The diffusion of patented oil and gas technology with environmental uses: a forward patent citation analysis

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Abstract:
Relevant advances in the mitigation of environmental impact could be obtained by the appropriate diffusion of existing environmental technologies. In this paper, we look at the diffusion of knowledge related to environmental technologies developed within the oil and gas industry. To assess knowledge spillovers from oil and gas inventions as a measure of technology diffusion, we rely on forward patent citations methodology. Results show that there is a strong likelihood that the citing patent will be eventually linked to environmental technologies if the original oil and gas invention has already environmental uses. Moreover, both intra and intersectoral spillovers produce a "turnabout" effect, meaning that citing patents show the opposite quality level of the cited patent. Our results support the idea that more sector-specific environmental policies, with an emphasis on diffusion, would significantly improve the use of environmental technologies developed within the oil and gas industry.

Keywords: Forward patent citations; petroleum industry; technology flows; environmental and technology policies.

1 Introduction

Since its origins, the petroleum[1] industry has undoubtedly contributed to the world's economic growth, to the generation of wealth, has enhanced prosperity and has certainly pushed the standards of living in many countries. In spite of substantial penetration of renewable energies in recent years (Aguirre and Ibikunle, 2014), the sector has remained central to the energy industry. Moreover, in spite of its perennial crisis (Mitchell and Mitchell, 2014) it is expected it will maintain this role for some time into the future (IEA, 2013). For instance, the sector covers nearly all of the energy requirements for transportation in the world and supplies a vast amount of raw materials for chemical products and processes (Hughes and Rudolph, 2011). The oil shocks of the 1970s have been the sole disruptions to an otherwise always increasing production trend during the 20th and the 21st centuries. Moreover, higher demand from developing countries will keep the production trend up, according to the conservative scenario for 2035 elaborated by the International Energy Agency (IEA, 2013).

As with many other economic activities, the oil and gas industry generates externalities –unintended positive or negative consequences on other economic and social agents that are not captured by the price mechanism. In this respect, some oil and gas energy sources have important negative effects on the environment. For instance, greenhouse gas (GHG) emissions and other pollutants are produced by the combustion of fossil fuels. Oil spills and additional by-products of refining discharged in lakes, rivers and the sea account for a significant amount of water pollution (Höök and Tang, 2013). To correct these market failures, environmental

[1] The petroleum industry includes the exploration, extraction, refining, transportation and commercialization of oil and gas products. In this paper we will refer to oil and gas industry or petroleum industry.

policies are needed to balance out marginal costs and benefits of environmental protection. Technologies such as carbon capture and sequestration (CCS) and flue-gas desulfurization (FGD) to name just two of the most widely known inhibit C02 and S02 emissions respectively (Yeh and Rubin, 2012). Technology can be used to reduce the cost per unit of energy or to improve the energy requirements to carry out activities and thus is welfare improving.

According to Carraro et al (2010), by changing relative prices, environmental policies induce technical change towards so called clean technologies. These are technologies that are supposed to deliver the same amount of goods and/or services with less environmental degradation. The change in relative prices comes from the application of different policy tools that normally lie within two broad groups: market based instruments (MBI) and command and control instruments (CAC). The latter refer to measures that establish constraints on the volume of pollution each agent can generate. The former set up explicit prices for negative environmental externalities by mans of taxes, tradable pollution permits or fees, among others.

The mitigation of these negative environmental effects produced by the petroleum industry and related activities can also be tackled from the perspective of technology policy. In this case, for instance R&D subsidies for clean technologies can be designed to promote complementary private investments to develop new inventions or modifications to existing ones that alleviate the negative environmental impacts of human activities. Both environmental and technology policies are justified by the existence of two different types of externalities, a situation normally referred to as the "double externality problem" (Carraro et al., 2010).

The case for environmental policy comes from the fact that without appropriate incentives, agents will not be able to benefit from their efforts to protect the environment and this generates an above-optimal level of pollution. The externality associated to R&D and innovations policies relies on the appropriability argument, stating that once the knowledge supporting a new technology or invention is disclosed, it is available to other agents to copy it and negatively affecting the benefits to the inventor causing a sub-optimal level of R&D investment. These arguments make clear that energy and the environment are naturally linked by technology. In this respect, energy policies, environmental policies and technology policies are strategically interconnected and each one has to be designed taking the others into account to enhance their effectiveness.

By promoting the generation of novel clean technologies, environmental policy is said to induce eco-innovations (del Rio et al., 2010). There is a large literature concerned with the role of environmental policy to promote the development of new technology by means of innovation (see Jafe et al., 2002 and Carraro et al., 2020 for surveys). However, an additional approach would be to consider that relevant advances in the mitigation of environmental impact could also be obtained by the appropriate *diffusion* of existing environmental technologies (Popp et al., 2011).

Diffusion of new technology is known to be a slow process. Jaffe et al. (2002) indicate two potential factors that explain this pattern. On one hand, the expected value of the new technology will vary with the heterogeneity of potential adopters. If adopters are very different, the penetration rate of the new technology will be normally low, at least during the first stages of its development. On the other hand, the adoption of new technology implies an uncertain amount of risk. Prior to adoption, information regarding the relevant characteristics of the novel technology would have to have been diffused first. In addition, Carraro et al. (2010) argue that uncertainty also enters the slow rate of technology diffusion equation. When agents observe a rapid rate of innovation, they will expect a fast degree of technological obsolescence and hence they will be reluctant to adopt the technology. These authors also assert that there is sufficient evidence to support the notion that environmental policy is a relevant instrument to promote innovation and enhance diffusion of novel environmentally-friendly technologies. Here, we will look at the diffusion of knowledge related to environmental technologies developed within the oil and gas industry.

