garrone and Grilli (2010) have not found a significant effect of foreign innovative activities on, respectively, wind and solar innovations and climate-related indicators in OECD countries. By contrast, Verdolini and Galeotti (2011) have shown that international knowledge spillovers foster energy-related innovation, and discovered factors that govern cross-country knowledge transfers, but they referred only to the transmission of codified knowledge as represented by patent citations.[3] Perkins and Neumayer (2009, 2012) have compared different spillover channels, but their analysis concerns the transmission of pollution and carbon efficiency across countries, an outcome that includes but goes beyond the diffusion of technological knowledge.

In this paper, we focus on international knowledge spillovers in the RE sector. Technological knowledge can be transmitted from foreign countries to domestic players via a number of channels, such as international trade, foreign direct investments, mobility of personnel, published information in patent applications and scientific literature, but in this paper, similarly to Perkins and Neumayer (2009, 2012), we suggest that they are more consistent when cross-country connections are stronger, because knowledge about technologies is not fully codified and remains tacit and informal in nature (Keller, 2004). The most tacit elements of technological knowledge can only be transmitted through repeated interactions (Audretsch, 1998). This is the reason why spillovers exceed literature and patent citations.

[3] Nemet (2012a) also assumes that backward patent citations proxy knowledge spillovers, though his analysis regards inter-technology knowledge spillovers, i.e. knowledge flowing from non-energy to energy technological areas.

In particular, energy innovation systems are extremely country-specific (Sagar and Holdren, 2002; Sagar and van der Zwaan, 2006; Taylor, 2008), and international knowledge sourcing is even more likely to require established linkages between countries.

Relying on a knowledge production function à la Griliches-Jaffe (Griliches, 1979; Jaffe, 1986), we model country-level innovations in the RE sector as depending on domestic knowledge stocks, domestic human capital, and spillovers stemming from international knowledge stocks, after controlling for climate-energy policies. The innovation dynamics of 18 OECD countries (1990-2006) is represented through patent counts.

In particular, we estimate the model in order to test two propositions: (i) a country is more likely to develop RE innovations if international stocks of RE knowledge are larger; (ii) a country is more likely to develop innovations if it has more intense linkages with countries that have larger stocks of RE knowledge. In other words, our preferred indicator of cross-country knowledge spillovers weights the technological knowledge stock of a "donor" country with the intensity of cross-country interactions, which is measured by a function of mutual bilateral trade flows. We then compare estimates obtained for this indicator with two traditional spillover indicators, i.e. the un-weighted sum of international R&D stocks and the sum of international R&D stocks weighted by the reverse of the geographic distance. In order to distinguish between disembodied and embodied knowledge spillovers, imports of capital goods are used as control variable.

The paper is organized as follows. The next Section describes innovations in RE, and offers a descriptive analysis of their geographic distribution. Section 3 reviews the literature on climate-friendly innovations and international knowledge spillovers, and it formulates our research hypotheses. The sample, variables and the econometric method are illustrated in Section 4, while the empirical results are discussed in Section 5. The paper concludes by outlining some implications of our findings for climate-energy technology policy and by identifying further research opportunities.

2. Renewable energy innovations: Characteristics and geographic distribution

This Section briefly surveys the reasons why RE sources are a key technological domain. It also presents some information on the geographic distribution of RE innovations, in order to introduce our expectations about the role of international knowledge spillovers, especially when high-impact innovation activities are concentrated in just a few countries.

The commitment of governments and firms to RE innovation is primarily motivated by the challenge of climate change mitigation. To this aim, a priority is the improvement of energy efficiency in materials, technologies and equipment, but the spread of RE technologies is equally important insofar as they employ carbon-free, or low-carbon, energy sources and reduce carbon emissions per unit of energy sources (e.g. IPCC special report: Arvizu et al., 2011, pp. 34 and 37). In addition, greater reliance on RE sources is expected to strengthen the security of energy supply, particularly in countries that depend heavily on fuel imports. The RE domain covers sources that are highly diverse in terms of underlying scientific principles and current maturity degree and cost effectiveness of technologies. For example, the recent IPCC special report on RE sources discusses biomass energy, direct solar energy, geothermal energy, hydropower, ocean energy, wind energy.

Dechezleprêtre et al. (2011) overview the geographic distribution of 13 climate-mitigation innovations (RE technologies, energy-efficient lighting, electric and hybrid vehicles, and so on). The first key empirical evidence that has emerged from country-level patent counts is the high concentration of climate-friendly innovations. In the 2000-2005 period, Japan, the US, Germany and China accounted for 67% of the world's inventions. Secondly, the role of large non-OECD economies such as China, Russia and Brazil is far from being negligible, but high-value climate-friendly inventions are more likely to be sourced from more developed economies (namely, Germany, Japan, US and France that were the world quality leaders). Finally, knowledge transfer occurs above all between industrialized countries. In fact, only 22% of climate-friendly innovations flow from OECD countries to non-OCED countries, and a mere 4% flows the reverse way.

This evidence is coherent with climate-economy models, which show that technological change is the result of both R&D investments and learning-by-doing dynamics of the energy sector (e.g. van der Zwaan et al., 2002; Popp, 2004; Popp et al., 2009). In other words, a well developed energy innovation system is necessary to produce technological advancements (Sagar and van der Zwaan, 2006). In conjunction with the latter argument, the geographic distribution of RE innovations also reflects differences in climate-energy policies between countries. Although there are examples of innovations developed in response to foreign regulations, environmentally-sound inventions are more likely to respond to domestic environmental policies (Lanjouw and Mody, 1996), particularly as far as new energy technologies are concerned (Popp, 2006). In addition, incremental innovation can be stimulated by the demand-pull actions of a government, but technology-push policies are a necessary condition if non-incremental inventions are the goal (Nemet, 2009).[4]

In short, most countries are likely to use environment- or climate-friendly technologies that were developed in foreign countries. However, a more nuanced picture of the distribution of innovation activities emerges when only RE sources are focused on, and compared with other technological domains.

In particular, patent data drawn from the Europan Patent Office (EPO), and data on public R&D budgets censed by the IEA reveal that innovation in the RE sector is highly concentrated in a few countries (OECD countries account for almost 96% of the EPO world patents in RE during the 2000-2009 period).[5] Table 1 only focuses on OECD countries, and it shows that the first country accounts for 24% of the EPO renewable patents, while the top four countries account for the 65%. Nonetheless, the patents are relatively more homogeneously distributed than in other technological fields, e.g. biotechnology, ICT, nanotechnology, and, generally speaking, in all fields (in fact, the dispersion of patents across countries, i.e. the ratio between the standard deviation and the mean of the country-level patent counts, is smaller in RE technologies than in the other fields). Table 1 also shows that patent shares cumulated by the world leader and leading countries are regularly lower in the RE sector than in the other ones.

A first reason why late adopters need to develop own innovations can consist in the need to adapt foreign technologies, i.e. to make them compatible to local markets and regulations (Lanjouw and Mody, 1996; Popp, 2006). In addition, countries undertake R&D activities not only to adapt foreign energy technologies, but also to profit from the international flow of ideas and techniques, i.e. to "absorb" it, and to produce new technologies at home (Bosetti et al., 2008).

[4] Technology-push policies reduce the costs that environment-friendly innovators have to bear (e.g. public energy R&D, or tax credits for energy R&D), while demand-pull policies raise their revenues (e.g. feed-in tariffs, renewable energy obligations, or tax credits reserved to renewable energy investments) (Nemet, 2009).

[5] EPO classifies patents on the basis of highly relevant technology domains: biotechnology, ICT, nanotechnology, and environment-related technology. The latter includes renewable energy generation classes. IEA reports the budgets allocated by OECD governments to research, development and demonstration across energy technological fields, including renewable energy sources.

Table 1. Distribution of patents over OECD countries, 2000-2009

	All fields	**RE**	**Biotechnology**	**ICT**	**Nanotechnology**
Cumulated shares					
World leader	27%	24%	42%	30%	35%
4 top countries	71%	65%	71%	72%	75%
Leading countries	US	Germany	US	US	US
	Germany	United States	Germany	Japan	Japan
	Japan	Japan	Japan	Germany	Germany
	France	Denmark	UK	France	France
Dispersion	2.09	1.89	2.56	2.23	2.42

Source: Our elaboration on OECD data (Patents according to technology fields)

Legenda: The patent counts refer to the sum of patent applications made to the European Patent Office, 2000-2009 period (application date), 34 OECD countries (inventor's country of residence; Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States)

The evidence pertaining the geographic distribution of the patents is consistent with the analysis of publicly-funded R&D, a critical energy innovation input and policy measure (Garrone and Grilli 2010). Table 2 shows that only a few governments are particularly active in financing the development (and demonstration) of new RE technologies. Four OECD countries account for the 61% of the public R&D budget distributed by advanced countries in the 2000-2009 period. However, both the cumulated shares and dispersion coefficients show that the efforts of the advanced "follower" countries to support R&D activities are relatively greater in the RE sector than in other sectors.

Table 2. Distribution of public R&D budgets over OECD countries, 2000-2009

	All fields	**RE**
Cumulated shares		
World leader	47%	35%
4 top countries	70%	61%
Leading countries	US	US
	Japan	Japan
	Germany	Germany
	France	South Korea
Dispersion	2.67	1.86

Source: Our elaboration on OECD data (Main science and technology indicators), IEA data (RD&D statistics), IMF data (World Economic Outlook)

Legenda. The budgets are government budget appropriations or outlays for R&D (GBOARD) in Million USD (2009 prices and PPP), the mean value over the 2000-2009 period, 32 OECD countries for all fields

(Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, United Kingdom, United States), 27 OECD countries for RE (the same as in all fields, except Estonia, Iceland, Israel, Mexico, Poland)

In conclusion, the innovation activities pertaining to RE technologies are distributed unevenly over advanced countries, with a few leading countries that produce the majority of inventions. Nonetheless, even the industrialized countries that lag behind are relatively more active in RE innovations than in other technological domains. This intriguing evidence opens the question on the potential autonomy of countries, and conversely on the extent to which they rely on international knowledge sourcing in this sector.

3. Literature review and research questions

Although innovation activities are concentrated on a small number of countries, at the same time virtually no industrialized economies can refrain from conducting R&D activities in the RE sector (Section 2). This is the key stylized fact that motivates increasing attention to channels through which knowledge about the new technologies flows over countries. Nonetheless, the contribution of international knowledge diffusion to energy innovations is still a relatively untapped area of research. In this Section, after summarizing the empirical approaches to cross-country knowledge spillovers, we survey the main results that have been obtained by the emerging literature on climate-friendly technologies and international knowledge diffusion.

International knowledge diffusion involves both market transactions and externalities (Keller, 2004; Pizer and Popp, 2008). Most researchers argue that international diffusion of technological knowledge occurs to a great degree through cross-country knowledge or technology spillovers. The fact that technology is only partly codifiable makes contracts difficult to enforce (Keller, 2009), and cross-country knowledge spillovers have been shown to have a significant impact on the innovation activity of countries (Branstetter, 1998).

Most empirical analysis uses R&D spillover regressions to study international knowledge spillovers. Analyses have been extended to include particular channels for the spillovers. The most frequent channel that has been explored is international trade, and diverse trade pattern indicators have been used to investigate the effects of domestic and foreign knowledge stocks (Lo’pez-Pueyo et al., 2008). Coe and Helpman (1995), for instance, studied the relationship between productivity and foreign R&D as channelled by imports from foreign countries.

Another stream of studies instead uses patent citations as a proxy for knowledge flows between different innovating firms, regions or countries (Jaffe and Trajtenberg, 1996). However, as technological knowledge is not fully codified and remains tacit and informal in nature (Keller, 2004), patent citations only capture a part of the knowledge flows. Technological knowledge can actually flow between countries in various disembodied forms through cross-border flows of people, ideas, services, and products (Bye et al., 2011), and face-to-face contacts (Bottazzi and Peri, 2003). The idea that contacts, communication and exchange underpin the geographic spread of new innovations has long been recognized in diffusion theories (Rogers, 1995). Thus, transnational linkages can accelerate the cross-border diffusion of innovation as contacts, communications and exchanges allow the involved actors to learn about innovations developed elsewhere (Simmons and Elkins, 2004).

In environment related literature, there are only a few analyses of the role of international R&D spillovers.[6]

A first group of studies do not address directly the role played by international knowledge spillovers in technological change, but this literature confirms that relevant knowledge portions are sourced from other countries in environment- and climate-related technological domains. To our purposes, the most relevant results can be summarized as follows. Lanjouw and Mody (1996) studied the international diffusion of environmental innovations over the 1970s and 1980s. Their analysis of international patenting activity has shown that patents obtained by foreign inventors in developing countries are mainly aimed at protecting the export markets of holders, while disembodied knowledge transfers preferably occur between developed countries. Grubb et al. (2002) have explored the international transmission of climate-friendly technologies, and have found that both policy actions and technological development by industrialized countries affect emissions in developing countries. Popp (2006) focused on industrialized countries, and analyzed pollution control patents from the US, Japan and Germany. Since 1970, most new technologies for coal-fired power plants reflected

[6] A large part of literature on climate and innovation investigates the impact of climate-energy policies on the development and diffusion of new energy technologies (e.g. Taylor, 2008; Nemet 2009; Garrone and Grilli, 2010; Popp, 2011; Johnstone et al., 2010).

domestic regulation, i.e. they have rarely been developed to enter foreign markets created by stringent national regulations. An analysis of patent citations has led to the conclusion that technology transfers between developed countries have mainly been indirect. Follower countries have not only undertaken adaptive R&D, they have also benefitted from earlier innovation by leader countries as a portion of foreign advances become embodied in domestic innovations as a building block.

The idea that connectivity is important to explain the international diffusion of environment-friendly technologies has so far been given quite limited attention. A first example was offered by Perkins and Neumayer (2009), who empirically tested the influence of three transnational linkages on domestic improvements in CO_2 and SO_2 efficiency: import and export, inward foreign direct investment and telephone calls. They found that import ties with more environmentally efficient countries have fostered the transmission of CO_2 and SO_2 efficiency, while exports, inward foreign direct investment and telephone calls do not seem to play a significant role. More recently the same authors revealed that foreign direct investments can impinge on the transmission of CO_2 efficiency towards countries that are less CO_2-efficient or have a higher institutional quality (Perkins and Neumayer, 2012).

The literature that directly focuses on international knowledge spillovers in new energy technologies yielded mixed results, also because different modeling approaches have been used.

Bosetti et al. (2008) examined energy-efficient technologies, and integrated disembodied international R&D spillovers in a model of climate change mitigation efforts undertaken in different regions throughout the world. The effectiveness of spillovers has been assumed to depend on regional absorption capability. High-income countries have been shown to reduce their energy R&D investments thanks to international spillovers, but free-riding does not impair the overall knowledge stock. Braun et al. (2010) instead investigated the determinants of innovative activity in wind and solar technologies for OECD countries, and found that international knowledge spillovers, as represented by pooled patent stocks, play a negligible role compared to domestic intra- and inter-sectoral spillovers. Similarly, an analysis reported by Garrone and Grilli (2010) found that international public energy R&D has virtually no effect on domestic energy intensity or on the carbon factor, regardless of whether an un-weighted or import-weighted R&D pool is used as a proxy. Verdolini and Galeotti (2011) used backward patent citations to model international knowledge flows, and to weigh the knowledge stocks cumulated by foreign countries in energy-supply and energy–demand technologies. Their estimates revealed that greater geographical and technological distances between countries imply a lower probability of knowledge flows, and greater flows from international knowledge stocks increase the innovation probability.

The present paper is an attempt to continue along the line of analysis adopted by Perkins and Neumayer (2009, 2012), by examining the role of cross-country linkages as a channel for spillovers between countries. However we depart from their work, by focusing on the effect of international knowledge spillovers on technological change in RE innovations, i.e. the relationship between knowledge stocks of foreign countries and domestic innovation. In particular, we claim that:

(i) international knowledge stocks have positive effects on the development of RE innovations in a given country;

(ii) effects are greater if the country has more intense linkages with countries that have larger knowledge stocks.

4. Sample, variables, and econometric model

In order to test our propositions, we model innovation in RE technologies at the country level through a knowledge production function (Griliches, 1979; Jaffe, 1986), where the inputs are domestic knowledge stocks, domestic human capital and international knowledge spillovers. The output is innovation, as proxied by patents that have been obtained by countries in RE technologies from the European Patent Office. The sample includes 18 industrialized countries over the 1990-2006 period: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States. The data are sourced from the April 2010 version of Patstat (OECD, 2010). Patent classes are determined according to the classification used by Johnstone et al. (2010), i.e. hydro technologies are excluded from the analysis, also because in most countries they are not supported by climate policies that are enforced topromote other renewable energies.

4.1 Variables

As far as the *human capital stock* (*HC*) is concerned, we resort to the average years of schooling for people over 25, as measured by Barro-Lee (2010). In order to describe knowledge stocks, the series of public energy R&D budgets of each sample country for RE technologies has been collected from the IEA Energy Technology Research and Development Database (IEA, 2010a); hydro R&D budgets have been subtracted from the total R&D budget. The *domestic knowledge stock* (*DRD*) of country *i* is computed from the *public energy R&D budgets* (*RD*) through the perpetual inventory model:

$$DRD_{it} = (1-\delta)DRD_{i,t-1} + RD_{i,t} \ . \qquad (1)$$

The initial value of the stock is defined as follows:

$$DRD_{i,t_0} = \frac{RD_{i,t_0}}{\delta + g}, \qquad (2)$$

where δ, i.e. the depreciation rate, is set equal to 5%, as in Coe and Helpman (1995), and g, the R&D growth rate, is set equal to 20%, as in Braun et al. (2010). Sensitivity analyses are available upon request from the authors.

Cross-country knowledge spillovers have been computed by aggregating the domestic knowledge stock of other countries in three different ways. The first indicator of knowledge spillovers used by country *i* is an un-weighted pool of the R&D stocks of all other countries in the sample, $j \neq i$:

$$POOLKS_{i,t} = \sum_{j \neq i} \left[DRD_{j,t} \right]. \qquad (3)$$

Disembodied knowledge flows may be impeded by geographic distance; i.e., geographic proximity can be argued to matter for the international transmission of knowledge. To this aim, a second indicator for country *i*, *DISKS*, has been obtained by aggregating the other countries' R&D stocks through inverse functions of geographic distance (Xu and Wang, 1999):

$$DISKS_{i,t} = \sum_{j \neq i} \left[DRD_{j,t} \times wd_{i,j} \right], \qquad (4)$$

$$wd_{i,j} = \frac{1/ln(gd_{i,j})}{\sum_{j \neq i} 1/ln(gd_{i,j})},$$

where $wd_{i,j}$ is a function of the geographic distance between countries *i* and *j* (i.e., between the capital cities or other major cities), $gd_{i,j}$.

The third indicator, *CNTKS*, has been obtained by aggregating other countries' R&D stocks through bilateral trade flows as a proxy of mutual connections. Country *i* benefits from country *j*'s R&D efforts if the bilateral trade flows are sufficiently large in comparison to country *j*'s economy and trade flows with other countries:

$$CNTKS_{i,t} = \sum_{j \neq i} \left[DRD_{j,t} \times wg_{i,j} \right], \qquad (5)$$

$$wg_{i,j} = \frac{\ln\left[\frac{\left(import_{i,t}^{j} + export_{i,t}^{j}\right)}{GDP_{j,t}}\right]}{\sum_{j \neq i} \ln\left[\frac{\left(import_{i,t}^{j} + export_{i,t}^{j}\right)}{GDP_{j,t}}\right]}.$$

Trade flows are calculated as the sum of the total imports and exports between country *i* and partner country *j*, as reported in the UN Comtrade database (2010). The partner country's GDP is the normalization recommended by Lichtenberg and Van Pottelsberghe de la Potterie (1998) and Xu and Wang (1999).