In this paper we focus on the diffusion of patented oil and gas technologies, with an especial focus on the environmental uses these inventions declare to have. Since the petroleum industry is responsible for an important amount of the adverse impact on the global environment, knowing to what extent technologies developed within this sector embrace environmentally friendly uses is of great importance to the design of future energy and environmental policies as well as to inform international climate change negotiations. To study knowledge diffusion from oil and gas patented inventions we rely on patent applications and citations to patents as a measure of knowledge diffusion (Jaffe et al., 1993)

The paper is organized as follows. In Section 2 we describe the data, we discuss the advantages and drawbacks of patents as measures of technology inventions and we clarify how citations can be used to track technological diffusion. We also expose the empirical methodology to be used in the analysis of forward patent citations in the oil and gas industry. The results are then presented in section 3 along with the discussion of the main findings. Finally, section 4 contains the conclusions of the research. Here, particular emphasis is put on the policy dimension.

2 Data and Methods

In this section we first describe the dataset used to analyse the diffusion of patented oil and gas technologies and we discuss some advantages and some drawbacks of patents as indicators of invention. In addition, we conduct an explanatory and descriptive analysis of the data. Finally, we explain the methodologies we use for the empirical analysis of forward citations, namely a count data model to assess citation counts (Hausman et al., 1984) and a multilevel model (Wooldridge, 2003) in order to capture the characteristics of both the citing and the cited patents.

2.1 Patents data and exploratory analysis

The objective of this paper is to analyse the diffusion of patented oil and gas technologies. Although several indicators are available for that purpose we will focus on forward patent citations to examine the extent of knowledge spillovers arising from oil and gas inventions. Citation linkages from one patent to another patent are believed to be valuable –although imperfect- mappings of knowledge flows (Hall et al., 2005).

Patent data have a number of attractive features for the analysis of the interactions between technology and the environment (Popp, 2005). For example, the technological breakdown for which patents are available is quite detailed, making them a suitable indicator for the analysis of technology invention and diffusion. Moreover, patents contain citations to previous inventions, as patent applicants are required to include references to previous patents that have been used to develop the new technology or knowledge described in the patent. Hence, they represent a form of knowledge and/or technology flow (Jaffe et al., 1993). However, there are also some issues to take into account. Not all inventions are patented, so patent citations may underestimate the real amount of knowledge spillovers. Self-citations are also a concern, since they represent internalised knowledge transfer different from true knowledge spillovers represented by citations to other inventors' patents. Finally, patent examiners add citations during the evaluation process and may introduce some bias in the measures of knowledge spillovers.

Despite these controversies and additional issues regarding quality, strategic behaviour and geographic agglomeration of knowledge, there is some consensus in the literature on the economics of innovation that patents are good indicators to proxy the output of innovation efforts (for a recent review see Hall and Harhoff, 2012). In particular, citations to previous patents signal the relevance a determined patented invention has on succeeding innovations. Citations can then be used to follow the trial of knowledge flows in several dimensions (time, technologies, geographies, institutions). Since the seminal work of Trajtenberg (1990), numerous contributions have established the validity of patent citations as a measure of technology diffusion (see Hall et al., 2005 for a survey). In particular, Jaffe et al. (2000) showed that citations are reasonable representations of knowledge flows even if they include some noise. The literature on patent analysis in the energy sector collapses to few papers (Lee and Lee, 2013). However, there is an increasing trend in using patent data to tackle energy related issues. For instance, Bointner (2014), Nemet (2012) or Johnstone et al. (2010) are recent examples.

The analysis of the diffusion of oil and gas technologies is done with data from the World Patent Statistical Database (PATSTAT). Created and secured by the European Patent Office (EPO), this database includes around 70 million patent documents from more than 100 patent offices around the world and it is the largest patent repository of the world. Other sources of patent information are the United States Patent and Trademark Office (USPTO) which includes around 11 million of patent documents and other national patent offices with much less information (Canada, Japan and more recently China). Among the multinational databases, the Derwent World Patent Index (DWPI) includes patent applications from 44 different patent offices and provides information on 45 million documents.

The identification of oil and gas patents is done with the help of the DWPI classification system (Thompson Reuters, 2010). Here, class H refers to petroleum, and contains comprehensive coverage of all aspects of the oil and gas industry. Moreover, it identifies the relevant International Patent Classification (IPC) codes to characterize the data from the PATSTAT database. The IPC is the system used to classify patents uniformly in more than 100 countries, being the standard established by the World Intellectual Property Organization (WIPO). Recently, the USPTO and the EPO developed a new classification scheme, the Cooperative Patent Classification system (CPC), which apparently better identifies the different technologies. However, it was only adopted in 2013 by the EPO, it will enter into force in the USPTO in 2015; it is the result of a bilateral (instead of multilateral) agreement and has not been embraced by any other countries except China (in 2014). Table 1 shows the number of applications, families and citations extracted from the database and referred to the petroleum industry according to the DWPI.

Table 1 around here

The same invention can be patented in several countries. To avoid double counting of citations to the same fundamental invention, we focus on patent families (the set of patents covering the same invention in several countries). This means treating multiple filings of a patent as one invention and count citations at the family level instead of at the individual patent level. In total, our dataset includes 389,607 patent applications in the period 1990-2010, representing 190,284 inventions (families). Figure 1 shows the evolution of patent applications and families as well as the R&D expenditures devoted to oil and gas in the IEA countries in the period under consideration. The figure shows a notorious increase in the number of patent applications (and families) starting in the second half of the nineties and a high correlation with oil and gas R&D expenditures. To what extent this could be the industry's response to the adoption by many countries of the Kyoto protocol is a separate research question, but certainly the data show some time coincidence.

Figure 1 around here

When filing a patent, applicants must indicate the IPC code or codes the invention is related to. IPC codes reflect technological areas as defined by the WIPO. Similarly to citations, patent examiners can add IPC codes if relevant uses are found during the evaluation process. Hence, a given patent can have many IPC codes (or uses). In order to proceed with the analysis, the original (cited) patent families were classified into two groups: i) *exclusive* patents containing only the IPC codes related to oil and gas (column 2 in table 2); ii) inclusive patents, defined as patent documents containing in addition IPC codes from other non-oil and gas uses.

Moreover, we constructed a new variable that takes the value one if the citing patent has linkages with environmental technology; in order to assess the likelihood that an original oil and gas patent can be used in the development of environmental technologies to cope with climate change and energy efficiency objectives. Here, we rely on the WIPO IPC-technology concordance table that identifies the nature of the IPC codes and maps them into technological areas –one of these being environmental technologies. The WIPO defines environmental technologies as a variety of different technologies and applications including filters, waste disposal, water cleaning, gas-flow silencers and exhaust apparatus, waste combustion or noise absorption walls, among others (Schmoch, 2008). Table 2 shows the share of exclusive and environmental families by sector. On aggregate, around 20% of the oil and gas inventions in the period 1990-2010 were for exclusive use, i.e. without linkages to sectors outside the oil and gas industry. In addition, around 8% of the cited oil and gas families have links with environmental technologies (13% in the case of the citing patents). Figure 2 shows the evolution of these trends. As can be seen, the share of patent families with exclusive use has been raising steadily, passing from 17% on average in the early 90s to an average of 35% in the last years of the period under analysis. In contrast, the share of patent families in this sector that are linked to environmental technologies has decreased from an average of 9% in the beginning of the period to less than 5% at the end.

Figure 2 around here

Table 2 around here

Once the relevant patent applications (and families) for the oil and gas industry have been identified and selected, we identify and obtain –also from PATSTAT- those patent documents that contain citations to the above-mentioned original oil and gas patents. A total of 141,554 patent families contain citations to the original oil and gas patent families identified, generating 661,482 citations overall. As before, it is possible to identify the citing patent IPC code. By doing so, we are able to determine the use of the oil and gas technology and hence we can carry out a thorough analysis of the characteristics of the citing patent. This will be the core of the multilevel econometric analysis in section 2. For now, we concentrate exclusively on the counts of citations by every original oil and gas invention registered in the period 1990-2010.

Table 3 indicates that, overall, exclusive oil and gas inventions have received on average 5.4 citations while inclusive inventions have only received 3. In addition, inventions with environmental linkages receive only 2.7 citations while inventions not related to the environment receive on average 3.5 citations. Similar patterns are observed by sector. These differences are statistically significant in all cases (at sector level and at the aggregate level).

Table 3 around here

One obvious problem with this simple comparison lies in the fact that patents filed in more recent years have had less time to be cited. This will require controlling for the fact that a potential truncation may affect the results in the econometric section. Citations reflect the direction and intensity of knowledge flows. However, citations can also reflect the inherent quality of the patent instead. In what follows, we will use two widely accepted measures of patent quality. On one hand, patent family size that reflects the different number of patent offices where the same invention has been filed. Second, we will use the grant status of the invention indicating if the patent has been granted by the patent office. It is generally accepted that a granted patent is of higher quality that a patent that has not been granted. However, there may be also quality differences among granted patents, which will be controlled for with the variable family size and, eventually, also with the number of citations. Table 4 shows information on the quality of cited and citing inventions in the oil and gas industry. In general, we observe that the family size is lower for citing than for cited patents, and that the probability that the invention is granted is higher in the case of cited inventions than for the citing patents.

Table 4 around here

2.2 Econometric analysis

We will assess the existence and relevance of knowledge spillovers from oil and gas patented technologies by means of two different methodologies. First, we will rely on citation counts to test the existence and significance of intersectoral knowledge spillovers. Second, we will use the characteristics of the citing patents to add more information on the patterns of knowledge diffusion derived from the oil and gas patented technologies. As we already mentioned in previous sections, one fundamental objective will be to analyse the links these patent families have with environmental technologies.

2.2.1 Citation counts

In this sub-section we estimate a simple count data model of the type

$$C_i = exp(\beta E_i + \gamma X_i) + \epsilon_i \quad (1)$$

where C_i refers to the quantity of citations made to patent i, E_i is a dichotomous variable that indicates if patent i is exclusive -or has environmental uses- or not, the vector X_i includes a set of variables to control for observed characteristics and ϵ_i is the error term. As explained in the previous section, our dataset includes all oil and gas patent families filed in the period 1990-2010. Here, β is the main coefficient of interest, capturing the difference –all other things equal- between the number of citations received by exclusive and inclusive patents, or between those with environmental applications and those without. The count data nature of the dependent variable C_i, suggests estimating equation 1 by poisson pseudo-maximum likelihood (Hausman et al., 1984; Santos-Silva and Tenreyro, 2011).

In order to clean the estimates from as many potential confounding factors as possible, we include a number of control variables in X_i. First, differences in patent office practices across time and technological areas may produce artificial differences in citations intensities. We therefore include a full range of patent office and sector fixed effects. Second, the mean count of citations received and made evolve over time. Specifically, there is a problem related to those patents filed in recent years since the time they have been exposed to citations is considerably shorter than for patents filed in the early years of our sample. Hence, a full collection of time effects (filing year) is also included. Finally, we also control for the type of applicant (individual, company, government, university) by including type of applicant fixed effects since their patenting strategies could also differ. This allows us to effectively compare exclusive and/or environmentally related oil and gas patents filed for instance in the EPO in 2000 with inclusive patents -or patents not related to environmental technologies- filed at the EPO the same year.