The three cross-country knowledge spillover indicators can be interpreted in a rather straight-forward way. *POOLKS* represents a global pool of RE technologies, and it captures the essence of cross-country spillovers only if there is no need to have repeated contact and interaction to facilitate the diffusion of knowledge because of, for example, the global reach of computers and online documents. The *DISKS* variable takes into account the geographic dimension and assumes that closer countries quite naturally have a larger amount of contact and interaction to exchange technological knowledge, i.e. it captures localized knowledge spillovers. *CNTKS* has the purpose of representing the diffusion of the components of technological ideas that are more tacit and less codified and as such need repeated contact and interaction to be exchanged. Trade flows are assumed to capture the frequency and size of contact between two countries, i.e., the intensity of cross-country interaction and relations.

Among the control variables, *GDP* has been included as a measure of the economy's size. Three binary variables are used to capture the presence of climate-energy policies that support the development and diffusion of RE technologies: *OB*, i.e., performance standards or obligations (e.g., portfolio standards, quota systems), *FIT*, i.e., guaranteed prices or feed-in-tariffs, *REC*, i.e., carbon emissions or RE certificate trade systems. A policy indicator is set equal to 1 if country *i* is enforcing the corresponding measure in year *t*, and it is set equal to 0 otherwise. The main reference source for these binary variables is IEA (2004). We have resorted to IEA Policies and Measures Database (2010b) for more recent years. We also include the ratio between the import of capital goods from the world and the GDP of the focal country, i.e., CGI, as a control of the impact of spillovers that are embodied in capital goods imports, in order to reduce the risk of biased estimates for disembodied spillovers.

Table 3 shows the summary statistics of the variables. The final sample includes 285 observations, because some data on the patents, R&D budgets or policy indicators were missing.

Table 3. Variables: Descriptive statistics

Variable	Definition	Obs.	Mean	St.Dev.	Min	Max
RPAT	Patent count	285	28.6	43.4	0	258
HC	Human capital (nr years)	285	9.6	1.6	6	13
DRD	Domestic knowledge stock (million USD, 2008 and PPP)	285	751.6	1,352.8	12	6,094
POOLKS	Unweighted sum of international knowledge stocks (million USD, 2008 and PPP)	285	12,572.9	1,469.0	6,409.8	14,698.0
DISKS	Distance-weighted sum of international knowledge stocks (million USD, 2008 and PPP)	285	698.4	87.6	377.7	943.0
CNTKS	Trade-flow weighted sum of international knowledge stocks (million USD, 2008 and PPP)	285	856.4	146.4	362.4	1061.1
GDP	GDP (million USD, 2005 and PPP)	285	1,440,629	2,433,020	103,816	12,900,000
CGI	Capital goods imports divided by GDP	285	0.1	0.0	0.0	0.2
FIT	Feed-in tariffs (binary)	285	0.4	0.5	0	1
REC	Tradable certificates (binary)	285	0.1	0.3	0	1
OB	Performance standards (binary)	285	0.3	0.5	0	1

Table 4 reports the correlation matrix. High correlation ratios between spillover variables should not be considered as a problem, because they are used in different models. Since GDP is closely correlated to most knowledge production inputs, it has been excluded from the control models in order to check the robustness of estimates. The negative correlation between *DRD* and spillover variables is not a surprise, insofar as larger countries have larger R&D budgets (*DRD*), and are more likely to face foreign countries and R&D stock that are smaller (spillover indicators) and vice versa. This is unavoidable in a knowledge production model.

Table 4. Variables: Correlation matrix

	RPAT	lnHC	lnDRD	lnPOOLKS	lnDISKS	lnCNTKS	GDP	CGI	FIT	REC	OB
RPAT	1										
lnHC	0.32	1									
lnDRD	0.68	0.39	1								
lnPOOLKS	-0.59	-0.32	-0.67	1							
lnDISKS	-0.61	-0.19	-0.57	0.91	1						
lnCNTKS	-0.42	-0.45	-0.61	0.87	0.60	1					
GDP	0.71	0.38	0.75	-0.89	-0.78	-0.80	1				
CGI	-0.33	0.02	-0.40	0.43	0.43	0.35	-0.46	1			
FIT	-0.03	-0.38	-0.12	0.26	0.14	0.39	-0.21	0.13	1		
REC	0.09	0.14	0.15	0.00	0.01	-0.01	0.18	-0.07	-0.06	1	
OB	0.05	0.05	-0.02	0.19	0.13	0.23	-0.11	0.21	0.02	0.25	1

We model the innovation activity of countries in RE technologies by specifying the following knowledge production function:

$$RPAT_{i,t} = \alpha + \beta_1 lnHC_{i,t-1} + \beta_2 lnDRD_{i,t-1} + \beta_3 lnCCKS_{i,t-1} + controls + \phi_i + \varepsilon_{i,t}, \quad (6)$$

where *RPAT* is the number of patents obtained in the RE sector, *HC* is the human capital, *DRD* is the domestic R&D stock, *CCKS* is one of the cross-country knowledge spillover variables (i.e. *POOLKS*, *DISKS*, or *CNTKS*), φ are unobservable country-specific characteristics, and ε is the error term. In order to have coefficients that are comparable in magnitude, both the knowledge production variables and controls were normalized by their mean. The former, i.e., human capital, domestic R&D stocks and cross-country knowledge spillover variables, were also transformed via a natural logarithm, to facilitate the interpretation of the results, and then lagged by one period, to reduce endogeneity problems.

5. Empirical results

We used a negative binomial model with fixed effects. On the one hand the dependent variable is found to be over dispersed. On the other hand, fixed effects have been compared to random effects through a test of over-identifying restrictions on linear regressions, and have been found to be more consistent (i.e. random effect models hypothesize that independent variables are uncorrelated to the country-specific error; this assumption has been always rejected).

In this Section, we first illustrate the estimates of different model (6) specifications. In order to respond to the research hypotheses, we then simulate the effects of cross-country spillovers on country-level RE innovations under different specifications.

Table 5 presents the estimates of a baseline model in which the knowledge spillover variable is not included (a), and estimates of models which rely upon different cross-country knowledge spillovers measures (b-d). First, we focus on the sign and significance of coefficients, while impacts will be discussed in detail in the remaining part of this Section.

In the Baseline Model (a), the human capital and domestic knowledge stocks, *HC* and *DRD*, are found to have a positive effect on the country's patenting activities, at a 0.1% significance level. The total imports of capital goods, *CGI*, are also found to have a positive and significant impact (0.1% significance level).

In the POOLKS Model (b), cross-country spillovers on RE technologies are described by the pool of international knowledge stocks, *POOLKS*. All the knowledge production function variables, including *POOLKS*, have positive and significant coefficients. The *DRD* and *HC* coefficients are shown to be significant at the 0.1% level. Cross-country knowledge spillovers, as represented by the pooled indicator, are shown to play a significant role at the 1% significance level. The policy variable *OB* also plays a role (5% significance level). Among other control variables only imports of capital goods, *CGI*, is estimated to have a significant effect (5% significance level).

The DISKS Model (c) describes cross-country knowledge spillovers by aggregating international knowledge stocks through the inverse functions of geographic distance. While the *DRD* and *HC* coefficients are found to be positive and highly significant, the cross-country knowledge spillover variable, *DISKS*, is not found to play a significant role. *OB* and *CGI*, i.e. the policy and capital goods import indicators that are also shown to affect *RPAT* in other models, maintain a 5% significance level.

Finally, the CNTKS Model (d) includes our preferred spillover indicator, *CNTKS.* All the knowledge production function variables are shown to have significant and positive effects on patenting activities. The coefficients of domestic R&D stock (*DRD*), human capital (*HC*), and the cross-country knowledge spillovers (*CNTKS*) are positive and significant at a 0.1%, 1% and 0.1% levels, respectively. The coefficients of capital goods import and policy variables, *CGI* and *OB*, are found to be significant and positive (5% and 1% significance levels).

The effects of cross-country knowledge spillovers are captured by *POOLKS*, *DISKS* and *CNTKS* coefficients (Models (b), (c) and (d) of Table 5). Since the spillover indicators and other knowledge production function variables (i.e., HC and DRD) have been divided by their mean value and transformed by natural logarithms, the coefficients of these variables represent the variation in patent count that is caused by a 1% increase, other things being equal. Foreign R&D stocks have been found to have a significant effect on RE innovations (Models (b) and (d)), regardless of whether they are pooled or weighted by the intensity of cross-country connections. Geographic distance does not seem to affect the effectiveness of spillovers (Model (c)).

Table 5. Negative binomial model with fixed effects: RE patents

	a) Baseline	**b) POOLKS**	**c) DISKS**	**d) CNTKS**
lnHC	1.487***	1.204***	1.342***	0.737**
	(0.371)	(0.397)	(0.394)	(0.348)
lnDRD	0.462***	0.484***	0.469***	0.544***
	(0.102)	(0.110)	(0.106)	(0.117)
GDP	-0.013	-0.055	-0.043	-0.056
	(0.037)	(0.046)	(0.046)	(0.055)
CGI	0.411***	0.280*	0.322*	0.186*
	(0.150)	(0.163)	(0.165)	(0.157)
FIT	-0.038	-0.055	-0.050	-0.056
	(0.042)	(0.041)	(0.042)	(0.038)
REC	0.006	-0.002	0.001	-0.006
	(0.006)	(0.008)	(0.008)	(0.008)
OB	0.026	0.030*	0.028*	0.032**
	(0.017)	(0.017)	(0.017)	(0.015)
lnPOOLKS		1.703**		
		(0.867)		
lnDISKS			1.064	
			(0.866)	
lnCNTKS				2.906***
				(0.700)
Constant	2.562***	2.896***	2.793***	3.239***
	(0.232)	(0.285)	(0.296)	(0.299)
N	285			

Legenda. Standard errors in parentheses, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

However, a further analysis is necessary to gain some insight into the magnitude of the effects of cross-country spillovers on innovation outputs, since a uniform 1% increase does not reflect the true sample distribution of different spillover indicators. In order to gauge the impact of spillovers, and to compare the explaining strength of different spillover indicators between Models (b)-(d), the analysis should focus on plausible variations. Differences that can typically be observed between countries and between years are better captured by the standard deviation statistic than by a uniform 1% increase. In particular, the standard variations, i.e., the ratios between the sample standard deviations and means, of *POOLKS, DISKS* and *CNTKS* indicators are equal to 11.68%, 12.54% and 17.10%, respectively. To this aim, each knowledge production function input has been given a realistic shock, other things being equal, and the response of *RPAT* has been simulated (Table 6).

Table 6. Simulations: Variation in the number of RE patents

Standard variation of independent variables[a]		**RPAT variation**			
		a) Baseline	**b) POOLKS**	**c) DISKS**	**d) CNTKS**
Cross-country knowledge spillovers					
POOLKS	11.68%		0.199		
DISKS	12.54%			ns	
CNTKS	17.10%				0.497
Domestic knowledge sourcing					
HC	17.03%	0.253	0.205	0.229	0.126
DRD	180.00%	0.832	0.871	0.844	0.979

Legenda. ns: not significant; a: independent variables are given a variation equal to the ratio between the sample standard deviation and the mean value.

DISKS has not been found to have a significant effect (Table 5, Model (c)). If *POOLKS* and *CNTKS* instead increase according to their standard variation, they yield an increase in the patent number that is positive and significant (Table 6). When the cross-country knowledge spillovers are represented by the pooled international R&D stocks (*POOLKS*), a typical increase in knowledge spillovers causes the patent count of countries to increase by 0.199 (Table 6, Model (b)). If the differences in linkage intensity between countries are taken into account, as with *CNTKS*, the effect of the cross-country spillover indicator is shown to be comparable in magnitude, but slightly greater, i.e. the *RPAT* variation is equal to 0.497 (Table 6, Model (d)). In other words, international R&D activities have a sizeable and significant impact on RE innovations, though it is smaller than the effect of domestic knowledge, as represented by *DRD*.

Finally, the *CNTKS* variable seems to be a robust and sensible indicator of cross-country knowledge spillovers. Since GDP is highly correlated to the spillover indicators (Table 4), in order to check the robustness of the results, we have also run the regression excluding GDP as a control variable; Table 7 reports the regression results. Only *CNTKS* maintains its significance at the 5% level, while the spillover variable *POOLKS* loses in significance. In addition, the magnitude of the other variables in the *CNTKS* model of Table 7 is almost the same as in their counterparts in Table 5. It should be recalled that imports of capital goods can embody additional technological knowledge. *CGI* coefficients are found to have a positive and significant effect at the 5% level (Models (d) in Tables 5 and 7). In other words patenting activities in the RE sector become more intense as imports of capital goods grow.

Table 7. Negative binomial model with fixed effects and without GDP: RE patents

	a) **Baseline**	b) **POOLKS**	c) **DISKS**	d) **CNTKS**
lnHC	1.462***	1.146***	1.333***	0.634*
	(0.364)	(0.415)	(0.397)	(0.333)
lnDRD	0.452***	0.425***	0.436***	0.478***
	(0.098)	(0.100)	(0.101)	(0.096)
CGI	0.409***	0.305*	0.353**	0.201*
	(0.150)	(0.163)	(0.164)	(0.157)
FIT	-0.035	-0.043	-0.038	-0.050
	(0.041)	(0.040)	(0.041)	(0.037)
REC	0.005	-0.005	0.000	-0.009
	(0.006)	(0.008)	(0.008)	(0.007)
OB	0.027	0.032*	0.030*	0.034**
	(0.017)	(0.017)	(0.017)	(0.015)
lnPOOLKS		1.545		
		(1.077)		
lnDISKS			0.695	
			(0.857)	
lnCNTKS				3.101***
				(0.705)
Constant	2.532***	2.701***	2.624***	3.081***
	(0.218)	(0.236)	(0.240)	(0.253)
N	285			

Standard errors in parentheses, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

6. Conclusions

This paper addresses the role of cross-country knowledge spillovers in RE innovations. Our empirical analysis has been undertaken in order to add to the scholarly and policy debate on technological strategies that can be adopted by industrialized countries to meet carbon reduction targets.

Our empirical findings have confirmed that cross-country knowledge spillovers are a central element of climate-friendly technological change. The ability of advanced economies to develop new RE technologies depends to a great extent on foreign R&D. The effect of international knowledge spillovers is significant, and comparable with the effect of domestic R&D, even though it is smaller. The analysis that was presented in the previous Sections also allows us to identify factors that enable developed countries to build on foreign technologies and to join the renewable innovation arena. To this aim, we have tested a new indicator of cross-country knowledge spillover indicator, *CNTKS*, which assumes that the most tacit components of technological knowledge need international linkages in order to diffuse. The indicator has been validated through a comparison with more traditional spillover indicators and a robustness check. Our estimates indicate that knowledge on new RE technologies can be sourced internationally if the focal country maintains repeated contact, exchange and interaction with the countries that invest more intensely in R&D activities. International technological knowledge is of little use to countries that have not established interactions with R&D leaders, whether the geographic distances are limited or not.

Our research can be considered as a contribution to the design of climate-energy innovation policies. First, public energy R&D expenditure is a key input to innovation in the RE field, i.e. a relevant element in global efforts towards carbon stabilization. Public support to climate-energy research should not be abandoned in favor of other measures, all the more because its effects spread beyond national borders, and help follower countries to join the energy innovation race. Consistently with the results of previous research (e.g. Bosetti et al., 2008, Bohnstedt et al., 2012; Popp, 2011), policies aimed at strengthening international knowledge flows should be encouraged. International policies that favor technological cooperation between countries in climate-friendly innovation activities are warranted to reduce free-riding risks without haltering cross-country spillovers. Interestingly, technological cooperation can be viewed as complementary to climate cooperation. An evolving strand of research investigates exactly the design of international technology-oriented agreements, with the purpose of remedying to the public good failure that characterizes climate stabilization (Lessman and Edenhofer, 2011). Finally, the international diffusion of technological knowledge in the RE sector is not uniform. In other words, disembodied technological knowledge is more likely to flow between countries that have already established intense mutual relations. International institutions that govern climate policies, such as for instance the European Commission or Intergovernmental Panel of Climate Change, should consider the presence of mutual linkages between international technological partners as an implementation criterion of the flexibility mechanisms for carbon reduction.

Our analysis has focused on connections related to bilateral trade flows as a proxy of cross-country linkages, but has not yielded any evidence on the effectiveness of alternative instruments of cross-country interactions. This might be considered a limitation insofar as some scholars argue that FDIs are also related to international knowledge transmission. This may be a subject of further research. Another development of the present analysis could involve its extension to individual renewable technologies, which are likely to exhibit different technological patterns and different proneness to benefit from foreign technological knowledge. As far as the latter is concerned, however, the current domain-level perspective seems to be acceptable, given our purposes. Most climate-energy policies, a key variable of our model, are technology-neutral. Moreover, since international knowledge diffusion has been shown to foster the development of RE technologies overall, whatever their mutual differences, it can be claimed with greater confidence that the coordination of climate-energy policies at the international level is necessary.

International Technology Spillovers and Carbon Emissions From Developing Country

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Abstract

In this paper we examine the effect of technology transfer from 24 developed countries on energy intensity of GDP, carbon intensity of energy use and labour productivity of 56 developing countries empirically. We model specific spillovers embodied in trade of capital goods (machinery and equipment) and find that the technological spillovers will lead to higher carbon emissions than if no spillovers occurred. Specifically, technological spillovers can significantly improve energy efficiency of the destination countries, which is expected to lead to lower carbon emissions due to the energy saving bias of technology spillovers. Technological spillovers have positive effect on the GDP per labour. Such an increase in labour productivity is supposed to result in greater carbon emissions due to output expanding effect of spillovers. Regarding the effect of spillovers on carbon intensity of energy use, industrialization stages play a role. On the sample mean, the effect of trade mediated spillover is found to increase carbon intensity of energy use rather than lowering it. In sum, the emission-increasing influences of trade mediated spillovers due to higher labour productivity significantly outweigh the emission-reducing influences of technology transfer due to higher energy efficiency.

Keywords:
International technology transfer, CO_2 emissions, Energy efficiency, Growth effect

1. Introduction

Addressing the threat of anthropogenic climate change requires concerted international action to mitigate emissions of greenhouse gases (GHGs) to the atmosphere (IPCC, 2007). Developing countries are crucial to this effort. They are already responsible for more than 50% of world carbon dioxide (CO_2) emissions and are expected to account for two-thirds of the increase in global CO_2 over the next 30 years (IEA, 2011a,b; U.S. Energy information Administration, 2011). Historically, increases in population and per-capita income have been the major drivers of GHG emissions growth, while reductions in energy use per unit of GDP have been the principal moderator (Raupach et al., 2007). These trends are expected to continue (IPCC, 2007), but their future trajectories are the subject of much speculation and debate (e.g., Grubb et al., 2002; Bosetti et al., 2007).

The objective of this paper is to strengthen the empirical basis for these projections, focusing on technological progress in developing countries. Productivity increase has long been known to be the key driver of output growth (Islam, 2004). Energy intensity decline arises from energy price changes, shifts in the composition of output and improvements in energy efficiency (e.g., Metcalf, 2008; Sue Wing, 2008), but the last of these is thought to exert the most important influence on long run emissions (Popp et al., 2009). Understanding how these forces are likely to play out in developing economies is challenging because of the paucity of direct observations of technical change there (cf Johnstone et al. 2010; Garrone et al., 2011). The vast majority of R&D investment and technology development take place in industrialized economies, while poor nations acquire technology through disembodied transfers of know-how and innovations embodied in imported commodities. Therefore, to develop the requisite insights it is necessary to investigate the relationship between measures of international technology diffusion and the precursors of CO_2 emissions in developing economies.