As we discussed in the previous section, citations can also reflect the intrinsic quality of the patent instead of knowledge flows. To control for this issue we include two widely accepted measures of patent quality. First, we use the patent family size reflecting the number of different patent offices where the same invention has been filed. Second, we use the grant status of the invention indicating if the patent has been granted by the patent office.

2.2.2 Multilevel analysis

To complement the analysis described in the previous sub-section, we identify the main characteristics of the citing patent to control for the observed characteristics of the technology using oil and gas original inventions. For that purpose, we define four dependent variables capturing the different uses of oil and gas technological knowledge which will allow us to analyse the potential knowledge spillovers derived from these patented inventions. The knowledge embedded in the original oil and gas patent applications is defined employing the IPC code(s) included in the patents that cite those original inventions. The dependent variables are: i) OUTER, is equal to 1 if the citing patent includes non-oil and gas IPC codes exclusively and 0 otherwise; ii) MIXED, equal to 1 if the citing patent includes both outer and oil and gas codes and 0 otherwise; iii) INNER, equal to 1 if the citing patent includes solely oil and gas IPC codes and 0 otherwise; and iv) ENVIRONMENTAL, equal to 1 if the citing patent has environmental uses and 0 otherwise. These three variables capture the extent to which knowledge derived in the oil and gas industry spills over other sectors and particularly to inventions related to the environment.

For instance, we will consider that the original oil and gas invention has been used for "outer" purposes if the IPC codes of the citing patents do not include oil and gas ones (those included in table 1). This would be the case of intersectoral spillovers. In the same line of argument, if the IPC codes of the citing patents include other codes as well as oil and gas codes, we consider that the oil and gas original patent has been used for mixed purposes and generate “shared” spillovers. Finally, when one of these patents has only oil and gas IPC codes we will say that the knowledge embedded in the reference oil and gas invention have had "inner" uses exclusively. In this case, spillovers are from an intraindustry nature. As before, one particular and interesting case arises within interindustry spillovers when the citing (or cited or both) patents have linkages with environmental technologies (Acosta et al., 2009).

According to this structure, the independent variables can be divided into two groups. The first corresponds to factors that represent characteristics of the citing document. The second contains indicators reflecting the attributes of the original invention. In what follows, we will concentrate in the quality of both citing and cited patents. Here, we still rely in the two variables used to proxy quality: family size and granted status. In addition, we introduce patent office, application year, sector and type of applicant individual effects as in the previous sub-section to take into account as many confounders as possible.

Two issues condition the appropriate econometric methodology to be used. First, in order to capture relevant spillovers we have defined four different binary dependent variables depending on the use of the oil and gas technology (outer, mixed or inner uses and environmental). Second, and more importantly, the explanatory variables are of two different types. On one hand, we have variables reflecting the characteristics of the citing patents. On the other hand, we also have to consider the attributes of the original oil and gas invention. In this last case, given that some citing patents are linked to the same original patent, the values of these explanatory variables are repeated. These arguments suggest that the multilevel logit model is the more adequate econometric estimation method to analyse the uses of the oil and gas patented technology from the perspective of forward patent citation analysis (Wooldridge, 2003). With these considerations at hand, the empirical model is specified as follows:

$$\Pr\left(y_{ij} = 1 \middle| \mathbf{u}_j\right) = H(\mathbf{x}_{ij}\beta + \mathbf{z}_{ij}\mathbf{u}_j)$$

where j indexes the group or cluster (in our case the original patent) and i indexes observations (the citing patent) within group, conditional on a set of random effects $\mathbf{u}_j$. The row vector $\mathbf{x}_{ij}$ includes the covariates for the fixed effects and the vector $\mathbf{z}_{ij}$ are the random effects consequent covariates. Finally, H is the logistic cumulative distribution function, relating the the probability of success to the linear predictors. Stating the model from the perspective of a latent linear response variable, we have that

$$y_{ij}^{*} = \mathbf{x}_{ij}\beta + \mathbf{z}_{ij}\mathbf{u}_j + \epsilon_{ij} \qquad (2)$$

where ϵ_{ij} is an stochastic error term distributed as logistic and independent of $\mathbf{u}_j$.

This type of models is well suited to evaluate the unobserved heterogeneity derived from the characteristics of the original oil and gas patents with the introduction of a comprehensive set of individual effects. In addition, the natural heterogeneity across original patents in which the citing patents are grouped calls for the introduction of random effects in the model. Moreover, this estimation technique allows a more precise estimation of the confidence intervals, by considering random effects due to the aggregation of all the citing patents derived from the same original patent. Severe biases could be introduced in the results if the clustered nature of the data is not appropriately taken into account (Antweiler, 2001; Wooldridge, 2003). The implementation of the estimation method is exposed in more detail in Rabe-Hesketh and Skrondal (2008).

3 Results and discussion

In this section we present the results derived from the econometric exercises explained in the previous section. First, we concentrate on the results derived from the analysis of citation counts. Next, we turn to the explanation of our results regarding the multilevel forward patent citation analysis. Finally, we discuss our results and link them to both technology and environmental policies.

3.1 Results from citation counts

Results from equation 1 are shown in table 5. The results from the econometric analysis indicate that, conditional on patent office, application year, sector, type of applicant and quality, exclusive oil and gas inventions have a larger citation count than inclusive oil and gas patents. On average across the different sectors, exclusive oil and gas patents receive around 77% more citations than inclusive patents, with little variation across specifications. Given that the quality measures introduced in specification 3 are strongly statistically significant, this is our preferred specification. Not surprisingly, more quality patents receive more citations as indicated by the two quality variables.