We consider the impact of technology spillovers on emissions, mediated through the channels of influence highlighted by Kaya (1990), Grossman and Krueger (1993) and Antweiler et al. (2001):

The scale effect Spillover-induced aggregate technical progress increases per-capita output, and with it energy use and emissions.

The composition effect Energy-saving (-using) innovations reduce (increase) the growth rate of energy use relative to that of GDP, offsetting (amplifying) the scale effect. Historical energy intensity declines would appear to indicate that the net bias of technical change has been energy-saving.

The technique effect Adoption of innovations in various sectors, in conjunction with changes in the relative prices of fuels, induce substitution toward more or less CO_2 intensive fuels.[7]

We employ a simple empirical approach which allows us to statistically isolate the offsetting effects of the different channels on developing countries' emissions. We then use these results to establish how much higher or lower developing country emissions would be if there were no spillovers, as a means of attributing the components of emissions.

The main results indicate that spillover embodied in capital goods trade will result in higher CO_2 emissions in developing countries than if no spillover occurs. We find that capital goods import mediated spillovers tends to be effective in reducing the energy intensity of GDP in recipient countries. Regarding the carbon intensity of energy use, a sharp distinction should be made between “less industrialized” developing countries and “more industrialized” developing countries. To the former, embodied international knowledge spillovers from the North means that more carbon intense technologies are used. By contrast, the latter, i.e. countries that have already installed a significant stock of capital goods, were found to benefit from embodied spillovers in terms of transition towards low carbon technologies. In other words, the results provide evidence that industrialization stages play a role. With respect to the labour productivity, the result shows that the trade embodied spillover can lead to higher labour productivity in the recipient country.

The rest of the paper is organized as follows. Section 2 provides motivation and a review of the existing literature, examining the mechanisms of international spillover and the relationship between technology transfer and environmental quality. Section 3 describes our empirical modeling strategy and data, while section 4 presents and discusses our main econometric results. We assess the robustness of our results in section 5, and draw implications for overall impact of technology spillovers on CO_2 emissions in section 6. Section 7 concludes with a brief discussion of caveats and directions for future research.

2. Literature Review

2.1 International technology spillovers

To our knowledge, the impact of technology diffusion on emission intensity has not been investigated,

[7] For example, although an electricity-using bias of technical change can reduce emissions from end-use sectors, if the additional electricity is generated from a carbon-rich fuel such as coal overall emissions may increase.

and may be positive or negative. There are many mechanisms through which trade, FDI influence energy efficiency and GHG emissions in the recipient country. It is difficult to measure the effects of technology transfer on GHG emission in developing countries because of the difficulties of identifying and separating different channels (Peterson, 2008). There are indications that spillovers are associated with reductions in emissions intensity (Mielnik and Goldemberg, 2002; Perkins and Neumayer, 2009), but the mechanisms at work are contested (Hübler and Keller, 2010; Kretschmer et al., 2010). On the other hand, there is abundant evidence that spillovers positively affect economic growth (Borensztein et al., 1998; Schneider, 2005). One contribution of our paper is that we try to identify and separate the effect of technology transfer mediated through bilateral imports of equipment and machinery and assess whether the spillovers was on net amplifying or attenuating CO_2 emissions.

Technology diffusion can take place through a variety of channels that involve the transmission of ideas and new technologies. Official development assistance and official aid, foreign direct of investment by multinationals, adoption of foreign technology and acquisition of human capital through various means are certainly important channels through which technology diffusion take place (Keller, 2004; Peterson, 2008). Besides these channels, imports of capital and investment goods is seen as being the most relevant channel (Saggi, 2002) for the access to advanced technologies by developing countries. Imports may embody innovations that are not available in the local economy, and it can raise a country's output directly, as inputs into production, and indirectly, through reverse-engineering of these goods which contribute to domestic imitation and innovation. There is evidence that that the use of new equipment in the manufacturing and industrial sectors is an important source of technological progress and of economic growth (Jaffe et al., 2005; Carraro and De Cian, 2012). Therefore, trade can promote technological diffusion and economic growth by providing accessing advanced foreign innovations.

Several empirical studies explore the possible link between trade in physical goods and technology diffusion. In general, the finding of these papers support the notion that trade contributes significantly to technological diffusion. Most of these studies focus on general imports as a channel for technological diffusion (Coe and Helpman, 1995; Eaton and Kortum, 1996a,b; Coe et al., 2009). Other studies investigate the role of spillovers through a more disaggregate measure of imports (Coe et al., 1997; Keller, 1999; Xu and Wang, 1999; Connolly, 2003; Schneider, 2005). Focusing on industrialized countries, Xu and Wang (1999) consider R&D spillovers through capital goods trade and foreign direct investment. Coe et al. (1997) consider R&D spillovers to less developed countries through machine and equipment imports. Keller (1999) uses data for machinery goods imports to examine the effect of trade on technology diffusion in eight OECD countries. He finds that conditional on technology diffusion from domestic R&D, the import composition of a country matters, but only if it is strongly biased towards or away from technological leaders. His model predicts that the import patterns of countries matters for productivity since a country imports primarily from technological leaders receives more technology embodied in intermediated goods than another that imports primarily from follower countries.

Even though there exist papers that provides empirical analysis inclusive developing countries, there remains an under representation of less developed nations relative to developed nations. Coe et al. (1997) investigate the role of spillovers mediated through imports of machinery and equipment and find that developing countries, especially the ones oriented to trade towards developed countries that do more R&D, are tend to benefit more from technology externalities, and that the spillover effect increases with openness to trade and with greater secondary school enrollment. Connolly (2003) considers imports of certain specific SITC classes so as to separate out the effects of imports of goods that embody technology from general openness effects. She finds that high-technology imports from developed countries lead to increased GDP growth as higher quality capital goods are used in domestic production. Schneider (2005) investigates the role of imports of capital goods from developed countries in determining the rate of innovation and economic growth. His regression results show that the growth in per capita physical stock and growth in per capita capital goods imports have strong impact on real per capita GDP growth when the developed countries and developing countries are pooled together in the regression and included separately. He also found that FDI inflows only significantly affect per capita GDP growth when only developed countries are included, which is consistent with the work of Borensztein et al. (1998) which emphasizes the importance of minimum human capital level. Hakura and Jaumotte (1999) focus more directly on the question of how trade influences technology diffusion by using data for 87 countries and find that trade indeed serves as a channel of international technology transfer for developing countries. Using a dataset of 55 developing countries and seven most - industrialized countries (G7), Seck (2011) investigate the role of foreign R&D capital stocks mediated through bilateral import of machinery and equipment and

FDI shares. The results show that the R&D spillover gains are substantial among developing countries from developed countries and are mainly through import, although the inward FDI is also significant.

In the literature, FDI has been explored as another conduit for technology transfer. FDI has also been identified in the literature as another important channel for international diffusion (Keller, 2009). Although the occurrence of FDI spillovers has been widely investigated, empirical evidence on an aggregate level has provided mixed results (Wooster and Diebel, 2010). Focusing on 13 industrialized countries, van Pottelsberghe de la Potterie and Lichtenberg (2001) investigate whether FDI transfers technology across borders and find that a country's productivity is increased only if it invests in R&D intensive foreign countries, but not the other way around. They also employ the first difference specification to address the potential spurious relationship arising from the non stationary of the error term. Borensztein et al. (1998) investigate the effects of FDI inflows on economic growth of 69 developing countries and found that FDI stimulates economic growth but only for host economies that have reached a minimum threshold stock of human capital. Borensztein et al. (1998) point out that the correlation between FDI and growth rate could arise from an endogenous determination of FDI, which could bias the estimated coefficient. They control for the endogeneity problem by using some instruments and the results are qualitatively similar in the specification when the instrument variable estimation is not carried out. By contrast, Durham (2004) does not find significant correlation between lagged FDI and per capita GDP growth using data on 80 countries from 1979 through 1998, and does not confirm the results in Borensztein et al. (1998) in terms of the role of a threshold of educational development in the host country.

2.2 Environmental implications

There are scare empirical studies that examine directly the impact of international technology transfer on environmental outcomes, let alone technology transfer channeled through imports of capital goods. Empirical efforts, although lagged behind the theoretical work, have been made in examining the effect of trade on environmental quality (Grossman and Krueger, 1991; Copeland and Taylor, 2004). Theoretical work has identified two series of hypotheses linking openness to trade and environmental quality. The first is the pollution heaven hypothesis which postulates that rich countries should get cleaner with trade and relatively low-income developing countries will be made dirtier with trade. Its alternative, the factor endowments hypothesis suggests that capital abundant countries should get dirtier with trade. Composition effect refers to the trade-induced changes in the composition of output that affects pollution concentrations. Antweiler et al. (2001) estimate econometrically the effects of openness to international market on pollution levels using SO_2 concentrations in 108 cities in 43 countries over period 1971-1996. They explain the SO_2 concentrations as a function of scale effect (measured by the size of economy), technique effect (defined as per capita income), composition effect (defined as capital to labour ratio), openness to trade interacted with comparative advantage which depends on capital to labour ratio and income per capita, and other variables. They assume that the technique effect is likely to be beneficial to the environment, while the scale effect is likely to lead to more pollution. The composition effect is expected to vary across countries, depending on the country's comparative advantage. Therefore, the net effect of free trade on environment depends on the relative strength of each opposing force. They find international trade creates relatively small changes in pollution concentrations when it alters the composition of national output. Moreover, because the trade-shifting effect is very small relative to technique effect, the net effects of trade is to reduce pollution for most countries in the sample.

Managi (2004) find that trade liberalization increases CO_2 emissions with an elasticity of 0.597 using time series data from 1960 to 1999 for 63 countries. Cole (2006) applying the theoretical model of Antweiler et al. (2001) to investigate the linkages between trade liberalization and energy use of 32 developed and developing countries for the period 1975-1995. Their results suggest that trade will increase energy use for the mean country in the sample. There is also evidence showing that pollutant-specific characteristics appear to cause the impact of trade on air pollution to vary by pollutant (Frankel and Rose, 2002; Cole and Elliott, 2003).

Another strand of literature examines the relationship between FDI and environmental performance. Empirical support for the influence of FDI is mixed. Using panel data analysis of 35 less-developed countries, Jorgenson (2007) find that primary sector foreign direct investment positively affects the growth of carbon dioxide emission resulting from agriculture production. The international spread of environmentally superior innovations is especially significant in the context of developing countries due to partly the limited innovation capacities, and partly the lack of environmental regulation which induce the incentives to innovate and adopt such technologies.

Some empirical studies examine the relationship between inward FDI and recipient countries' energy intensity. The support for the influence of FDI is mixed. Mielnik and Goldemberg (2002) find that inward FDI is negatively correlated with energy-intensity of 20 developing countries, over the period 1987 to 1998. They define the explanatory variable as inflows of foreign direct investment as a fraction of total gross investment in all countries. They apply a bivariate regression without controls. By contrast, Hübler and Keller (2010) do not find a favorable effect of FDI on energy intensity, using panel data techniques for the same 20 countries, but over the period 1979 to 2003. They suggest that the investigation into the interactions of FDI with other economic indicators could be a way for further research.

Scarce papers examine the impacts of other technology transfer channels. Kretschmer et al. (2010) examine the relationship between foreign aid and the energy intensity of GDP as well as carbon intensity of energy use in 80 developing countries over the period 1973-2005. They find that foreign aid tends to be effective in reducing the energy intensity of recipient countries, while the carbon intensity is hardly affected. They apply dynamic panel GMM estimation to address the endogeneity problem of both foreign aid and the lagged dependent variable. Applying a spatial lag specification, Perkins and Neumayer (2009) demonstrate that levels of inward FDI stock weighted CO_2 efficiency in other countries do not have statistically significant influence on CO_2 efficiency in developing countries.

3. Empirical Approach

3.1 Econometric specification

We employ a linear panel specification with country and time fixed effects in which the logarithms of per labour GDP, energy intensity and emission intensity are each explained by the log of a stock of spillover knowledge capital and additional statistical controls. Our baseline model is as follows:

$$\begin{aligned}\log(Y/L)_{i,t} &= \partial_i^{YL} + \theta_t^{YL} + \beta_1^{YL}\log L_{i,t-1} + \beta_2^{YL}\log K_{i,t-1} \\ &\quad + \beta_3^{YL}S_{i,t-1} + \beta_4^{YL}S_{i,t-1}\times\log K_{i,t-1} + Z_\gamma^{YL} + \varepsilon_{i,t}^{YL}\end{aligned} \tag{1a}$$

$$\begin{aligned}\log(E/Y)_{i,t} &= \partial_i^{EY} + \theta_t^{EY} + \beta_1^{EY}\log(Y/L)_{i,t-1} + \beta_2^{EY}\log(Y/L)_{i,t-1}^2 + \beta_3^{EY}\log K_{i,t-1} \\ &\quad + \beta_4^{EY}S_{i,t-1} + \beta_4^{EY}S_{i,t-1}\times\log K_{i,t-1} + Z_\gamma^{EY} + \varepsilon_{i,t}^{EY}\end{aligned} \tag{2a}$$

$$\begin{aligned}\log(C/E)_{i,t} &= \partial_i^{CE} + \theta_t^{CE} + \beta_1^{CE}\log(Y/L)_{i,t-1} + \beta_2^{CE}\log(Y/L)_{i,t-1}^2 + \beta_3^{CE}\log K_{i,t-1} \\ &\quad + \beta_4^{CE}S_{i,t-1} + \beta_4^{CE}S_{i,t-1}\times\log K_{i,t-1} + Z_\gamma^{CE} + \varepsilon_{i,t}^{CE}\end{aligned} \tag{3a}$$

where the i and t subscripts index countries and years, C, E, Y, L, N, K and Z respectively denote CO_2

emissions, final energy consumption, GDP, workers, population, physical capital stocks and a vector of control variables, α and θ are vectors of fixed country effects and time effects, β and γ are vectors of parameters to be estimated, and ε are random disturbance terms. While the ε are assumed to be uncorrelated with the explanatory variables, there may be correlation between the latent individual effects, α , and the explanatory variables. For example, capital goods imports of a country are likely to vary according to the type of industries present in the country, in addition to depending on whether the country is primarily agriculture or industrial. Similarly, a country's policy environment and culture institution will greatly affect the resources devoted to education and absorptive capacity. Hence, there is a priori reason to think that fixed effects estimation is the appropriate specification. Additionally, time fixed effects are taken into consideration because they are able to capture any time-specific influences that affect all countries in the sample in a similar way such as economic recession, energy prices, etc.

We are interested in the coefficients on S, the stock of potential spillover knowledge, which is assumed to accumulate proportionally with the technology gap between developing country i and its OECD trade partner j. We specify the gap as the ratio of j's and i's total factor productivities, A_j and A_i, which is a measure of the total amount of technology that i can instantaneously acquire from j. We assume that in a given year the quantity of technological knowledge that can potentially spill over depends on i's contemporaneous exposure to technology rich goods and services produced by j, which we denote $M_{i,j}$. In our baseline specification exposure takes the form of imports of capital goods:

$$S_{i,t} = \sum_{j \neq i} \max[1, A_{j,t} / A_{i,t}] \cdot M_{i,j,t} + (1-\delta) S_{i,t-1} \qquad (2)$$

where δ is the rate of depreciation of spillover knowledge, which we assume reflects the durability of the goods that serve as the conduit of international transmission. Since by default this is machinery and equipment, we use a baseline rate of 0.15.

Several aspects of eq. (1) merit discussion. The log of GDP per worker and its square proxy for a country's overall level of development, which is a blanket explanatory variable intended to capture the net effect of the myriad domestic forces that affect the components of the Kaya identity (e.g., the increasing demand for environmental regulation with rising affluence, breakthrough in the technological progress). Because of the potential for negative contemporaneous correlation between a county's energy-GDP ratio and its GDP per worker, we use the lag of log (Y/L). The capital stock proxies for the economy's productive capacity and industrialized level, which affects the level of output as well as energy use and emissions. We lag logK one period to minimize potentially spurious contemporaneous correlation with the latter variables. Similarly, we lag S because of potential simultaneity between output and $M_{i,j}$ in eq. (2), which is itself a contemporaneous component of GDP. An additional complication is that equipment and machinery imports form part of the succeeding year's aggregate capital stock, increasing the likelihood of positive correlation between S and K reducing the likelihood that the coefficients on spillover knowledge will be significant. Our remedy is to introduce an interaction between S and K, which captures the fact that embodied spillover knowledge changes the quality, and therefore the productivity, of capital.

With regard to the signs of the estimated coefficients, we expect β_3^{YL} and β_4^{YL} to be positive, reflecting the first-order influence of the scale effect on emissions, and β_4^{EY} and β_5^{EY} to be negative, reflecting the compositional implications of energy efficiency improvements. We have no priors on β_4^{CE} and β_5^{CE}. Overall, the effects of scale are expected to dominate those of composition and technique, giving rise to increasing emissions. A novel feature of our approach is that it facilitates imputation of the emissions associated with each of the three channels through the following decomposition technique. Note that, by the Kaya identity, emissions are

$$\begin{aligned} C_{i,t} &= L_{i,t} \times (Y/L)_{i,t} \times (E/Y)_{i,t} \times (C/E)_{i,t} \\ &= L_{i,t} \times \exp[S_{i,t-1}(\beta_3^{YL} + \beta_4^{YL} \log K_{i,t-1})]\phi_{i,t}^{YL} \\ &\quad \times \exp[S_{i,t-1}(\beta_4^{EY} + \beta_5^{EY} \log K_{i,t-1})]\phi_{i,t}^{EY} \times \exp[S_{i,t-1}(\beta_4^{CE} + \beta_5^{CE} \log K_{i,t-1})]\phi_{i,t}^{CE} \end{aligned} \quad (3)$$

where the Φ s are the right-hand-side terms in (1), and the ϕ s represent the sum of the of non-spillover terms in these expressions. The sum over economies on the left-hand side of (3) yields aggregate developing country emissions, C_t. The same operation on the right-hand side, omitting terms associated with one or more channels of the spillovers' impacts, allows us to construct counterfactual emission series, $\overline{C}_t$. The difference between these aggregate quantities is the CO2 attributable to the particular channel under consideration, ΔC_t:

$$\Delta C_t^{YL} = C_t - \overline{C}_t^{YL} = \sum_i C_{i,t} - \sum_i L_{i,t}(E/Y)_{i,t}(C/E)_{i.t}\phi_{i,t}^{YL} \quad (4a)$$

$$\Delta C_t^{EY} = C_t - \overline{C}_t^{EY} = \sum_i C_{i,t} - \sum_i L_{i,t}(Y/L)_{i,t}(C/E)_{i.t}\phi_{i,t}^{EY} \quad (4b)$$

$$\Delta C_t^{CE} = C_t - \overline{C}_t^{CE} = \sum_i C_{i,t} - \sum_i L_{i,t} (Y/L)_{i,t} (E/Y)_{i.t} \phi_{i,t}^{CE} \quad (4c)$$

$$\Delta C_t^{S} = C_t - \overline{C}_t^{S} = \sum_i C_{i,t} - \sum_i L_{i,t} \phi_{i,t}^{YL} \phi_{i,t}^{EY} \phi_{i,t}^{CE} \quad (4d)$$

3.2 Data and variables

Our main source for economic data is the Penn World Table 7.0, from which we take annual real GDP in 2005 international PPP dollars, population, workers, and calculate physical capital stocks from the investment-GDP ratio using the perpetual inventory method with a 7% depreciation rate. These data are matched to IEA annual time-series of non-OECD countries' CO_2 emissions and total final energy consumption. Human capital stock is constructed by using the educational attainment for population aged 25 and over provided by Barro and Lee (2010). The original data is by 5-year age intervals and we interpolate it linearly. We use the POLITY2 variable (Marshall et al., 2010) as a proxy for institutional quality. For additional controls we use United Nations data on the share of industrial value added in GDP. We consider four aggregate sectors: agriculture, industry, transportation and services and named them AGR, IND, SER and TRA respectively. We expect that a higher industry share raises energy intensity and carbon intensity in early stages of development because industrial production needs more energy inputs than agriculture or service sector. It is also possible that in the later stages of development, energy intensity and carbon intensity don't rise with the expansion of industry sector because production moves from heavy, high energy sectors to low energy sectors within the aggregate industry sector.

FDI has been investigated in the international technology diffusion literature (van Pottelsberghe de la Potterie and Lichtenberg, 2001). In fact, the authors considered only one diffusion channel, either trade-related or FDI-related R&D spillovers, which suffers from an omission bias. One exception is Seck (2011) which investigate both diffusion channels based on a dataset of 55 developing countries and seven most-industrialized countries. In our study, we also consider FDI as a potential source of technological spillover when examining the role of spillovers channeled through imports of machinery and equipment. Foreign spillovers that account for the channel of FDI is constructed as follows:

$$FDISPI_{i,t} = \sum_{j}^{n=24} (\frac{TFP_{j,t}}{TFP_{i,t}} \times fdi_{i,j,t}) + (1-\alpha) FDISPI_{i,t-1} \quad (5)$$

where $fdi_{i,j,t}$ is the bilateral inbound FDI and the data source is OECD International direct investment database.

Table 1 shows the summary statistics of the variables.

Table 1. Variables: Descritpve statistics

Variable	Definition	Obs.	Mean	St.Dev	Min	Max
GDPL	GDP per labour	2092	0.01	0.01	0.00	0.09
EI	Energy intensity	2092	0.24	0.39	0.02	3.73
CE	Carbon intensity	2092	2.32	1.41	0.03	7.19
CAP	Domestic capital stocks	2092	437534.70	1461840.00	2275.77	22600000.00
POP	Population	2092	61600000	188000000	525930	1320000000
CQSPI	Trade mediated spillover stocks	2092	0.19	0.43	0.00	5.56
AGR	Agriculture GDP share (%)	2092	0.07	0.04	0.00	0.21
IND	Industry GDP share (%)	2092	0.16	0.09	0.00	0.59
SER	Service GDP share (%)	2092	0.21	0.10	0.00	0.58
TRA	Transportation GDP share (%)	2092	0.03	0.02	0.00	0.11
POLITY2	Polity2 variable	2092	0.93	6.90	-10	10.00
SCHOOL	Human capital	2092	4.82	2.27	0.39	11.54

4. Results

Our main results are presented in Tables 2, 3 and 4. We use one period lagged explanatory variables to capture time-delayed effects and indirectly as instruments to overcome endogeneity problems (Hübler and Keller, 2010).

The results regarding labour productivity are reported in Table 2. In model (1), the spillover variable in included alone, while in model (2) we include capital embodied spillover and domestic capital stocks individually alongside their product. In model (3) we include only the interaction term, leaving the spillover variable. The interaction could be interpreted as quality improving impacts of advanced machinery and equipment imports on recipient countries' capital stocks. The difference between model (1) to (3) and model (4) to (6) is that year effects are not controlled for in the former three model specifications. In all the models, domestic capital stocks are found to have a positive effect on labour productivity, at a 5% significance level. Total population and agriculture sector share are found to have a negative effect at a 5% significance level. The negative relationship between GDP per worker and the agricultural GDP share corroborates with the theory that agriculture sector is more labor intensive compared to other economic sectors, and therefore an expansion of agriculture sector will lead to a decrease of labor productivity. We include the human capital stock as an independent variable as most traditional studies did when examining the effect of technology diffusion on economic growth (Borensztein1 et al., 1998; Xu, 2000). However, the human capital stock does not have significant effect on GDP per labour.

Regarding the coefficient of the variable of main interest, the capital goods embodied spillovers, is positive at a 10% significance level in model (1), which is in line with our expectation that the spillovers will induce labour productivity improvement. However, when the interaction term of domestic capital stocks and spillover variable in included, both the coefficients on spillovers are insignificant in model (2). In model (3), we include only the interaction term, without the spillover variable. It shows that the coefficient of the interaction term is positive and significant at a 5% significance level. In model (4), the significance of the spillover effect disappears when year effects are allowed for, implying that time effects play a role.

The results regarding energy intensity are reported in Table 3. In all the models, we find that domestic capital stocks are positively correlated with energy intensity as measured by energy consumption per GDP, and GDP per labour are negatively correlated with energy intensity, both at a 5% significance level. The positive effect of host country capital stocks on energy intensity is in line with Hübler and Keller (2010), and this result confirms the theory that comparative advantage is driven by factor endowments (Antweiler et al., 2001; Cole, 2006). Antweiler et al. (2001) find a positive relationship between factor endowments defined as capital-to-labour ratio and pollution. They argue that in the context of air pollution, the factor endowments effect predict that capital abundant (high income) countries would, in the face of trade liberalization, become increasingly energy intensive. The negative correlation between GDP per labour and energy intensity corroborates (Cole, 2006) and Hü bler and Keller (2010), which use GDP per capita instead of GDP per labour. Regarding the share of industrial value added in GDP, the agriculture share and the transportation share, we always find a positive and significant sign. This is under our expectation that industrial sectors are more energy intensive compared to service sector and therefore an expansion of industrial sector will lead to an increase in energy demand and energy intensity. Hübler and Keller (2010) also find a positive relationship between industrial share and energy intensity.

Consider our core variable representing trade mediated spillover stocks. In model (1) trade mediated spillover stocks are found to have a negative effect on energy intensity at a 5% significance level. This is consistent with our expectation that spillovers can induce energy efficiency improvement. From the bottom of Table 3 we see that a 1% increase in trade spillover stocks lead to a 0.0167% decrease in energy intensity, that is to say a 0.0167% improvement in energy efficiency. In model (2), we include spillover and domestic capital stocks individually alongside their product. The additional interaction term makes the effect of trade spillover stocks unsignificant. Because the models are nested, we test the restriction imposed in model (1) and model (2) via a likelihood ratio (LR) test. It appears that there is little gained in moving to model (2) from model (1). These empirical results together with our knowledge of the theory suggest that less emphasis be placed on estimates from model (2). In model (3) we replace the trade embodied spillover stocks by the product between S and K to investigate the effect of spillover knowledge on energy intensity. We prefer this specification to model (1) because we assume that the interaction captures the fact that trade embodied spillover knowledge changes the quality and therefore the productivity of recipient countries' capital. The coefficient on the interaction term is negative and significant at a 5% level. From the bottom of Table 3 we see that a 1% increase in trade spillover stocks will lead to a 0.012% decrease in energy intensity, which is only slightly different from the elasticity in model (1).

The results regarding carbon intensity of energy use are reported in Table 4. In both model (1) and model (2), domestic capital stocks are found to have a positive effect on carbon intensity, at a 5% significance level. GDP per worker and its square term are found to have a negative effect at a 5% significance level. With regard to the capital goods knowledge spillovers, it has a negative effect on carbon intensity, yet not significant in model (1). By contrast, in model (2), the spillover variable and the interaction term are both significant at a 5% level.

The coefficient of the spillover variable is positive and the coefficient of the interaction term is negative, indicating that when interpreting the effect of capital goods spillovers on carbon intensity, a distinction should be made between "less industrialized" developing countries and "more industrialized" developing countries. To the former, i.e. developing countries with relative smaller domestic capital stocks, embodied international knowledge spillovers from the North is likely to lead to carbon intensity increase. However, the latter, i.e. countries that have already installed a significant stock of capital goods, were found to benefit from embodied spillovers in terms of transition towards low carbon technologies. In other words, my results provide evidence that industrialization stages play a role. Overall, based on the sample mean, it is worth noting that 1% increasing in trade spillover stock will lead to 0.037% increase in carbon intensity, which suggests that the net effect of capital goods spillover stock is not improving carbon efficiency of energy use, but amplifying carbon intensity.

Table 2. Scale (GDP per Worker) Effect

	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
lnCAP(-1)	0.391***	0.393***	0.391***	0.407***	0.409***	0.406***
	(0.064)	(0.064)	(0.064)	(0.069)	(0.069)	(0.069)
lnPOP(-1)	-0.747***	-0.744***	-0.743***	-0.890***	-0.873***	-0.882***
	(0.142)	(0.141)	(0.142)	(0.174)	(0.175)	(0.175)
CQSPI(-1)	0.147*	-0.551		0.123	-0.518	
	(0.083)	(0.604)		(0.082)	(0.589)	
CQSPI(-1)*		0.044	0.010***		0.040	0.008*
lnCAP(-1)		(0.035)	(0.005)		(0.035)	(0.005)
AGR	-4.250***	-4.354***	-4.272***	-4.197***	-4.283***	-4.214***
	(1.313)	(1.363)	(1.314)	(1.336)	(1.389)	(1.338)
IND	-1.048	-1.110	-1.069	-0.931	-0.998	-0.952
	(0.832)	(0.821)	(0.829)	(0.870)	(0.859)	(0.868)
SER	-0.993	-1.095*	-1.020	-0.821	-0.920	-0.846
	(0.635)	(0.614)	(0.632)	(0.625)	(0.613)	(0.624)
TRA	2.629	3.019	2.711	0.808	1.296	0.918
	(2.656)	(2.618)	(2.651)	(3.518)	(3.503)	(3.518)
POLITY2	-0.004	-0.003	-0.004	-0.004	-0.004	-0.004
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
SCHOOL	0.032	0.032	0.031	0.015	0.016	0.015
	(0.029)	(0.028)	(0.029)	(0.031)	(0.031)	(0.031)
Year effects	No	No	No	Yes	Yes	Yes
Constant	3.466	3.444	3.417	5.639***	5.372*	5.522*
	(2.125)	(2.114)	(2.125)	(2.766)	(2.785)	(2.773)
R-sq.	0.556	0.545	0.555	0.466	0.469	0.468
Observations	2099	2099	2099	2099	2099	2099
Number of Groups	56	56	56	56	56	56

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$; Fixed effect model

Table 3. Composition (Energy Intensity of GDP) Effect

	(1)	**(2)**	**(3)**
ln(GDPL)(-1)	-0.485***	-0.481***	-0.483***
	(0.064)	(0.064)	(0.064)
lnCAP(-1)	0.134***	0.131***	0.133***
	(0.063)	(0.063)	(0.063)
CQSPI(-1)	-0.089***	0.193	
	(0.035)	(0.377)	
CQSPI(-1)*lnCAP(-1)		-0.018	-0.006***
		(0.023)	(0.002)
AGR	1.444*	1.496*	1.460*
	(0.822)	(0.798)	(0.819)
IND	0.798*	0.827*	0.811*
	(0.412)	(0.422)	(0.413)
SER	-0.597	-0.552	-0.580
	(0.917)	(0.936)	(0.919)
TRA	4.789***	4.585***	4.721***
	(2.092)	(2.206)	(2.099)
POLITY2	-0.003	-0.003	-0.003
	(0.003)	(0.003)	(0.003)
SCHOOL	0.050	0.048	0.049
	(0.038)	(0.038)	(0.038)
Year effects	Yes	Yes	Yes
Constant	-6.020***	-5.979***	-6.004***
	(0.951)	(0.945)	(0.950)
R-sq.	0.153	0.155	0.153
Observations	2089	2089	2089
Number of Groups	56	56	56
LR test	3.79*		
Trade spillover stock elasticity	-0.0167***	-0.00143	-0.0121***
GDP per labour elasticity	-0.486***		-0.483***
Domestic capital stocks elasticity	0.134***		0.132***

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$; Fixed effect model; Elasticities are evaluated at sample means using Delta method

Table 4. Technique (CO2 Intensity of Energy Use) Effect

	(1)	(2)
ln(GDPL)(-1)	-1.444***	-1.506***
	(0.270)	(0.280)
ln(GDPL)(-1)sq	-0.149***	-0.157***
	(0.027)	(0.028)
lnCAP(-1)	0.271***	0.261***
	(0.089)	(0.087)
CQSPI(-1)	-0.050	0.817***
	(0.043)	(0.334)
CQSPI(-1)*lnCAP(-1)		-0.055***
		(0.021)
AGR	-0.659	-0.486
	(1.359)	(1.404)
IND	0.790***	0.919***
	(0.354)	(0.374)
SER	0.748*	0.904***
	(0.395)	(0.390)
TRA	-5.277*	-5.807***
	(2.639)	(2.645)
POLITY2	0.000	-0.001
	(0.003)	(0.003)
Year effects	Yes	Yes
Constant	-5.862***	-5.940***
	(1.359)	(1.362)
R-sq.	0.303	0.315
Observations	2089	2089
Number of Groups	56	56

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$; Fixed effect model; Elasticities are evaluated at sample means using Delta method

5. Robustness Tests

5.1 Technology vs. composition of the capital stock

Technological progress takes place through a process of "capital deepening" in the form of the introduction of new varieties of capital goods. Therefore, it is necessary to test if the energy saving effect and productivity improving effect of spillovers are induced by increasing new capital through importing rather than stimulating technological progress. To this aim, we construct the foreign spillover stock as an accumulated unweighted sum - rather than the TFP gap ratio - of imports of machinery and equipment from 24 industrial countries. The accumulated unweighted sum can be thought of as a proxy for the effect of capital composition, which is the same for each country, in contrast to the previous used measure of the foreign spillover defined with country-specific weights. The results are presented in Tables 5, 6 and 7.

The effect of accumulation of imports of machinery and equipment on per worker GDP is significantly positive and larger than the TFP gap weighted imports. We can attribute this larger effect to the income effect, in which process the imported machinery and equipment induce improvement of productivity and economic growth. The unweighted sum spillover does not have significant effect on energy intensity, which implies that it is not the composition effect via imports that contributes to the increase of energy efficiency. The TFP gap ratio weighted bilateral imports performs somewhat better than a definition using weights common to each country. It indicates that the TFP gap between technological leader and laggard continues to play a crucial role when measuring imports of machinery and equipment as a technology transfer channel.

$$USPI_{i,t} = \sum_{j}^{n=24}(M_{i,j,t}) + (1-\alpha)USPI_{i,t-1} \qquad (6)$$

where M_{ijt} stands for imports of machinery and equipment from developed country j to developing country i, α is depreciation rate and we took 15%.

5.2 Double counting

As our capital stock is calculated from investment data of Penn World Table 7.0 using perpetual inventory method, it is possible that the imports of machinery and equipment from developed countries are fragments of these investments, which leads to mismeasurement of the domestic capital stocks. For the purpose of examining if the current domestic capital stocks in the regression consist of imports of machinery and equipment investment, we subtract the unweighted spillover from the domestic capital stocks. The regression results are shown in Table 8 and Table 9. There is little change in the magnitude and significance of the trade mediated spillover coefficient and we can exclude the possibility that we model the influence of imports of machinery and equipment twice mistakenly by assigning it to form the domestic capital stocks.

5.3 Depreciation spillover of knowledge

Test effect of δ = 0, 0.05, 0.1 in eq. (2). Regression results regarding GDP per worker is in Table 10 and regression results regarding energy intensity is in Table 11. The spillover variable and the interaction term are robust to different depreciation rate of knowledge spillover and the magnitude is slightly smaller when the deprecation rate takes 0, 0.05 and 0.1. Regression results regarding carbon intensity is in Table 12. In sum, the results are robust to different depreciation rate of knowledge spillover.

5.4 Regional heterogeneity in spillover impacts

Does regional heterogeneity play a role in benefiting from the capital goods spillovers? To this aim, estimating the spillover effect in different regions makes sense.

According to the world bank classification, the developing regions can be classified into 6 regions. Accordingly, we stratify our 56 sample countries into 6 regions. Sub-Saharan Africa includes 16 countries and they are: Benin, Botswana, Cameroon, Congo Dem, Congo Republic, Gabon, Ghana, Kenya, Mozambique, Namibia, Nigeria, Senegal, South Africa, Togo, Zambia and Zimbabwe. East Asia and Pacific includes 7 countries and they are: China, Indonesia, Malaysia, Philippines, Singapore, South Korea and Thailand. European and Central Asia includes Cyprus and Turkey. Latin America and Caribbean includes 21 countries and they are: Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Trinidad &Tobago, Uruguay and Venezuela. Middle East and North Africa includes Algeria, Egypt, Jordan, Morocco, Syria, Tunisia. South Asia includes: Bangladesh, India, Nepal and Sri Lanka.

We employ Hausman-Taylor estimator for the labour productivity model to test if there exists regional heterogeneity in spillover impacts. We set the spillover variable and its interaction with domestic stocks as time varying endogenous, and the 6 region variables as time invariant exogenous.

Results regarding labour productivity are in Table13. In both regressions, the coefficient on the dummy variable Africa is negative and significant, which indicates that the countries in the Sub-Saharan Africa will benefit less from the technology transfer than other regions, other things being equal. Regression results regarding the energy intensity is in Table14. The coefficient of Africa is positive and significant, which indicates that the countries in the Sub-Saharan Africa will gain less energy efficiency than countries in other regions, other things being equal. Regression results regarding the carbon intensity is in Table15. Except Sub-Saharan Africa, the coefficients on other regions are positive and significant, which suggests that only countries of Sub-Saharan Africa will be less affected by capital goods embodied spillover stock when measuring its effect on carbon intensity.

5.5 Mechanisms of spillover

In this section, we intend to find some clues about what kinds of equipment and machinery seem to be responsible for the effects. According to SITC Revision2, the import of machinery and equipment is comprised of 9 subcategories and they are: 71.Power generating machinery and equipment; 72.Machinery specialized for particular industries; 73.Metalworking machinery; 74.General industrial machinery & equipment and parts; 75.Office machines & automatic data processing equipment; 76.Telecommunications & sound recording apparatus; 77.Electrical machinery, apparatus & appliances; 78.Road vehicles (including air-cushion vehicles); 79.Other transport equipment.

Using the data of 118 countries in 1995, Caselli and Wilson (2004) calculated the correlation between per capita income and each capital type's share of total capital imports. It showed that 5 out of 9 of the capital types have positive correlation with per capita income. Among them, computers and related equipment has the highest correlation, and it is followed with the descenting sequence by: professional goods (scientific instruments), electrical equipment, communications equipment and aircraft. In contrast, non-electrical equipment, fabricated metal, motor vehicles and other transportation equipment have negative correlation with per capita income, with the descenting sequence. Wilson (2004) plots the correlation results from Caselli and Wilson (2004) against the global R&D intensity for each type. They assume that the R&D intensity of a capital type can be thought of as a proxy for the level of technology embodied in it and they found that capital types that embody more advanced technology tend to have a more positive relationship with income per capita. They pointed out that these results are perfectly consistent with the notion that there are spillovers from advanced countries to less advanced countries.

We calculated the correlation between per capita income and each capital type imports. The capital type imports are measured by two methods. One uses the value of each capital goods imports (2005 constant USD) and the other uses each capital type's share of total capital goods imports as Caselli and Wilson (2004). Figure5 presents a summary of the results. Although the capital goods classification is slightly different from the classification use by Caselli and Wilson (2004), the correlation results are almost consistent. Office machines & automatic data processing equipment has the highest correlation with per capita income when capital goods imports are measured in the value form and rank second when capital goods imports are measured in the share form. Electrical machinery has the highest correlation with per capita income when capital goods imports are measured in the share form and rank second when they are measured in the share form. We argue that countries that import proportionately more in R&D-intensive capital goods, in our example, office machines and relevant equipment and electrical machinery, appear to have higher productivity. Wilson (2002) showed that industries within the U.S. that import more in R&D-intensive capital goods tend to have higher productivity (income per worker).