To what extent oil and gas patents related to environmental technologies are cited? From the previous results we can infer that oil and gas patents linked to environmental technologies will receive fewer citations than exclusive patents since by definition they are in the reference group (oil and gas patents with inclusive use). Table 6 shows the results. In this case, oil and gas inclusive inventions that have links with environmental technologies receive on average around 17% fewer citations than patented oil and gas inventions without links to environmental technologies.

Table 5 around here

Table 6 around here

In tables 7 and 8 we present the results from the regressions at the sector level. Our findings indicate that exclusive oil and gas patents receive between 47% and 91% more citations than inclusive oil and gas patents. Lubricants (column 3) and earth drilling (column 4) exhibit the greatest exclusive invention advantage in terms of citations and also the greatest disadvantage in the case of inventions with environmental linkages. Interestingly, more quality patents systematically receive more citations than less quality patents.

Table 7 around here

Table 8 around here

When we compare the relative intensity of knowledge spillovers from exclusive and inclusive oil and gas patented technologies, our results show that exclusive oil and gas patents are more cited than inclusive patents. This result sheds some light on the existence of intrasectoral spillovers. Inventions made by agents within the oil and gas industry with specific uses to this industry tend to be more cited (used) than diversified knowledge with links to other uses. Particularly interesting are the results concerning inventions with links to environmental technologies, that show a significantly fewer number of citations than those oil and gas inventions no related with environmental technologies. In order to have a clearer picture of what type of patents are citing the original oil and gas inventions considered, in the next section we rely on citing patents characteristics[2].

3.2 Results from multilevel analysis

Table 9 presents the results when considering exclusive versus inclusive oil and gas original inventions, along with citing and cited patent characteristics. In addition, table 10 includes, besides the variables already cited, the indicator whether the cited patent contains links to environmental technologies or not. In both tables, all the regressions include the full set of patent office, filing year, sector and type of applicant fixed effects (not shown). We concentrate exclusively in the variables that take into account the quality of the citing and the cited inventions, as well as the indicator variables whether the original patent have exclusive or environmental uses. This distinction is interesting in itself, as environmental technologies lie at the heart of climate change and energy efficiency policies. Hence, our preferred estimations are those including this variable.

[2] One referee suggested introducing an interaction term between the use variable (exclusive or environmental) and the granted status. The results (not shown but available from the authors upon request) do not change qualitatively the findings reported here.

The results reveal that the probability that the knowledge embedded in an oil and gas invention diffuses to an invention with inner use (i.e. with exclusive oil and gas uses) is higher when the cited patent has exclusive use. On the other hand, the likelihood that the knowledge embedded in an oil and gas patent diffuses to either mixed uses (i.e. inventions with oil and gas and other uses as well) or outer uses (no uses in oil and gas) is higher when the cited invention is inclusive. Hence, intersectoral spillovers are more likely to occur when the cited patent contains diversified uses whereas intrasectoral spillovers are present when the original patent is restricted to exclusive oil and gas uses.

Table 9 around here

Regarding the links to environmental technology, the results in table 10 indicate that the probability that the knowledge embedded in an oil and gas invention diffuses to an invention with outer use (i.e. without oil and gas uses) is higher when the cited patent has linkages to environmental technologies. This means that intersectoral spillovers are more likely to occur when the original oil and gas invention has environmental uses. On the other hand, the likelihood that the knowledge embedded in an oil and gas patent diffuses to either mixed uses (i.e. inventions with oil and gas and other uses as well) or inner uses (exclusive uses in the oil and gas industry) is higher when the cited invention has no environmental linkages. In this case, intrasectoral spillovers are more likely when the original patent has no relation to environmental technologies.

Table 10 around here

An important and relevant outcome derived from the results in table 10 is related to the quality of the citing and cited patents. According to our measures of quality, the higher the quality of an oil and gas original patent, the more likely it will be diffused to inner use, the lower the quality of the citing patent will be. Hence, the appearance of intrasectoral spillovers will be more likely. On the other hand, the lower the quality of the original oil and gas invention, the probability it will be used by outer use inventions is higher and, at the same time, the higher the quality of the citing patent will be. Intermediate cases occur with mixed use citations, since both citing and cited inventions are of intermediate quality compared to the extreme cases. Hence, a very interesting pattern emerges, in which intrasectoral spillovers are characterised by high quality cited patents but low quality citing patents –the core of the oil and gas industry- while intersectoral spillovers are defined by low quality cited patents but high quality citing patents. We term this phenomenon as the "*turnabout effect*", by means of which knowledge diffusion makes low quality patents be used to generate high quality patents and vice versa.

One final step in the analysis rests in computing the probability that an original oil and gas invention that is related to environmental technology generates citations by newer inventions also related to environmental technologies. We identify for each citing patent if it has linkages to environmental technologies and re-estimate equation 2 substituting inner, mixed and outer uses for environmental uses. Results are presented in table 11. As it can be seen, if the original patent has linkages with environmental technologies, the likelihood that the citing patent also has these types of links increases considerably. The "*turnabout effect*" is also present in this case: even though the probability that the knowledge embedded in an oil and gas invention diffuses to environmentally-related inventions is higher for low quality original oil and gas inventions, this is offset by the fact that this probability will increase with the quality of the citing patent.

Table 11 around here

In order to check to what extent this result is robust, we perform the analysis by sector. Table 12 shows the results. As can be seen from the table, the probability that the citing patent declares to have environmental uses is positive and significantly affected by the fact that the original patent also declares linkages to environmental technologies. This result is robust and occurs in all sectors.

The processing sector behaves exactly as the industry. Here, then, the "turnabout" effect converts relatively low quality original oil and gas patents into high quality citing patents. The drilling sector –the one that concentrates the most observations-shows a partial or incomplete "turnabout" effect since the quality of the citing patent is only partially impulsed –the coefficient on family size is not significant-. A similar situation happens with lubricants, although in this case there is also a mixed quality feature of the original patent, for which the granted status turns out to be not significant.