De Cian and Parrado (2012) argue that the propensity to benefit from spillovers depends on the amount of spillover-inducing imported goods and the absorptive capacity. The absorptive capacity is defined as the share of machinery and equipment output in a country over the world machinery output. The technological receiving country is unlikely to benefit from the imported knowledge because a small absorptive capacity makes it difficult to exploit the transferred knowledge.

6. Implications for Developing Country Emissions

6.1 First order effect of spillovers

To assess the implications of our econometric results we subtract the estimated contributions of spillovers to each of the Kaya components above, and use the result to generate counterfactual emissions series for each of our 56 developing countries.

The red line in Figure1 and Figure2 is the actual aggregate CO_2 emissions of 56 developing countries. The total amount of real CO_2 emissions of these 56 countries is about 1970 million tons in 1972 and 12418.48 million tons in 2009, with an annual growth rate of about 5\%. The blue line, black line and green line in Figure 1 are the counterfactual CO_2 emissions series of these 56 developing countries in year t if there is no spillover effect on energy intensity, carbon intensity and labour productivity respectively.

Without the effect of spillovers on energy intensity, the counterfactual CO_2 emissions rises to 17829 million tones in 2009, which is about 44% increase than the 2009 level. It suggests that there is energy-saving effect of spillovers on CO_2 emissions. By contrast, the green line shows that if there is not effect of spillovers on carbon intensity, CO_2 emissions are reduced to 8150 million tones, which is about 41% decrease compared to the real emission level in 2009. It suggests that spillovers will lead to more CO_2 emissions through the growth channel. The black line goes parallely and slightly lower than the red line, which indicates that without the effect of spillovers on carbon intensity, CO_2 emissions will be lower.

Figure2 is the overall first order impacts of spillovers on CO_2 emissions. It is obvious that if there is no spillovers, the counterfactual CO_2 emissions is about 9000 million tones, 28% lower than the 2009 level. It implies that the net effect of spillovers was amplifying CO_2 emissions rather than attenuating it, which is in line with of our expectation.

The adverse effects of technology spillovers on developing countries' carbon emissions could arise from the ripple effect of the Kyoto Protocol (Babiker et al., 2000; Babiker, 2005). For example, under the Kyoto Protocol, Annex B countries are obliged to reducing greenhouse gas emissions. Emission restrictions will increase the cost to Annex B countries of using carbon-emitting fuels, thereby raising manufacturing costs of their manufactured goods, which may be exported to developing countries. Facing the higher price of manufacturing goods, developing countries will decrease their imports from developed countries. In addition, the emission controls will also lower the global demand for carbon-emitting fuels, thereby reducing their international prices. The reduced international prices of carbon-emitting fuels may trigger the energy demand increase in some developing countries, especially energy importing ones, leading to further CO_2 emissions.

Figure 1. Technology Spillovers: Channels of Impact on CO_2 Emissions in 56 Developing Countries

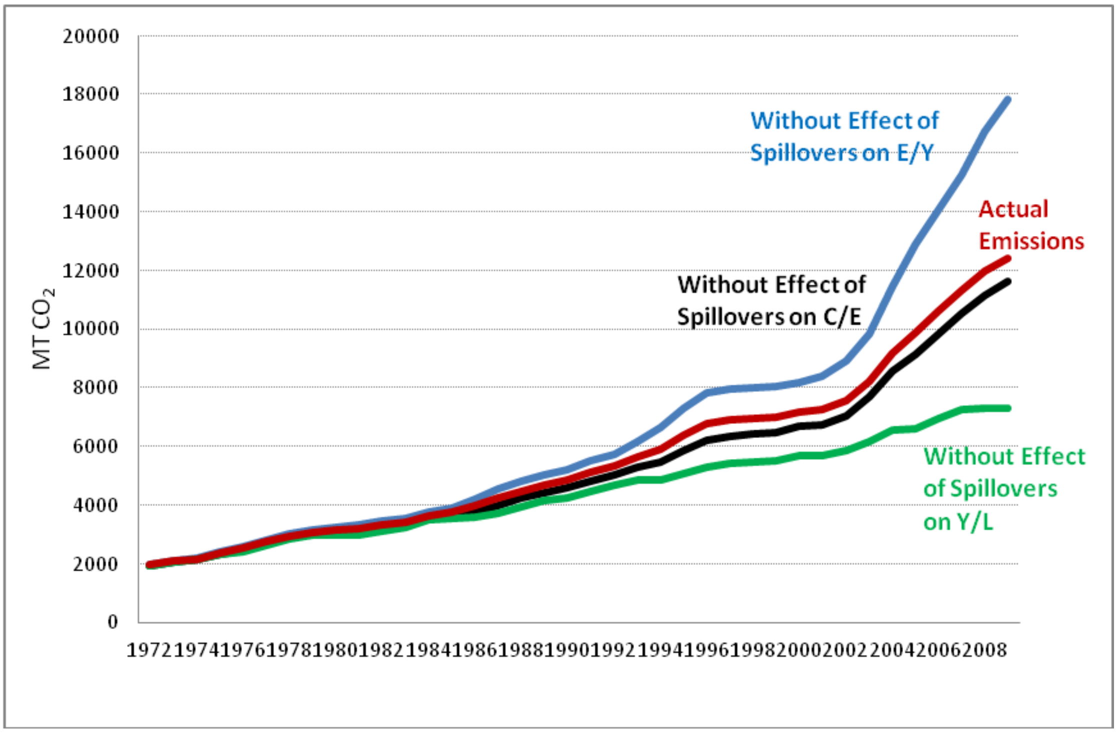
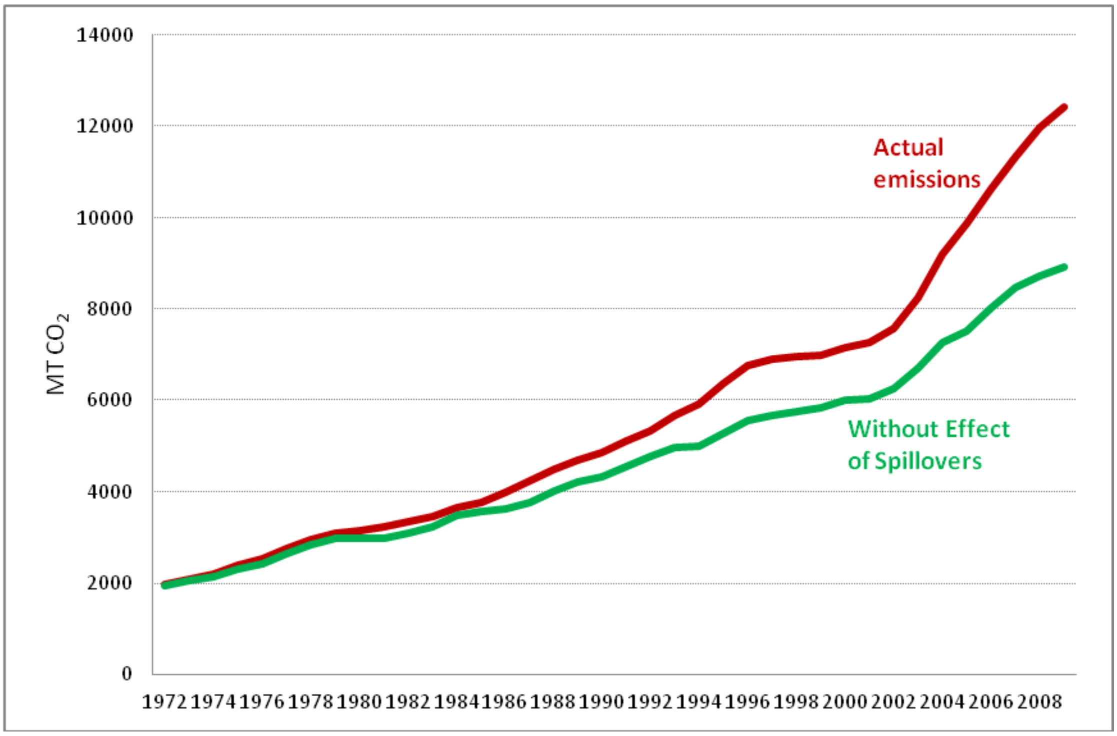


Figure 2. Technology Spillovers: Overall First-Order Impact



6.2 First and second order effect of spillovers

We use the fitted value of ln(Y/L) from regression (4) in Table2 to rerun the regressions, in which ln(E/Y) and ln(C/E) are the dependent variables. Again, to assess the implications of our econometric results in which case spillovers' positive impact on developing nations' economic expansion has been taken into account, we subtract the estimated contributions of spillovers to each of the Kaya components, and use the results to generate counterfactual emissions series for each of our 56 developing countries.

All the same, the red line, blue line, black line and green line in Figure3 represent actual CO_2 emissions, the counterfactual emissions if there is no spillover effect on energy intensity, carbon intensity and labour productivity respectively. It suggests that the capital goods embodied spillovers will induce CO_2 emissions growth via higher labour productivity, while it will lead to CO_2 emissions mitigation via improved energy efficiency. These results are consistent with the first order effect of spillover as in Figure1 and Figure2. The only difference is that the effect of spillover on energy intensity is amplified when the second order effect of spillover is taken into account.

When the effect of labour productivity on energy intensity is taken into account, the impact of spillovers' energy saving effect is reinforced. If there is no effect of spillovers on energy intensity, the counterfactual CO_2 emissions will reach nearly 28000 million tones, 125% increase than the 2009 emission level, which is a sharp contrast with 44% increase when the effect of labour productivity on energy intensity is not taken into account. Although there is potential strengthened effect of spillovers on energy intensity, the overall impacts of spillovers on CO_2 emissions remain almost unchanged. It probably because the effect of labour productivity on carbon intensity offsets its effect on energy intensity.

Figure 3. Technology Spillovers: first and second order effect

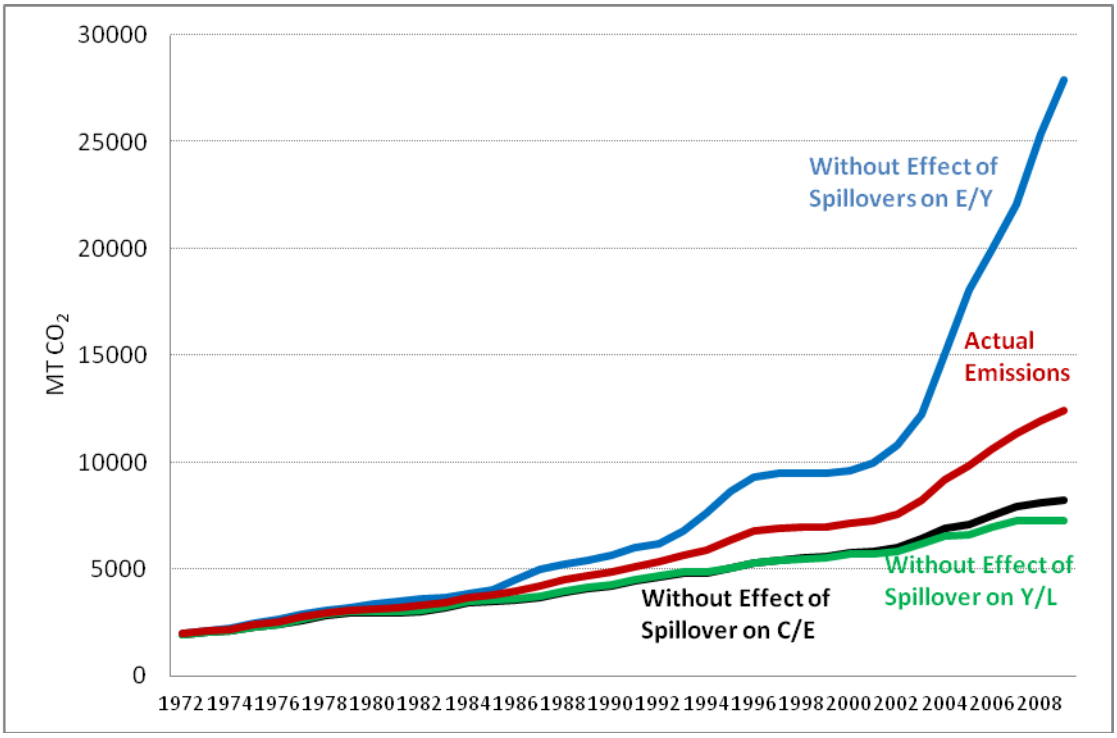


Figure 4. Technology Spillovers: Overall impact

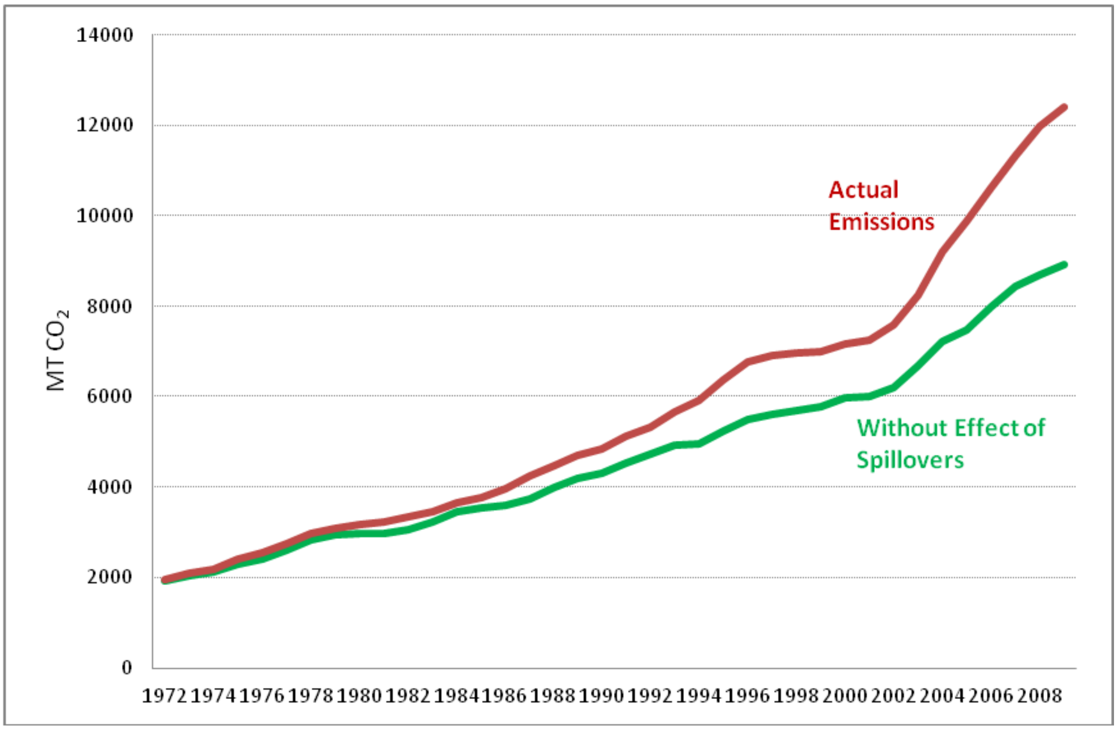
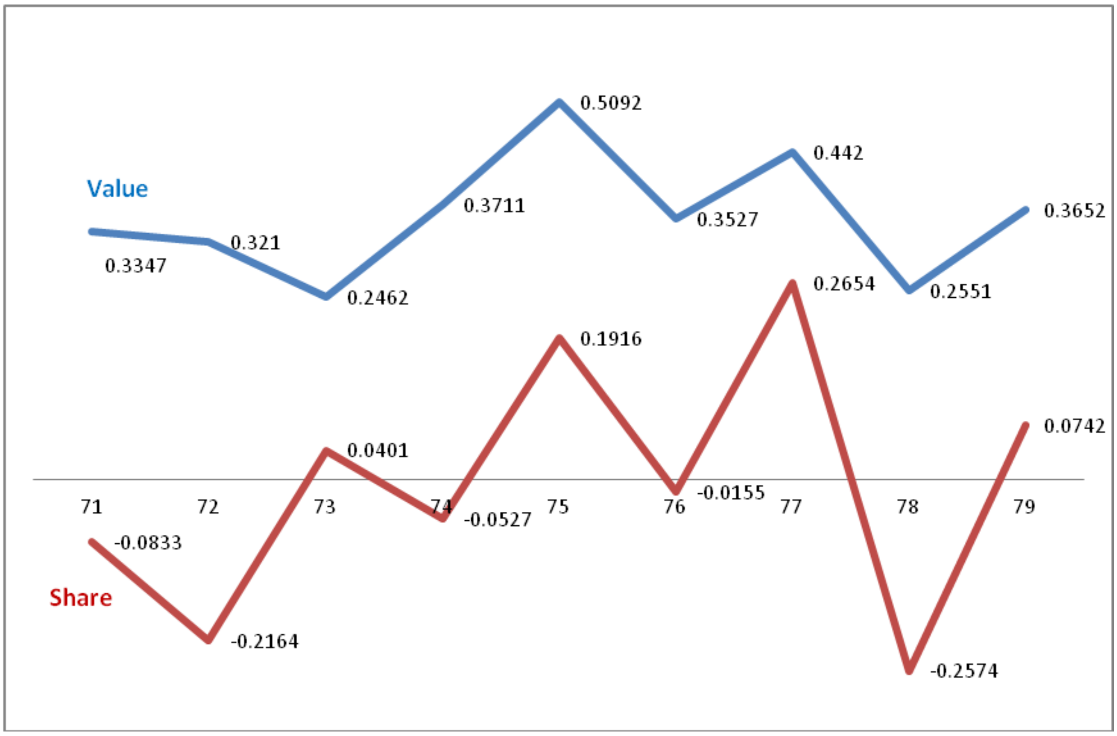


Figure 5. Correlation between per capita income and equipment imports, 56 countries



7. Conclusions

This paper examines the effects of international technological spillovers embodied in traded capital commodities. The study focuses on the effects of trade driven spillovers on energy intensity of GDP, carbon intensity of energy use and GDP per labor of 56 developing countries. The vehicle of technological spillovers is machinery and equipment imports from 24 OECD countries.

We find that the technological spillovers will lead to higher carbon emissions than if no spillovers occurred. Technological spillovers can significantly improve energy efficiency of the destination countries. Such an increase in energy efficiency of energy use will lead to lower carbon emissions due to the energy saving bias of technology spillovers. Technological spillovers has positive effect on the GDP per labor. Such an increase in labor intensity will result in greater carbon emissions due to output expanding effect of spillovers. This leads to higher economic growth and greater energy consumption by producers and consumers. We find, therefore, that the emissions-increasing influences of income effect due to the higher labor productivity significantly outweigh the emissions-reducing influence of technological effect induced by greater energy efficiency.

These results have important policy implications. Although the energy intensity of GDP is falling with importing technologies, the economic growth is higher than it would be if no importing activities occurred. Therefore a policy of increasing technology sourcing and to increase energy efficiency and reduce emissions may not meet its intended goals if the income effects are ignored. Our findings underscore the importance of considering the economy-wide implications of a technology policy, recognizing that better technology does not necessarily imply a cleaner environment.