Finally, the gaseous and liquid fuels sector is the only one in which the citing patent shows lower quality, as the coefficient of the citing family size is negative and statistically significant. However, the corresponding coefficient of the granted status is positive and affects the probability more than proportionally than the decrease derived from the family size effect. These results, on aggregate, indicate that the different sectors –as defined by the IPC codes that form the oil and gas industry- show different patterns with respect to the diffusion of knowledge of the inventions related to environmental technologies[3].

Table 12 around here

3.3 Discussion

Many studies have addressed the increasing complementarities between technology and environmental policies (see Kemp and Pontoglio, 2011; Carraro et al., 2010 and references therein). The intuition behind many of these studies is that, while technology policy is relevant for generating novel technologies, environmental policy is essential to guarantee their diffusion. Our results have important policy implications. First, the lower knowledge spillovers generated by oil and gas original inventions with environmental uses indicates that not all the clean technologies show larger knowledge spillovers than dirty technologies. Hence, there is weak or no justification for supporting more generous subsidies for R&D or ad-hoc R&D programmes devoted to clean technologies developed within the oil and gas industry. A case-by-case analysis would be needed in order to avoid subsidising clean technologies that eventually do not spread out sufficiently to justify the public support received. To what extent this is exclusive of the oil and gas industry or it is also present in other industries where environmental technologies are also relevant (i.e. automotive or lightning, among others) is a matter of future research.

Second, when taking into account the characteristics of the citing and the cited patents, our data shows that the environmental use of the original invention

[3] One referee suggested clustering the citations geographically. The results (not shown but available from the authors upon request) do not change qualitatively the findings reported here.

significantly increases the probability of interindustry spillovers (similar results are found in Nemet, 2012). Hence, a redirection of innovation policy towards environmental technologies could eventually help to reduce the net cost of environmental policies by activating the "turnabout effect", a mechanism that allows (relative) low quality oil and gas inventions to be diffused to high quality inventions (more cited and more internationally spread) with links to environmental technologies.

Without a proper environmental policy directed to effectively reduce carbon emissions derived from the combustion of fossil-fuels, there is no incentive for economic agents to adopt expensive technologies that cut emissions without providing supplementary benefits, maybe in terms of savings or cost reductions. On the other hand, by providing benefits to users in the form of cost reductions, technologies dealing with energy efficiency or fuel-saving, for instance, will disseminate easier even in the absence of policy (Popp, 2010). Hence, a further identification of the different environmental uses incorporated in oil and gas patent applications and citations would be of extreme importance to identify the existing incentives for diffusion and adoption of environmental technologies in this sector. This would also help inform both technology and environmental policies of the relative performance of the different instruments used.

Barriers to the diffusion of new technology in general and environmental technology in particular, can produce a sort of technological lock-in: new technologies are expensive hence fail to be adopted and they are not adopted because they are expensive. An important policy intervention in order to avoid this trap into suboptimal policies would require a compromise solution between short-run environmental protection measures while at the same time supporting the development of radical eco-innovations (del Rio et al., 2010).

The higher installed base of dirty technologies represents a clear disadvantage to clean technologies. Rapid development –and in particular diffusion- of clean technologies needs more active policy intervention (Veugelers, 2012). For instance, patent licensing could be a crucial ingredient in the design of innovation policies directed to spur clean technologies particularly in the energy industry (Aalbers et al., 2013). Other policy instruments well suited to deal with technological diffusion are the establishment of environmental standards, eco-taxes, tradable permits, and investment subsidies. Particularly relevant are those instruments that address the information externalities of diffusion, such as eco-labels or network management (del Rio et al., 2010; Kemp, 2000).

If technologies have been already developed, only government involvement can accelerate the diffusion rate relative to the one the market would provide. The mitigation of environmental threats faces a matching problem. On one hand, the most suitable clean technology is developed in high-income countries. On the other, it is in the developing world where emissions grow more rapidly. Hence, new policies in the future will have to take into account the potential role of international technology transfer schemes as incentive-based mechanisms to promote world-scale diffusion of clean technologies. Popp (2012) suggests that a low cost way to promote spillovers could be achieved by improving absorptive capacity or fostering access to trade. First, the potential of benefiting from knowledge spillovers increase with the measures directed to enhance the absorptive capacity of a country. Hascic and Johnstone (2011), -considering patent filings to be a good proxy for technology transfer- find that absorptive capacity turns out to be more relevant than ordinary technology transfer policies. Second, technology transfer agreements embedded in trade policies can also contribute to knowledge spillovers by providing access to relevant technology. The elimination of trade (bot tariff and non-tariff) barriers could help to promote significant advances in the trade flows of environmentally-friendly energy technologies (World Bank, 2008).

4 Conclusions and policy implications

The results discussed in the previous sections show, first, the absence of relevant knowledge externalities derived from patented oil and gas technology since the majority of this knowledge remains within the industry. Importantly, oil and gas patents with environmental applications are only an insignificant fraction of applications in this sector and receive fewer citations than either inclusive patents in other fields or exclusive patents. Second, by separating the nature of the citing patent, we show that the probability of a non oil and gas patent citing oil and gas patent is higher when the patent is not exclusive and especially when it includes links to environmental technologies. These results suggest some orientations to reinforce the effectiveness of both environmental and technology policies.

In a nutshell, our main result is that knowledge spillovers in the oil and gas industry are, even in the best scenario, modest. This implies that the performance of technology policy instruments designed to address environmental innovations in this sector is rather poor. On the contrary, a major role to spur green technologies should come from environmental policies. In this respect, our contribution provides results to overcome the lack of evidence on the effectiveness of public R&D

expenditure as a component of the technology policy mix to tackle climate change (Veugelers, 2012).

With very few exceptions worldwide, the true costs of environmental damages are not included in the market prices of fossil fuels, generating inefficiencies, weakening the incentives to reduce these sources of energy, and therefore hindering the uptake of clean energy. To effectively promote the adoption of environmental friendly technologies in the oil and gas sector, a re-balance of the policy mix would be required, reducing the role of technology instruments and relying more intensively on environmental policy instruments. This would help to accelerate the phasing-out of significant but inefficient oil and gas subsidies, particularly those related to R&D for fossil fuels. In fact, the OECD (2012) shows that in the past years the IEA governments around the world have devoted between US$ 1.4 and US$ 1.8 billion to R&D in fossil fuels, of which only around 10% is allocated to clean technologies such as CCS. Our results show that even if this public support may have helped to increase innovation in the sector, a very small fraction of it is directed to protect the environment.

This transformation would require relying more on MBI within environmental policies. In particular, more transparent price signals would be necessary in order to promote adequate reductions in emissions as to cope with climate change and environmental sustainability. To this end, appropriately designed instruments (new taxes or improved emission trading systems) would be an effective tool to deal with the multidimensional threats posed by the global climate plight. These MBI can create the appropriate incentives to induce decision-makers not only to attenuate the volume of emissions, but also to embrace conservation, to promote dirty-to-clean energy substitution, and to boost innovation in the sector.

In addition, complementary policies such as eco-labels, voluntary agreements or "green" public procurement can also be implemented to re-balance the policy mix, ensuring to take advantage of all the possible synergies among the different instruments used. In line with our results, governments around the world should take the issue of strengthening technological capabilities in this sector. Given the strong complementarities between technology policy and environmental policy, concrete steps should be taken to increase policy coherence at the sectoral, national and international levels (Crespi, 2013).

Environmental policies are designed and implemented at the national level, and the degree of international cooperation is rather low. A major drawback to worldwide climate change mitigation efforts is that large users of carbon resources are resisting the adoption of MBI. The World Bank (2014) has reported that the number of countries using this type of instruments today is quite limited. A propagation effect could be initiated if one of the big energy players would eventually adopt MBI as a central piece of its environmental policy. Hence, there is also a need for global action –at least with respect to the oil and gas sector- since countries cannot protect their own climate and environment alone. This calls for a revision and further development of international environmental agreements that should foster more innovation and particularly technology diffusion. By increasing demand for environmental friendly technologies, they can expand innovation in leading countries or sectors and the transfer of technology. However, their effectiveness will largely be based upon the instruments used. Although Ockwell et al. (2010) suggest relying on technology-oriented instead of emissions-oriented instruments, our results for the specific case of the oil and gas industry suggest otherwise.

Our work can be extended in several dimensions. First, it would be interesting to extend the analysis to other sectors with relevant environmental impacts, such as the power sector[4]. Second, we have concentrated in inter and intraindustry spillovers, but knowledge diffusion can take many other forms: across countries (particularly developed and developing), across applicant types (for example companies, governments, or universities), and also the temporal profile of citations is relevant. Finally, there is an increasing concern on the crowding out effects of environmental technologies, which call for an analysis of the technologies that are being displaced. All these topics are relevant to assist policy makers in fine tuning of environmental and technology policies in the future. Following Pollitt (2012), even if the liberalisation of energy has improved the quality of policy measures to mitigate negative environmental impacts, the transition to a low carbon economy heavily depends on how much societies are willing to assume the substantial costs implied.

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[4] We thank one of the referees for the suggestion.

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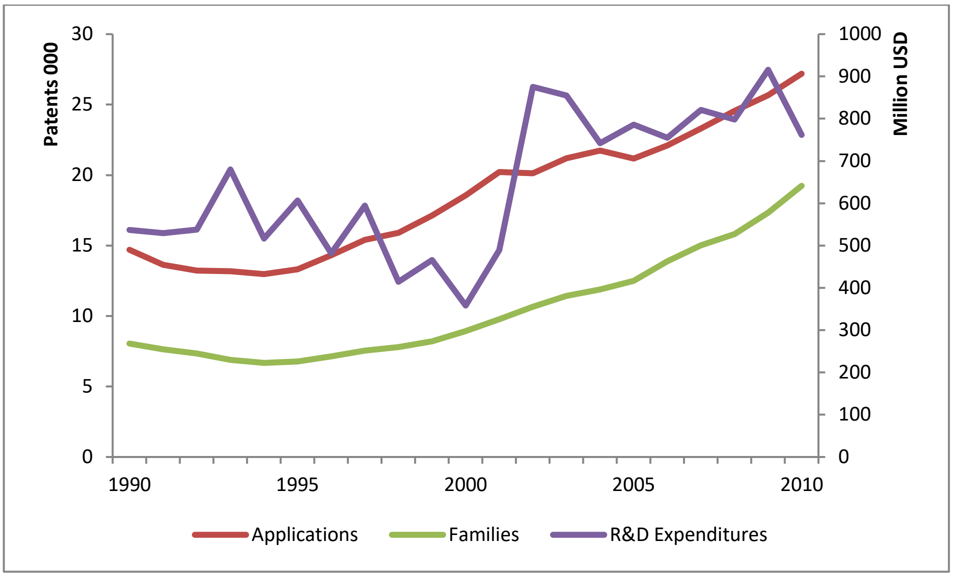
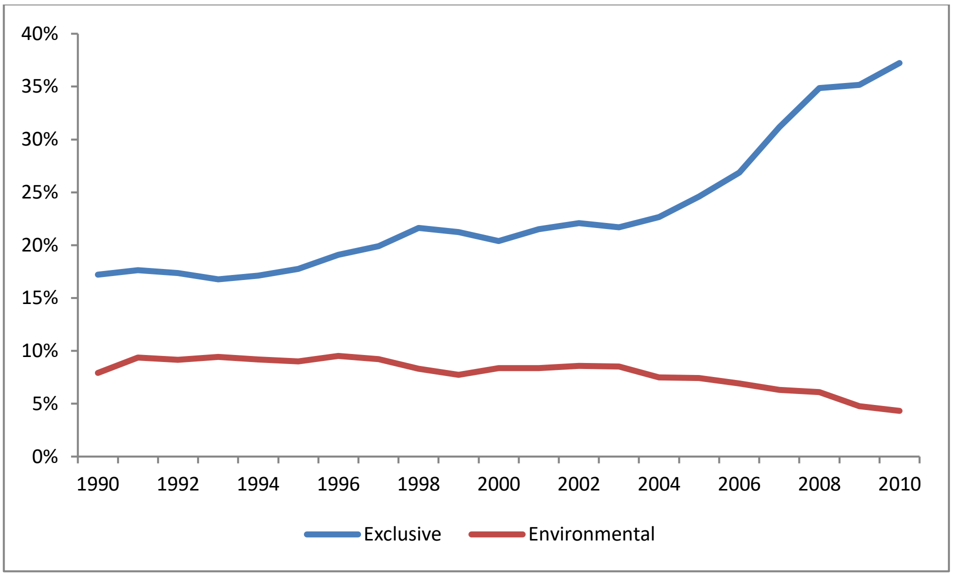
Figure 1 Evolution of oil and gas patent applications and R&D expenditure