Table 5. Composition, GDP per worker

	(1)	**(2)**	**(3)**
lnCAP(-1)	0.391***	0.391***	0.393***
	(0.067)	(0.068)	(0.067)
lnPOP(-1)	-0.918***	-0.918***	-0.916***
	(0.176)	(0.174)	(0.175)
USPI(-1)	0.299*	0.266	
	(0.171)	(1.528)	
USPI(-1)*lnCAP(-1)		0.002	0.019*
		(0.091)	(0.010)
AGR	-3.924***	-3.926***	-3.943***
	(1.316)	(1.344)	(1.322)
IND	-1.013	-1.014	-1.024
	(0.874)	(0.873)	(0.872)
SER	-0.761	-0.763	-0.779
	(0.611)	(0.607)	(0.610)
TRA	0.636	0.649	0.753
	(3.504)	(3.528)	(3.511)
POLITY2	-0.004	-0.004	-0.004
	(0.003)	(0.003)	(0.003)
SCHOOL	0.001	0.001	0.002
	(0.029)	(0.029)	(0.030)
Year effects	Yes	Yes	Yes
Constant	6.285***	6.278***	6.235***
	(2.717)	(2.679)	(2.720)
R-sq.	0.426	0.426	0.427
Observations	2089	2089	2089
Number of Groups	56	56	56

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$; Fixed effect model;

Table 6. Composition, Energy intensity

	(1)	(2)	(3)
ln(GDPL)(-1)	-0.504***	-0.503***	-0.501***
	(0.069)	(0.069)	(0.068)
lnCAP(-1)	0.137***	0.128***	0.137***
	(0.064)	(0.063)	(0.064)
USPI(-1)	-0.087	1.239	
	(0.101)	(0.876)	
USPI(-1)*lnCAP(-1)		-0.084	-0.006
		(0.050)	(0.006)
AGR	1.466*	1.531*	1.473*
	(0.836)	(0.785)	(0.834)
IND	0.692	0.748*	0.708
	(0.434)	(0.431)	(0.433)
SER	-0.670	-0.584	-0.658
	(0.936)	(0.943)	(0.936)
TRA	4.889***	4.391***	4.850***
	(2.078)	(2.166)	(2.084)
POLITY2	-0.003	-0.004	-0.003
	(0.003)	(0.003)	(0.003)
SCHOOL	0.047	0.043	0.047
	(0.038)	(0.038)	(0.038)
Year effect	Yes	Yes	Yes
Constant	-6.110***	-6.029***	-6.100***
	(0.966)	(0.950)	(0.963)
R-sq.	0.155	0.159	0.154
Observations	2089	2089	2089
Number of Groups	56	56	56

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$; Fixed effect model;

Table 7. Composition, Carbon intensity

	(1)	(2)	(3)
ln(GDPL)(-1)	-1.312***	-1.390***	-1.319***
	(0.215)	(0.238)	(0.216)
ln(GDPL)(-1)sq	-0.137***	-0.144***	-0.137***
	(0.021)	(0.024)	(0.021)
lnCAP(-1)	0.287***	0.280***	0.286***
	(0.088)	(0.088)	(0.088)
USPI(-1)	-0.121	0.976	
	(0.091)	(0.649)	
USPI(-1)*lnCAP(-1)		-0.069	-0.008
		(0.042)	(0.006)
AGR	-0.697	-0.630	-0.688
	(1.310)	(1.330)	(1.312)
IND	0.649*	0.725***	0.666*
	(0.343)	(0.360)	(0.348)
SER	0.759*	0.847***	0.773*
	(0.385)	(0.389)	(0.386)
TRA	-5.538***	-5.845***	-5.577***
	(2.506)	(2.530)	(2.514)
POLITY2	-0.000	-0.000	-0.000
	(0.003)	(0.003)	(0.003)
SCHOOL	-0.051	-0.053	-0.051
	(0.048)	(0.048)	(0.048)
Year effect			
Constant	-5.510***	-5.659***	-5.523***
	(1.190)	(1.209)	(1.190)
R-sq.	0.241	0.248	0.244
Observations	2089	2089	2089
Number of Groups	56	56	56

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$; Fixed effect model;

Table 8. Double counting, Energy intensity

	(1)	(2)
ln(GDPL)(-1)	-0.483***	-0.474***
	(0.064)	(0.063)
lnCAP(-1)	0.133***	
	(0.063)	
CQSPI(-1)*lnCAP(-1)	-0.006***	
	(0.002)	
Log(K stock-USPI)(-1)		0.121***
		(0.060)
Trade spillover stock(-1)*Log(K stock -USPI)(-1)		-0.006***
		(0.002)
AGR	1.460*	1.386*
	(0.819)	(0.819)
IND	0.811*	0.817*
	(0.413)	(0.417)
SER	-0.580	-0.570
	(0.919)	(0.919)
TRA	4.721***	4.708***
	(2.099)	(2.118)
POLITY2	-0.003	-0.003
	(0.003)	(0.003)
SCHOOL	0.049	0.050
	(0.038)	(0.038)
Year effects	Yes	Yes
Constant	-6.004***	-5.826***
	(0.950)	(0.893)
R-sq.	0.153	0.163
Observations	2089	2089
Number of Groups	56	56

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$; Fixed effect model;

Table 9. Double counting, Carbon intensity

	(1)	(2)
ln(GDPL)(-1)	-1.413***	-1.390***
	(0.241)	(0.239)
ln(GDPL)(-1)sq	-0.147***	-0.147***
	(0.024)	(0.024)
lnCAP(-1)	0.273***	
	(0.087)	
CQSPI(-1)	0.863***	0.970***
	(0.316)	(0.325)
CQSPI(-1)*lnCAP(-1)	-0.056***	
	(0.020)	
Log(K stock-USPI)(-1)		0.231***
		(0.082)
Trade spillover stock(-1)*Log(K stock		-0.063***
-USPI)(-1)		(0.021)
AGR	-0.539	-0.728
	(1.356)	(1.356)
IND	0.749*	0.798***
	(0.379)	(0.378)
SER	0.918***	0.961***
	(0.384)	(0.394)
TRA	-6.075***	-6.153***
	(2.513)	(2.515)
POLITY2	-0.001	-0.001
	(0.003)	(0.004)
SCHOOL	-0.055	-0.054
	(0.047)	(0.047)
Constant	-5.660***	-5.094***
	(1.199)	(1.150)
R-sq.	0.242	0.254
Observations	2089	2089
Number of Groups	56	56

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$; Fixed effect model;

Table 10. GDP per labour

	(1)	(2)	(3)	(4)
lnCAP(-1)	0.406***	0.406***	0.406***	0.406***
	(0.069)	(0.069)	(0.069)	(0.069)
lnPOP(-1)	-0.882***	-0.882***	-0.882***	-0.882***
	(0.175)	(0.175)	(0.175)	(0.175)
CQSPI(-1)*lnCAP(-1)(depreciation=0.15)	0.008*			
	(0.005)			
CQSPI(-1)*lnCAP(-1)(depreciation=0)		0.007*		
		(0.004)		
CQSPI(-1)*lnCAP(-1)(depreciation=0.05)			0.008*	
			(0.004)	
CQSPI(-1)*lnCAP(-1) (depreciation=0.1)				0.008*
				(0.005)
AGR	-4.214***	-4.215***	-4.214***	-4.214***
	(1.338)	(1.338)	(1.338)	(1.338)
IND	-0.952	-0.952	-0.952	-0.952
	(0.868)	(0.868)	(0.868)	(0.868)
SER	-0.846	-0.846	-0.846	-0.846
	(0.624)	(0.624)	(0.624)	(0.624)
TRA	0.918	0.917	0.918	0.918
	(3.518)	(3.518)	(3.518)	(3.518)
POLITY2	-0.004	-0.004	-0.004	-0.004
	(0.003)	(0.003)	(0.003)	(0.003)
SCHOOL	0.015	0.015	0.015	0.015
	(0.031)	(0.031)	(0.031)	(0.031)
Year effect	Yes	Yes	Yes	Yes
Constant	5.522*	5.528*	5.526*	5.524*
	(2.773)	(2.772)	(2.772)	(2.773)
R-sq.	0.468	0.468	0.468	0.468
Observations	2099	2099	2099	2099
Number of Groups	56	56	56	56

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$; Fixed effect model;

Table 11. Depreciation rate, Energy intensity

	(1)	(2)	(3)	(4)
ln(GDPL)(-1)	-0.483***	-0.483***	-0.483***	-0.483***
	(0.064)	(0.064)	(0.064)	(0.064)
lnCAP(-1)	0.133***	0.133***	0.133***	0.133***
	(0.063)	(0.063)	(0.063)	(0.063)
CQSPI(-1)*lnCAP(-1)(depreciation=0.15)	-0.006***			
	(0.002)			
CQSPI(-1)*lnCAP(-1)(depreciation=0)		-0.005***		
		(0.002)		
CQSPI(-1)*lnCAP(-1)(depreciation=0.05)			-0.005***	
			(0.002)	
CQSPI(-1)*lnCAP(-1) (depreciation=0.1)				-0.006***
				(0.002)
AGR	1.460*	1.461*	1.460*	1.460*
	(0.819)	(0.819)	(0.819)	(0.819)
IND	0.811*	0.810*	0.810*	0.811*
	(0.413)	(0.413)	(0.413)	(0.413)
SER	-0.580	-0.581	-0.580	-0.580
	(0.919)	(0.919)	(0.919)	(0.919)
TRA	4.721***	4.722***	4.721***	4.721***
	(2.099)	(2.099)	(2.099)	(2.099)
POLITY2	-0.003	-0.003	-0.003	-0.003
	(0.003)	(0.003)	(0.003)	(0.003)
SCHOOL	0.049	0.049	0.049	0.049
	(0.038)	(0.038)	(0.038)	(0.038)
Year effect	Yes	Yes	Yes	Yes
Constant	-6.004***	-6.005***	-6.005***	-6.005***
	(0.950)	(0.950)	(0.950)	(0.950)
R-sq.	0.153	0.153	0.153	0.153
Observations	2089	2089	2089	2089
Number of Groups	56	56	56	56

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$; Fixed effect model;

Table 12. Depreciation rate, Carbon intensity

	(1)	(2)	(3)	(4)
ln(GDPL)(-1)	-1.413***	-1.413***	-1.413***	-1.413***
	(0.241)	(0.241)	(0.241)	(0.241)
ln(GDPL)(-1)sq	-0.147***	-0.147***	-0.147***	-0.147***
	(0.024)	(0.024)	(0.024)	(0.024)
lnCAP(-1)	0.273***	0.273***	0.273***	0.273***
	(0.087)	(0.087)	(0.087)	(0.087)
CQSPI(-1) (depreciation=0.15)	0.863***			
	(0.316)			
CQSPI(-1)*lnCAP(-1) (depreciation=0.15)	-0.056***			
	(0.020)			
CQSPI(-1) (depreciation=0)		0.798***		
		(0.293)		
CQSPI(-1)*lnCAP(-1) (depreciation=0)		-0.052***		
		(0.019)		
CQSPI(-1) (depreciation=0.05)			0.819***	
			(0.300)	
CQSPI(-1)*lnCAP(-1) (depreciation=0.05)			-0.054***	
			(0.019)	
CQSPI(-1) (depreciation=0.1)				0.840***
				(0.308)
CQSPI(-1)*lnCAP(-1) (depreciation=0.1)				-0.055***
				(0.020)
AGR	-0.539	-0.539	-0.539	-0.539
	(1.356)	(1.356)	(1.356)	(1.355)
IND	0.749*	0.750*	0.749*	0.749*
	(0.379)	(0.379)	(0.379)	(0.379)
SER	0.918***	0.917***	0.918***	0.918***
	(0.384)	(0.384)	(0.384)	(0.384)
TRA	-6.075***	-6.073***	-6.074***	-6.074***
	(2.513)	(2.513)	(2.513)	(2.513)
POLITY2	-0.001	-0.001	-0.001	-0.001
	(0.003)	(0.004)	(0.004)	(0.003)
SCHOOL	-0.055	-0.055	-0.055	-0.055
	(0.047)	(0.047)	(0.047)	(0.047)
Year effect	Yes	Yes	Yes	Yes
Constant	-5.660***	-5.658***	-5.659***	-5.659***
	(1.199)	(1.199)	(1.199)	(1.199)
R-sq.	0.242	0.242	0.242	0.242
Observations	2089	2089	2089	2089
Number of Groups	56	56	56	56

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$; Fixed effect model;

Table 13. Regional difference, GDP per worker

	(1)	(2)	(3)
lnCAP(-1)	0.413***	0.415***	0.412***
	(0.016)	(0.016)	(0.016)
lnPOP(-1)	-0.762***	-0.748***	-0.755***
	(0.041)	(0.040)	(0.040)
CQSPI(-1)	0.133***	-0.525***	
	(0.014)	(0.149)	
CQSPI(-1)*lnCAP(-1)		0.041***	0.009***
		(0.009)	(0.001)
SCHOOL	0.010	0.012	0.010
	(0.008)	(0.008)	(0.008)
POLITY2	-0.004***	-0.004***	-0.004***
	(0.001)	(0.001)	(0.001)
AGR	-4.239***	-4.324***	-4.256***
	(0.294)	(0.294)	(0.294)
IND	-0.974***	-1.040***	-0.995***
	(0.112)	(0.113)	(0.112)
SER	-0.793***	-0.891***	-0.818***
	(0.156)	(0.157)	(0.156)
TRA	1.166*	1.661***	1.282***
	(0.622)	(0.629)	(0.621)
Africa	-0.902*	-0.907*	-0.907*
	(0.532)	(0.525)	(0.527)
East Asia	-0.127	-0.149	-0.143
	(0.574)	(0.567)	(0.569)
Latin America&	-0.416	-0.433	-0.421
Caribbean	(0.524)	(0.517)	(0.519)
Middle East and North	-0.327	-0.346	-0.335
Africa	(0.579)	(0.572)	(0.574)
South Asia	-0.532	-0.593	-0.557
	(0.622)	(0.614)	(0.616)
Year effect	Yes	Yes	Yes
Constant	4.040***	3.837***	3.945***
	(0.780)	(0.773)	(0.775)
Observations	2099	2099	2099
Number of Groups	56	56	56

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$;

Table 14. Regional difference, Energy intensity

	(1)	(2)	(3)
ln(GDPL)(-1)	-0.509***	-0.507***	-0.508***
	(0.020)	(0.020)	(0.020)
lnCAP(-1)	0.103***	0.100***	0.102***
	(0.017)	(0.017)	(0.017)
CQSPI(-1)	-0.091***	0.133	
	(0.014)	(0.150)	
CQSPI(-1)*lnCAP(-1)		-0.014	-0.006***
		(0.009)	(0.001)
SCHOOL	0.050***	0.049***	0.050***
	(0.008)	(0.008)	(0.008)
IND	0.766***	0.788***	0.778***
	(0.115)	(0.116)	(0.116)
SER	-0.558***	-0.523***	-0.543***
	(0.156)	(0.157)	(0.156)
TRA	4.638***	4.472***	4.568***
	(0.610)	(0.620)	(0.610)
POLITY2	-0.003***	-0.003***	-0.003***
	(0.001)	(0.001)	(0.001)
Africa	0.690*	0.677*	0.684*
	(0.355)	(0.354)	(0.354)
East Asia	0.058	0.046	0.052
	(0.396)	(0.395)	(0.395)
Europe and Central Asia	0.206	0.192	0.198
	(0.550)	(0.549)	(0.549)
Latin America&	0.254	0.244	0.249
Caribbean	(0.347)	(0.347)	(0.347)
Middle East and North	0.167	0.156	0.161
Africa	(0.408)	(0.408)	(0.408)
Year effect	Yes	Yes	Yes
Constant	-6.020***	-5.973***	-5.998***
	(0.418)	(0.419)	(0.418)
Observations	2089	2089	2089
Number of Groups	56	56	56

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$;

Table 15. Regional difference, Carbon intensity

	(1)	(2)	(3)
ln(GDPL)(-1)	-1.348***	-1.410***	-1.354***
	(0.092)	(0.092)	(0.092)
ln(GDPL)(-1)sq	-0.140***	-0.148***	-0.141***
	(0.009)	(0.009)	(0.009)
lnCAP(-1)	0.268***	0.258***	0.267***
	(0.023)	(0.023)	(0.023)
CQSPI(-1)	-0.040***	0.872***	
	(0.019)	(0.195)	
CQSPI(-1)*lnCAP(-1)		-0.057***	-0.003***
		(0.012)	(0.001)
AGR	-0.791***	-0.615	-0.782***
	(0.392)	(0.392)	(0.392)
IND	0.706***	0.832***	0.731***
	(0.154)	(0.155)	(0.154)
SER	0.896***	1.054***	0.915***
	(0.201)	(0.203)	(0.201)
TRA	-5.254***	-5.820***	-5.286***
	(0.793)	(0.798)	(0.793)
POLITY2	0.000	-0.001	0.000
	(0.001)	(0.001)	(0.001)
SCHOOL	-0.047***	-0.049***	-0.047***
	(0.011)	(0.010)	(0.011)
Africa	0.421	0.365	0.414
	(0.403)	(0.401)	(0.401)
East Asia	0.802*	0.743*	0.795*
	(0.449)	(0.447)	(0.447)
Europe and Central Asia	1.444***	1.369***	1.428***
	(0.624)	(0.622)	(0.622)
Latin America&	0.807***	0.759*	0.795***
Caribbean	(0.394)	(0.392)	(0.393)
Middle East and North	1.262***	1.210***	1.252***
Africa	(0.463)	(0.461)	(0.461)
Year effect	Yes	Yes	Yes
Constant	-6.156***	-6.187***	-6.156***
	(0.554)	(0.551)	(0.553)
Observations	2089	2089	2089
Number of Groups	56	56	56

Note: Robust standard errors in parentheses, * $p < 0.1$, *** $p < 0.05$;

The Diffusion of Renewable Energy Technologies:

R&D, Learning and Cross-country Spillovers

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Abstract

This paper focuses on the relationship between international knowledge spillovers and the diffusion of renewable energy technologies. I model the investment activities of 18 OECD countries in wind and solar photovoltaic (PV) technologies throughout the 1990-2006 period. In addition to cross-country spillovers from R&D, I consider international spillovers from experience, i.e. international learning spillovers, and domestic learning effects. I focus on the experience that is accumulated in the installation and operation of renewable energy technologies for electricity production. Three hypotheses are tested: renewable energy investments are supported by international knowledge spillovers from R&D; they are supported by domestic learning effects; they are supported by international learning spillovers. Empirical findings indicate that while IKS arising from R&D knowledge stocks are not effective in inducing wind investment, they have positive and significant effects on the increase of PV capacity. Domestic learning effects are shown to foster the diffusion of wind and PV technologies, while international learning spillovers does not play a role.

Keywords

Renewable energies, Diffusion, Learning by doing, International knowledge spillovers

1. Introduction

This paper empirically analyzes the role of learning effects and international knowledge spillovers (IKS) in the diffusion of renewable energy (RE) technologies in advanced economies.[8] It builds on a seminal study of Popp et al. (2011), which investigated the determinants of RE investment in OECD countries, and demonstrated that knowledge that was generated from world R&D activities has a small yet positive effect on the decision to increase the installed capacity of individual RE technologies. This paper attempts to make two additions to this emerging strand of research. First, similarly to the first paper it analyses the relationship between IKS and RE innovation, and more particularly it investigates the relationship between IKS and RE diffusion, by distinguishing the role of domestic R&D stocks from the role of international R&D stocks. Secondly, it brings in the framework the knowledge generated through experience or learning-by-doing (LbD), rather than by R&D activities, as a major potential input to the diffusion of RE technologies, and admits that knowledge can be sourced from international and domestic experience. In other words, the paper is intended to answer three specific questions: whether IKS from R&D activities have a significant effect on RE investment; whether experience that countries have cumulated through capacity installations has a significant effect on their investment in RE facilities (i.e. whether countries learn from the deployment and diffusion experience they have cumulated); whether IKS from experience (i.e. international learning spillovers) have a significant effect on RE investment (i.e. whether countries learn from the deployment and diffusion experience cumulated by other countries). The analysis has been conducted on solar photovoltaic (PV) and wind (W) investment.

Three arguments motivate my interest in domestic learning effects and international learning spillovers as potential determinants of RE diffusion. First, in order to overcome market, cost and infrastructure barriers that hinder the deployment and diffusion of new climate-friendly technologies, a repeated use of the technology (i.e. experience or learning-by-doing, LbD) is necessary. LbD can speed up and improve the efficiency of deployment activities, i.e. early trials to introduce a new

[8] Clarke et al. (2008) define IKS as technological change that arises from innovation activities of other countries, as distinct from domestic R&D, domestic learning-by-doing, domestic intra- and inter-industry spillovers. Again according to Clarke et al. (2008), technological change is a modification of current technologies, i.e. of devices and methods that are currently used to transform resources and to produce services, and technological knowledge, or knowledge, refers to ideas, methods, know-how, and experience that support technological change.

energy technology (Sagar and van der Zwaan, 2006; Clarke et al., 2008). In other words, aside from knowledge generated from R&D activities, countries that are willing to spread new climate-friendly technologies also need the "practical" knowledge that arise from the accumulation of production and installation experience. Knowledge from experience encompasses a broad set of intangible resources: technical know-how, operating competences, management skills, commercial abilities. More particularly, LbD is experienced not only by technology suppliers and research centers, but also by installers and customers, if knowledge flows between different players are not hindered by transaction costs (Taylor, 2008). Second, some of the benefits obtained from experience in production, installation, or operation may not be fully appropriable by those who have produced, installed, or operated the technology. In principle, spillovers from experience, both domestic within-firm and intra-industry spillovers and international learning spillovers, could be even greater than spillovers from R&D, because "in contrast to laboratory and R&D settings, new technologies in real commercial use cannot be hidden from competitors firms" (Nemet, 2012b). Finally, should spillovers from experience in RE sectors have an international scope, i.e. should IKS from experience determine RE diffusion, it could be concluded that laggard countries can converge rapidly towards RE production and installation targets that were introduced by climate policies. There are huge cross-country differences in the diffusion of RE technologies, even between advanced countries (IPCC, 2011; see also Section 3). As a result there are also huge gaps in installation and operating experience, which need to be filled if RE shares have to increase. However, knowledge from experience can be even more tacit than knowledge from R&D, and the most tacit elements of technological knowledge cannot be acquired via market transactions (e.g. cross-country technology licensing or technical reports may be necessary but they are not sufficient because they channel only codified pieces of knowledge). IKS from experience could potentially fill the cross-country gap in experience, but their effectiveness depends on the channel through which experience is transmitted across countries. Since knowledge from experience is tacit it cannot be transmitted "in the void", and cross-country connections are likely to be necessary. Whether they are sufficient is an open question.

I thus concluded that domestic learning effects and IKS from learning and not only from R&D can be a key input to the diffusion of RE technologies. In this respect, my key research question is whether countries can learn only from domestic experience, or instead whether knowledge born from experience can spill across countries. In order to represent the diffusion of a specific RE technology, I use the increase of installed capacity per capita, while I use installed capacities to represent domestic experience stocks, again for each RE technology (Nemet, 2012b). Regarding international learning spillovers (i.e. IKS from experience), the indicator is constructed as the weighted sum of capacities installed in “donor” countries; weights are cross-country interactions, proxied by trade intensity as in the first paper. In order to disentangle the role of embodied spillovers, capital good imports are used as a control variable.

The paper is organized as follows. The next section reviews the literature on determinants of RE diffusion, international knowledge spillovers and learning spillovers, and it formulates the research hypotheses. The sample, variables and the econometric method are illustrated in Section 3, while the empirical results are discussed in Section 4.

2. Survey of empirical literature and research hypotheses

This Section reviews the literature results on the determinants of RE diffusion, i.e. climate-energy policies, other social, economic and institutional factors, learning-by-doing and knowledge spillovers.

The literature that investigates the determinants of RE diffusion seems to consider public climate-energy policies as the most relevant factors, as private firms do not have the incentive to adopt more costly technologies that reduce emissions but do not bring additional cost savings or revenues to the firms (Gan et al., 2007; Popp, 2010). Focusing on the USA, Menz and Vachon (2006) analyzes the contribution of several state-level policies (renewable portfolio standards or RPS, fuel generation disclosure rules, mandatory green power options and public benefits funds) to the diffusion of wind power.[9] The time period covered by the analysis is since 1998 to the end of 2003, a period during which many states began restructuring their electricity markets and adopted policies to promote wind power and other forms of green electricity. They find a positive relationship between RPS and wind power diffusion. Similarly, focusing on the USA, Yin and Powers (2010) investigate the impacts of RPS on in-state RE investment using panel data. They define the dependent variable as the non-hydro RE percentage of generation capacity in the state. They construct a new measure of RPS stringency, which allows for the heterogeneity in RPS design that has been ignored in previous

[9] RPS is a policy that ensures a minimum amount of renewable energy is included in the portfolio of power generation resources serving a state.

econometric analyses. In addition to the RPS policy variable, other four policy instruments are included as controls. The results indicate that RPS policies have positive effects on in-state RE investment. Popp et al. (2011) examine various factors behind investments in wind, solar photovoltaic, geothermal and electricity from biomass and waste across 26 OECD countries from 1991 to 2004. The Kyoto Protocol ratification, which is a signal of strong policy commitment to reduce carbon emissions, has a positive and significant impact for wind and biomass and waste, whereas its impact becomes insignificant for wind when controlling for the country effects. Moreover, when replacing the Kyoto dummy with various policy variables, e.g. feed-in tariffs or renewable energy certificates, these individual policy variables are never significant.[10]

A wider body of empirical studies focuses on the diffusion or the adoption of environmental technologies, other than RE technologies, arguing that the choice to adopt environmental technology is driven by regulatory pressures (Gray and Shadbegian, 1998; Kerr and Newell, 2003; Snyder et al., 2003). For instance, there is evidence that the phasedown of lead in gasoline by U.S. petroleum refineries during the 1970s and 1980s was the first major success in implementing a market-based environmental policy (Kerr and Newell, 2003). Among the most recent examples of this literature, Frey (2013) focuses on scrubbers, a highly effective SO_2 abatement technology, and examines the effect of environmental regulation on the adoption of scrubbers by coal-fired power plants, using a survival analysis. He found that electric generating units that face more stringent state regulations are more likely to install soon a scrubber.

The diffusion of RE technologies also depends on socio-economic, technological and institutional factors, other than regulation (Marques et al., 2010). From the point of view of a country, the deployment and diffusion of RE technologies can be driven not only by climate change concerns, but also by the increasingly serious energy security concerns arising from the finity of fossil fuel sources. Or, from the point of view of customers, the deployment of RE technologies depends largely on motivation intrinsic to the public and eventually on the change of values towards the appreciation of

[10] This result suggests that the diffusion responses to a policy may be different from the R&D responses to the same policy. Johnstone et al. (2010) show that RE policies lead to increased innovation in RE technologies in 25 OECD countries and these effects vary by technology. Particularly, feed-in tariff is an effective way to induce innovation in more costly technologies, such as solar technologies and tradable certificates are more likely to induce innovation on technologies that are more likely to be competitive with fossil fuels, such as wind technologies.

the environment. In this respect, Popp et al. (2011) found that countries with large hydropower and nuclear power installed capacity are less likely to invest in RE technologies. These technologies substitute for RE technologies in environmental and energy security perspectives. They also tested the effects of world technological advances, as represented by the world stock of patents in relevant technological classes, on investment, and found a small positive effect.

In spite of the fact that the effect of international learning spillovers on RE diffusion has not yet been the subject of a wide empirical research (to the best of my knowledge), it is worth mentioning that the first stream of quantitative studies on the diffusion of wind energy relied almost exclusively on the so called learning curve analysis, but only domestic learning was considered, while IKS from experience were neglected. The basic idea is that the unitary costs of wind technology decrease with the increase of the wind market share, due exactly to LbD. However, later studies point out the endogeneity problem when estimating learning curves, arguing that innovation (i.e. cost reduction in their analysis) and diffusion are simultaneously determined and should not be analyzed in isolation (Soderholm and Sundqvist, 2007). In order to address this concern, Soderholm and Klaassen (2007) propose a simultaneous model of wind power innovation and diffusion, applying these models to four European countries (Denmark, Germany, Spain and the United Kingdom) over the period 1986-2000. In the diffusion equation, the dependent variable is the chosen level of total installed wind power capacity. Among the diffusion regressors, they include: the feed-in price for electricity generated by wind, the coal price in the power sector, the real engineering unit cost (per kW) of installing a windmill, i.e. all investment cost items, such as grid connection, foundations, and the cost of the turbine, and public R&D budget as a proxy of the government's attitude towards wind power. The results indicate that the reduction in unitary investment costs is explained by LbD on existing plants, and leads to a large penetration of wind energy in these countries, which in turn supports a further reduction of technology costs.

Some studies have tried to examine the role of domestic learning spillovers in industries other than RE. Notable examples are Thornton and Thopson (2001) and Kellogg (2011). Thornton and Thopson (2001) studied learning spillovers by exploiting a dataset of 4560 shipbuilding cases from 25 different yards in World War II. They analyzed the effects of experience measured by the cumulative hours worked on the labour requirement for each ship produced. They found that learning spillovers were a significant source of productivity growth, but the size of learning externalities across yards is small.

Kellogg (2011) examined the effects of learning-by-doing on drilling productivity in the oil and gas industry. He measured drilling industry's overall experience, producer experience, experience from a specific rig and the joint experience of a specific rig and a specific producer. He found that the productivity of an oil production company and its drilling contractor increases with their joint experience.

However these studies did not model learning spillovers as a source of knowledge and competences for RE diffusion. In the realm of RE technologies, Nemet (2012b) addressed the question of whether firms learn from the experience of other firms and countries in the wind energy technology sector. The effect of learning from within-firm experience is found to be larger than the effect of learning from external sources. Specifically, he analyzed the operating performance of a sample of California wind power plants (312 projects, 44 quarters, 1985-1995). The paper focuses on the effect of learning and learning spillovers on firm operating performances rather than on wind technology diffusion. Nonetheless the main result, i.e. learning is a major determinant of wind technology operation, is relevant to my purposes. Since the decision to invest in a new technology leans on expectations of its operating success, it can be argued that learning will also have an indirect yet positive impact on the diffusion of wind technology (i.e. the choice to invest in wind capacity). The unit of analysis is the "project", which corresponds to a group of wind turbines of the same type installed at a single location. Ownership of each project can change over the course of the study period. He used electricity produced by each project measured to measure performance, as the amount of electricity a wind turbine can produce depends on various activities made at the time of installation (i.e. equipment purchase, site selection and operations), and LbD potentially plays a role in each of them. When identifying the role of experience in improving the choices made at the time of installation, two types of experience are used: the depreciated cumulative electricity production at the time of installation for each firm, as well as for each state, to represent operating experience, and the depreciated cumulative number of turbines installed at the time of installation for each firm and each state to represent installation experience. The dependent variable is the quarterly electricity production at time of installation. The results provide evidence of LbD, albeit with diminishing returns, and it appears that experience in installing turbines is a significant predictor of initial performance, but experience in generating electricity is not. The results also provide evidence of knowledge spillovers from external experience. But, due to collinearity problems, spillover estimates are not conclusive on the nature of learning spillovers, whether they are cross-country or inter-firm.

My research propositions are:

(1) IKS from R&D activities have positive effects on RE investment (international R&D spillovers).

(2a) Domestic experience has positive effects on RE investment (LbD effects).

(2b) IKS from experience have positive effects on RE investment (international learning spillovers).

3. Sample, variables, and econometric model

My analysis of RE diffusion relies upon the country-level series of installed capacity in wind and solar PV power generation technologies, measured in electrical megawatts per inhabitant, as in Popp et al. (2011). The data source is the International Energy Agency, Renewables Information (online access). The sample includes 18 industrialized countries over the 1990-2006 period: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States.

Two renewable technologies - wind and solar PV - are indexed by j. I define the dependent variable as the net investment per capita in capacity of renewable energy j installed in country i at time t, $INVEST_{i,j,t}$. The model allows for potential country-fixed, α_i, and year-fixed, δ_t, effects:

$$INVEST_{i,j,t} = \beta_1 DOM_{i,j,t-1} + \beta_2 IKS_{i,j,t-1} + \beta_3 HYDR_{i,t-1} + \beta_4 NUCL_{i,t-1} + \beta_5 ELCG_{i,t-1}$$
$$+ \beta_6 EIMP_{i,t-1} + \beta_7 CIMP_{i,t-1} + \beta_8 FIT_{i,j,t} + \beta_8 REC_{i,t} + \beta_8 OB_{i,j,t} + \alpha_i + \delta_t + \varepsilon_{i.t}$$

Since my first proposition is aimed at testing the effects of IKS from R&D, in addition to domestic R&D stocks, explanatory variables of a first specification of the model include a measure of IKS from international R&D stocks. $DOM_{i,j,t-1}$ is specified as $DOMRD_{i,j,t-1}$, i.e. the domestic R&D stocks for technology j, while $IKS_{i,j,t-1}$, i.e. the global knowledge stocks, are represented as the international R&D stocks for each technology j weighted by mutual trade flows, $CNTRD_{i,j,t-1}$. These stock variables are constructed in the same way as in Garrone et al. (2011; see the first paper.

The first part of my second proposition, Proposition 2.a, is addressed through a test of LbD effects, i.e. an analysis of the role of experience arising from installed capacity stocks. The model is then specified in a different way. $DOM_{i,j,t-1}$ is specified as $DOMI_{i,j,t-1}$, i.e. the domestic installed capacity for technology j. The second part of my second proposition, Proposition 2.b, is addressed through a test of IKS from experience. The variable $CNTI_{i,j,t-1}$ represents the weighted sum of technology j capacity that was installed in other advanced countries, with bilateral trade flows as weights (similarly to Garrone et al. 2011).

Other variables are the same in the two main model specifications. In order to control for the country income, I include GDP per capita, $GDPC_{i,t}$. I also use population, $POP_{i,t}$, to control for the size effect. The need for new installed electricity generating capacity will be greater when the demand for electricity is growing, therefore I use the growth rate of electricity consumption, $ELCG_{i, t-1}$ to capture expectations about future demand. The variable is lagged one year to avoid endogeneity concerns. Moreover, it is assumed that a country has greater incentives to invest in RE technologies if it relies more on energy imports from other countries or it relies less on other carbon-free sources, such as hydroelectric and nuclear power. $HYDR_{i,t-1}$ and $NUCL_{i,t-1}$ are percentages of electricity supplied by hydropower and nuclear power, and they are lagged one year. I also include the percentage of energy imports as total energy use to control for the energy dependency, $EIMP_{i,t-1.}$ The ratio between the import of capital goods from the world and the GDP of the focal country, i.e., $CIMP_{i, t-1}$, is a control of the impact of spillovers that are embodied in capital goods imports, in order to reduce the risk of biased estimates for disembodied spillovers. Finally, I include a vector of policy variables. $FIT_{i,j,t}$ represents feed-in tariffs (euro/kWh) in country i for technology j in year t. $REC_{i,,t}$ represents RE certificates, and it is the share (percentage) of RE electricity that should be certified. $OB_{i,j,t}$ is a binary variable, and is equal to 1 in year t in country i, if there exists obligation for technology j (e.g., portfolio standards, or quota systems). The main reference source for these variables is IEA (2004). I have resorted to IEA Policies and Measures Database (2010b) for more recent years.

Tables 1 and 2 report descriptive statistics for, respectively, wind and solar PV variables.

Figure 1 shows the development of wind power capacity over time. Spain and the United States have since 1990 experienced a consistent increase in wind power capacity. From 1994, Germany wind power capacity exceeded Danish capacity. After 1999 Germany experienced a soar in the capacity investment and Germany is today the largest producer of wind electricity worldwide. Also due to a size effect, the corresponding development in the Denmark was much more modest during the studied period. Figure 2 shows the development of solar PV power capacity over time. The United States has experienced a consistent increase on solar PV power capacity, and the capacity developments in Germany and Japan have been significant as well. From 2002, Germany capacity exceeded American capacity, and Germany is today the largest solar PV installer and producer.

Table 1. Descriptive statistics for wind

Variable	Obs.	Mean	St.Dev.	Min	Max
INVEST	277	6.31	13.77	-0.59	118.55
DOMRD	277	107.83	164.66	3	749
CNTRD	277	29.01	23.18	3.15	102.17
DOMI	277	1067.40	2744.09	0	20622
CNTI	277	327.29	481.59	3.37	2557.66
HYDR	277	25.07	27.68	0	100
NUCL	277	21.83	21.84	0	79
EIMP	277	-6.21	176.43	-842	86
ELCG	277	0.02	0.02	-0.05	0.08
CIMP	277	0.09	0.04	0.01	0.21
FIT	277	54.43	91.01	0	450
REC	277	0.38	1.55	0	12.6
OB	277	0.32	0.47	0	1
GDPC	277	2.41	0.74	0.91	4.06
POP	277	47244.35	65816.01	4261.73	298379.9

Table 2. Descriptive statistics for solar PV

Variable	Obs.	Mean	St.Dev.	Min	Max
INVEST	278	0.26	1.19	0	16.06
DOMRD	278	442.79	856.39	4	4154
CNTRD	278	88.99	70.22	13.12	287.05
DOMI	278	66.79	260.57	0	2831
CNTI	278	14.54	31.21	0	263
HYDR	278	25.33	27.98	0	100
NUCL	278	21.76	21.84	0	79
EIMP	278	-8.68	180.87	-842	86
ELCG	278	0.02	0.02	-0.05	0.08
CIMP	278	0.09	0.04	0.01	0.21
FIT	278	94.82	159.83	0	545
REC	278	0.38	1.55	0	12.6
OB	278	0.29	0.46	0	1
GDPC	278	2.41	0.74	0.91	4.12
POP	278	47091.17	65746.73	4261.73	298379.9

Figure 1. Installed wind power capacity (MWe)

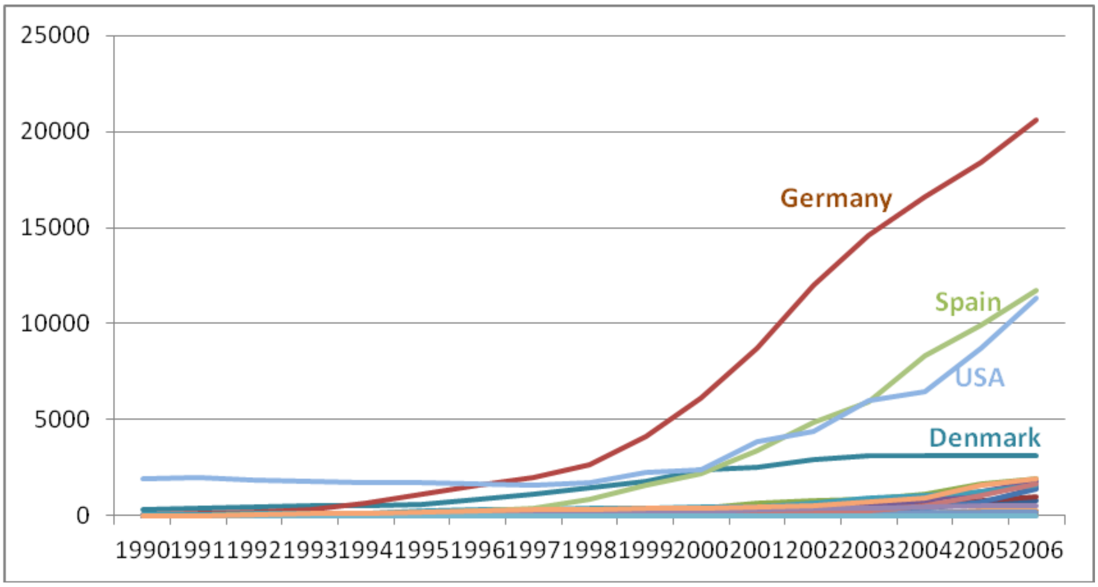
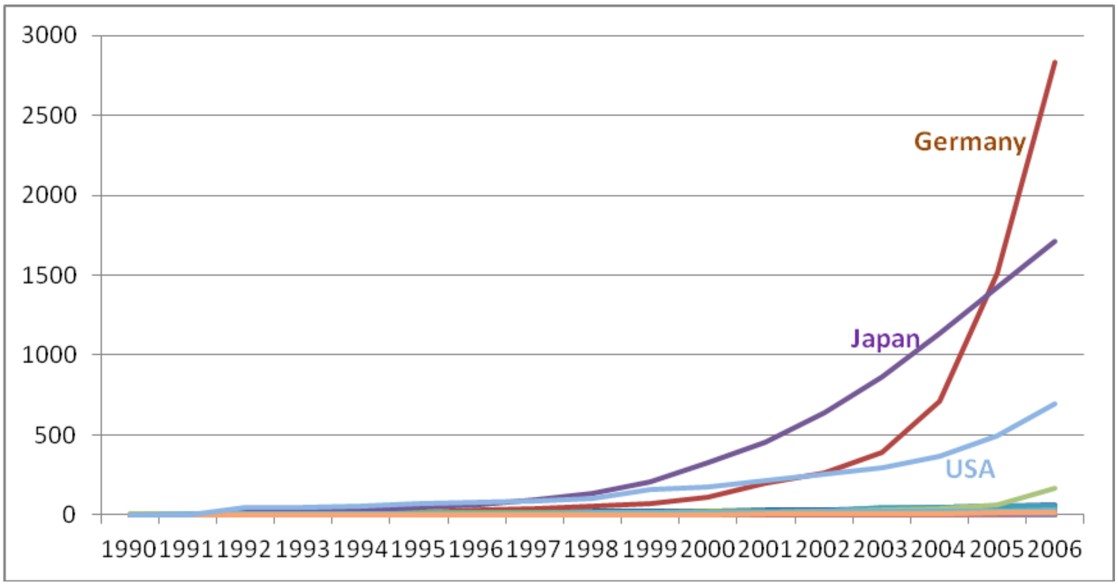


Figure 2. Installed solar PV capacity (MWe)



4. Econometric results

This section discusses the model estimates. Similarly to Popp et al. (2011) I corrected potential country-specific autocorrelation and heteroskedasticity of standard errors by using a Generalized Least Squares estimator (i.e. xtgls command in Stata).

Table 3 and Table 4 show the econometric findings that are related to Proposition 1, i.e. estimates of the effects of IKS from R&D activities on investment in wind and solar PV technologies. The only difference between regression (1) and regression (2) in Table 3 (and in the following tables as well) is that regression (2) does not include the variable POP; it acts as a robustness check, because correlation between POP and DOMRD is equal to 0.87 and 0.94 respectively for wind and solar PV datasets.

Coefficients reported by Table 3 allows to conclude that domestic R&D stocks have positive and significant effects (5% significance level of the lagged DOMRD coefficient) on wind energy technology investment, yet IKS do not. By contrast, the effect of domestic R&D knowledge stocks on solar PV investment is found not to be robust, because it loses any significance when the variable POP is included (Table 4). It is likely that the high correlation between population and domestic R&D stocks renders it difficult to distinguish their effects in the model of solar PV diffusion. By contrast, the effects of IKS from R&D stocks (CNTRD variable) are shown to be positive at a 1% significance level in model estimates for solar PV diffusion (Table 4), while the diffusion of wind technology is not impacted by IKS from R&D (Table 3). Proposition 1 is thus accepted as far as solar PV is concerned, while it should be rejected when wind technologies are considered. International R&D activities were demonstrated by Garrone et al. (2011) to spill over to domestic RE innovation. When RE diffusion rather than development is under the lens, knowledge cumulated through R&D is instead found not to have a homogenous impact across different RE sources.

Table 5 shows the effects of domestic experience and IKS from experience on wind energy technology investment. Similar results for solar PV technologies are reported by Table 6.

Tables 5 and 6 show that domestic LbD (DOMI variable) have positive effects on the diffusion of both wind and solar PV technologies at respectively 5% significance level and 1% significance level. Proposition 2a is thus to be accepted. By contrast, CNTI, the variable that is deemed to capture international learning spillovers, is never found to play a significant role in the diffusion of wind or solar PV technologies. Proposition 2b should be rejected. My results confirm the relevance of domestic leaning effects, similarly to what Nemet (2012b) demonstrated for the performances of Californian wind plants. Learning spillovers however seem to have a domestic nature. Their international scope is not significant.

As far as the wind model is concerned (Tables 3 and 5), some other explanatory variables are significant as expected. I focus here on robust empirical evidence. Consistent with Popp et al. 2011, the availability of clean substitutes (NUCL and HYDR) is correlated with lower wind investment; hydropower particulary is found to be a substitutive source in a robust way. Regarding individual policies, only obligations for the installation of wind technologies is found to have a positive and significant impact. By contrast, the effect of electricity consumptions growth is not significant, suggesting that the wind investment is not driven by future electricity demand, but rather by policy.

On average, estimates of the solar PV model seem to be weaker (Tables 4 and 6)

Table 3. Diffusion model for wind technologies (GLS estimates): the role of IKS from R&D activities (Proposition 1)

	(1)	(2)
L.DOMRD	13.188**	10.328**
	(5.307)	(4.546)
L.CNTRD	3.606	-0.277
	(6.846)	(5.747)
L.HYDR	-14.087***	-13.703**
	(5.439)	(5.438)
L.NUCL	-15.491**	-15.589**
	(7.448)	(7.463)
L.EIMP	-0.177	-0.130
	(0.280)	(0.277)
L.ELCG	-0.319	-0.275
	(0.779)	(0.780)
L.CIMP	-3.590	-2.213
	(5.930)	(5.792)
FIT	0.873	0.962
	(0.674)	(0.670)
REC	-0.110	-0.138
	(0.214)	(0.213)
OB	1.701***	1.754***
	(0.658)	(0.657)
POP	-14.644	
	(14.098)	
GDPC	-19.863	-24.378
	(22.991)	(22.622)
Country effect	yes	yes
Year effect	yes	yes
Constant	38.959*	36.842*
	(21.358)	(21.305)
Observations	262	262

Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; Dependent variable is the per capita investment in wind installed capacity; independent variables have been divided by their mean.

Table 4. Diffusion model for solar PV technologies (GLS estimates): the role of IKS from R&D activities (Proposition 1)

	(1)	**(2)**
L.DOMRD	0.675	0.918*
	(0.724)	(0.480)
L.CNTRD	2.950***	2.967***
	(0.632)	(0.631)
L.HYDR	0.876	0.863
	(0.538)	(0.537)
L.NUCL	-0.888	-0.901
	(0.711)	(0.710)
L.EIMP	0.030	0.032
	(0.027)	(0.026)
L.ELCG	-0.083	-0.081
	(0.076)	(0.076)
L.CIMP	1.286**	1.318**
	(0.597)	(0.593)
SFIT	-0.057	-0.052
	(0.067)	(0.066)
SREC	-0.001	0.000
	(0.021)	(0.021)
SOB	-0.029	-0.032
	(0.059)	(0.059)
POP	-0.826	
	(1.845)	
GDPC	-7.234***	-7.067***
	(2.427)	(2.399)
Country effect	yes	yes
Year effect	yes	yes
Constant	6.616**	5.939**
	(2.809)	(2.367)
Observations	260	260

Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; Dependent variable is the per capita investment in wind installed capacity; independent variables have been divided by their mean.

Table 5. Diffusion model for wind technologies (GLS estimates): the role of LbD (Proposition 2a) and international learning spillovers (Proposition 2b)

	(1)	**(2)**
L.DOMI	1.248**	1.212**
	(0.493)	(0.486)
L.CNTI	-0.511	-0.681
	(1.275)	(1.212)
L.HYDR	-12.974**	-12.772**
	(5.428)	(5.410)
L.NUCL	-10.610	-10.655
	(7.527)	(7.529)
L.EIMP	-0.277	-0.246
	(0.282)	(0.273)
L.ELCG	-0.353	-0.336
	(0.779)	(0.778)
L.CIMP	-5.777	-5.131
	(6.094)	(5.906)
FIT	0.859	0.865
	(0.673)	(0.673)
REC	-0.164	-0.166
	(0.218)	(0.218)
OB	1.647**	1.670**
	(0.659)	(0.657)
POP	-4.986	
	(11.653)	
GDPC	-10.178	-14.006
	(24.303)	(22.604)
Country effect	yes	yes
Year effect	yes	yes
Constant	30.870	31.932
	(22.414)	(22.284)
Observations	262	262

Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; Dependent variable is the per capita investment in wind installed capacity; independent variables have been divided by their mean.

Table 6. Diffusion model for solar PV technologies (GLS estimates): the role of LbD (Proposition 2a) and international learning spillovers (Proposition 2b)

	(1)	**(2)**
L.DOMI	0.408***	0.394***
	(0.024)	(0.024)
L.CNTI	0.003	0.003
	(0.003)	(0.003)
L.HYDR	-0.143	-0.063
	(0.385)	(0.391)
L.NUCL	-0.844*	-0.837
	(0.504)	(0.513)
L.EIMP	0.013	0.028
	(0.019)	(0.019)
L.ELCG	-0.020	-0.016
	(0.054)	(0.055)
L.CIMP	0.317	0.600
	(0.428)	(0.425)
FIT	0.107**	0.110**
	(0.046)	(0.046)
REC	0.015	0.010
	(0.015)	(0.015)
OB	-0.136***	-0.120***
	(0.041)	(0.042)
POP	-2.290***	
	(0.763)	
GDPC	-1.833	-3.218**
	(1.643)	(1.604)
Country effect	yes	yes
Year effect	yes	yes
Constant	2.051	1.843
	(1.527)	(1.552)
Observations	260	260

Standard errors in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; Dependent variable is the per capita investment in wind installed capacity; independent variables have been divided by their mean.

5. Discussion of results and further developments

This paper empirically modelled the relationship between R&D activities, learning and cross-country spillovers, on the one hand, and RE diffusion in advance countries, on the other hand. While in some respects my findings should be regarded as preliminary and need further refinements, two main results are worth being discussed.

First, learning-by-doing is a primary source of knowledge when investment in RE technologies is decided. The experience cumulated by a country through previous installations and cumulated operation of wind or solar PV plants makes new investments in wind or solar PV technology more likely to occur. Knowledge from domestic R&D is slightly less significant or relatively less robust as a diffusion determinant. This set of findings confirms the role of learning-by-doing that was demonstrated by the simultaneous model of wind power innovation and diffusion of Soderholm and Klaassen (2007), and more recently by Nemet's micro-econometric analysis of wind plant performances (Nemet 2012b).

Second, cross-country knowledge spillovers are relevant not only to explain the production of new RE technologies (paper 1), but also to explain the diffusion of such technologies. However, this conclusion should be qualified in two respects. Knowledge was found to spill to other countries when it is generated from R&D, while learning-by-doing knowledge spreads only to other domestic players. This result seems to be in continuity with Nemet (2012b), who found that within-firm experience was by far more relevant that experience of external sources. In addition, it should be underlined that the occurrence of international knowledge spillovers from R&D is uneven over technologies; for instance, IKS from R&D were found to have a role in solar PV technologies, but not in wind technologies. Popp et al. (2011) found that the world patent stock drives the diffusion of all individual RE technologies, but since he did not distinguishes domestic from international knowledge, my and their result are not necessarily at odds.

At least two policy recommendations arise from my results, particularly if they will be confirmed by further analyses. First, the main implication of my first paper is strengthened. International coordination in R&D programs is necessary to support the cross-country transmission of R&D knowledge and to avoid free-riding conducts (e.g. the public good trap). Second, since learning-by-doing was found to enable the diffusion of RE technologies, public policies should be targeted to favor the early deployment of a RE technology, all the more because knowledge from experience cannot spill from other countries. This reflection is in line with Taylor (2008) who pointed out that in addition to demand-pull (e.g. quota obligations or feed-in-tariff)) and technology-push (e.g. technology standards or R&D grants) measures, "interface" policies, such as demonstration initiatives ot training programs for installers, are warranted, in order to overcome cost, infrastructure and technology barriers that impede the technology take-off.

Results presented by this paper should be regarded as preliminary. Further empirical refinemens are likely to be necessary in order to reach a greater confidence on the empirical evidence discussed so far. First, it is dubious whether the whole installed capacity of solar PV can represent the usable experience in this technology. Solar PV technology was designed and produced in radically different ways over time, and a discounted sum of capital additions (e.g. perpetual inventory method, paper 1) is likely to take into account the obsolescence issue better than the simple installed capacity. Second, diminishing returns are deemed to represent the diffusion dynamics of a new technology (e.g. Nemet 2012b). At the same time a greater flexibility of econometric model (e.g. the introduction of squared terms and cross-terms) could cause multi-collinearity issues to occur. A modeling strategy that trade-off the need for a more flexible functional form against the multi-collinearity risk should then be devised. Finally the extension of dataset to more recent years and to other RE technologies can confer a greater robustness to my empirical evidence.

Conclusions

I can summarize the results of my thesis by arguing that major cross-country knowledge flows occur in the domain of new climate-friendly technologies. Here it is worth recalling that I assumed that relevant parts of technological knowledge in renewable energy (RE) and energy-efficient (EE) technologies were tacit, and as such hardly contractible. As a result, I focused on international knowledge spillovers (IKS), rather than on knowledge sourcing through technology licensing and other market transactions. Overall the dissertation demonstrated that the international diffusion of knowledge is a major element of climate-friendly technological change.

Firstly, the thesis reveals that a consistent transmission of technological knowledge about RE technologies occurs between OECD countries. It takes different forms, and it is not homogeneous between different renewable energy sources. The production of renewable energy innovations benefit from renewable energy activities of other countries, but this effect relies upon connections between countries. In other words, outputs of R&D activities can spill over to other advanced countries but recipient countries should have established interactions and contacts with donor countries to facilitate the flow of technological knowledge. International knowledge spillovers from R&D activities also support the diffusion of selected renewable energy technologies, such as solar PV, but this impact is not homogeneous, for instance, the decision to invest in wind technology is hardly affected. Still in a North to North perspective, and by contrast, we discovered that learning spillovers are domestic in scope. Put it in another way, international knowledge spillovers from experience do not have a significant impact on the diffusion of renewable energy technologies.

Second, my thesis also sheds light on the North to South transmission of technological knowledge in climate-friendly technologies. Here, I considered knowledge flows embodied in capital goods trade, the most typical mechanism of knowledge acquisition for developing countries. A differentiated picture arose. My findings show that more energy efficient uses were adopted by developing countries, which benefitted from embodied spillovers coming from developed countries. As far as knowledge about low- and high-carbon technologies is concerned, a sharp distinction should be made between “less industrialized developing” countries and “more industrialized developing” countries. To the former, embodied international knowledge spillovers from the North means that more carbon intense technologies are used. By contrast, the latter, i.e. countries that have already installed a significant stock of capital goods, were found to benefit from embodied spillovers in terms of transition towards low carbon technologies. In other words, my results provide evidence that industrialization stages play a role in knowledge transmission patterns.

4.1 Discussion of main results

In the sample of OECD countries, domestic R&D stocks and foreign knowledge stocks are found to have a positive impact on the innovation activities. The effect of international knowledge spillovers is comparable with the effect of domestic R&D, even though it is smaller. The proved effectiveness of IKS corroborates what Verdolini and Galeotti (2011) have found, i.e. that IKS from R&D is a significant input to the production of environmental-friendly innovations, although their analysis focused only on codified knowledge as represented by patent citations. Our findings confirm that mutual connections are necessary to facilitate the spread of knowledge across countries, which is consistent with Perkins and Neumayer (2009, 2012) who found that cross-country linkages are necessary for the transmission of carbon and pollution efficiency across countries. With regard to the renewable energy technology diffusion, results indicate that countries learn from domestic experience in installations, i.e. domestic installed capacity has positive effect on the diffusion of solar PV and wind technologies. This is consistent with Nemet (2012b) who provides evidence that operating performances of California wind plants benefits from their own learning spillovers cumulated through wind installed capacities. By contrast, IKS, related to both R&D and experience, are found not to have a significant impact on the diffusion of wind technologies. Nemet (2012b) found that external learning spillovers have positive effect on the operating performance of wind plants, but he could not distinguish the nature of the spillovers, whether inter-firm spillovers or international learning spillovers. Solar PV technologies, instead, are shown to spread more intensely when IKS from R&D activities are larger.

Regarding the developing counties, spillovers embodied in capital goods trade result in an increase of CO_2 emissions in developing countries. In particular, IKS are found to significantly improve energy efficiency of the destination countries, i.e. to lower carbon emissions due to the energy saving bias of technology spillovers. This is not consistent with Hübler and Keller (2010) who don't find a negative effect of technology transfer through trade. Our results show that on the sample average IKS have positive – rather than negative - effects on carbon intensity, i.e. they lead to higher carbon emissions per energy unit. This is in contrast to Kretschmer et al. (2010) who provide evidence that international technology transfer is effective in lowering carbon intensity of recipient countries, although they focus on transfer mediated through foreign aid. Finally, as expected, IKS have positive effects on labour productivity, and through the growth effect they increase carbon emissions

One limitation of the thesis is that in the third paper, I did not take into account the depreciation of learning, i.e. knowledge cumulated through wind and solar PV installed capacities. This is a matter for further research. Moreover, I should also consider the diminishing returns of experience which is a common phenomenon of learning by doing (Nemet, 2012b).

4.2 Policy implications

As far as developing countries are concerned, the thesis offers empirical evidence on the relations between climate stabilization, productivity growth and energy efficiency. International technology sourcing from the North does lead to an improved energy efficiency, but this is not sufficient to ensure carbon emissions reduction due to a simultaneous increase of labour productivity (i.e. economic growth). It can be concluded that policies aimed to favoring international technology transfers towards developing countries in the sector of climate-friendly technology are warranted, but they do not necessarily contribute to the reduction of carbon emissions in developing countries. However, it should be emphasized that developing countries are highly differentiated in the capability to benefit from spillovers. “Less industrialized” developing countries are the most fragile economies, in particular, with respect to the goal of carbon intensity reduction (i.e. penetration of low-carbon technologies).

Regarding advanced countries and the domain of renewable energy technologies, public energy R&D expenditure is a key input to innovation in the RE field, i.e. a relevant element in global efforts towards carbon stabilization. Public support to climate-energy research should not be abandoned in favor of other measures, all the more because its effects spread beyond national borders, and help follower countries to join the energy innovation race. Policies aimed at strengthening international knowledge flows should be encouraged. International policies that favor technological cooperation between countries in climate-friendly innovation activities are warranted to reduce free-riding risks without haltering cross-country spillovers.

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