Note: patent applications and families correspond to the world's total as extracted from the PATSTAT database. The R&D expenditure data corresponds to millions of 2013 US dollars in the 29 IEA countries. There is a high correspondence between the countries with the largest patent applications and the IEA country members.
Source: PATSTAT and IEA.

Figure 2 Evolution of the share of exclusive and environmental uses in oil and gas patent applications



Source: PATSTAT.

Table 1 Number of inventions and citations by sector, 1990-2010

Sector	IPC code	Applications	Families	Citations
Processing	C10G	78,246	39,493	134,775
Gaseous and liquid fuels	C10L	55,767	29,294	77,932
Lubricants	C10M	61,365	29,004	80,829
Drilling	E21B	194,229	92,493	367,946
Oil and Gas		**389,607**	**190,284**	**661,482**

Source: PATSTAT.

Table 2 Uses of oil and gas inventions (in %)

Sector	Exclusive	Environmental
Processing	13.8	14.0
Gaseous and liquid fuels	14.9	21.0
Lubricants	18.3	2.0
Drilling	28.4	3.7
Oil and Gas	**21.7**	**8.2**

Table 3 Mean number of citations by uses of original patents

	Exclusive	Inclusive	Environmental	Non environmental
Processing	4.9	3.2	2.8	3.5
Gaseous and liquid fuels	3.6	2.5	2.3	2.7
Lubricants	4.3	2.5	2.1	2.8
Drilling	6.0	3.2	3.3	4.0
Oil and Gas	**5.4**	**3.0**	**2.7**	**3.5**

Table 4 Quality of cited and citing inventions

	Cited		Citing	
	Family size	Granted	Family size	Granted
Processing	6.3	0.665	6.1	0.517
Gaseous and liquid fuels	5.9	0.596	5.6	0.466
Lubricants	5.4	0.608	5.3	0.500
Drilling	4.8	0.732	4.6	0.590
Oil and Gas	**5.4**	**0.687**	**5.1**	**0.549**

Table 5 Basic results: exclusive use

	(1)	(2)	(3)
Exclusive	0.572***	0.588***	0.588***
	(0.0027)	(0.0027)	(0.0027)
Family size		0.0165***	0.0165***
		(0.00020)	(0.0002)
Granted			0.0551***
			(0.0031)
Constant	2.125***	1.961***	1.926***
	(0.0960)	(0.0960)	(0.0961)
Observations	190,284	190,284	190,284

Note: all estimations include patent office, sector, filing year and type of applicant fixed effects. Robust standard errors in parentheses with *** p<0.01, ** p<0.05, * p<0.1. The dependent variable is the total number of citations received by invention.

Table 6 Basic results: environmental use

	(1)	(2)	(3)
Environmental	-0.187***	-0.185***	-0.185***
	(0.0052)	(0.0052)	(0.0052)
Family size		0.0133***	0.0132***
		(0.0002)	(0.0002)
Granted			0.0499***
			(0.0032)
Constant	2.329***	2.189***	2.159***
	(0.0960)	(0.0960)	(0.0961)
Observations	190,284	190,284	190,284

Note: all estimations include patent office, sector, filing year and type of applicant fixed effects. Robust standard errors in parentheses with *** p<0.01, ** p<0.05, * p<0.1. The dependent variable is the total number of citations received by invention.

Table 7 Results by sector: exclusive use

	Processing	Gaseous and liquid fuels	Lubricants	Drilling
Exclusive	0.460***	0.386***	0.560***	0.649***
	(0.007)	(0.0093)	(0.0082)	(0.0035)
Family size	0.0174***	0.0194***	0.0197***	0.0130***
	(0.0003)	(0.0006)	(0.0007)	(0.0004)
Granted	0.0395***	0.0643***	0.116***	0.0479***
	(0.0071)	(0.0087)	(0.0085)	(0.0044)
Constant	2.267***	1.704***	-0.464	1.739***
	(0.153)	(0.201)	(1.000)	(0.158)
Observations	39,493	29,294	29,004	92,493

Note: all estimations include patent office, filing year and type of applicant fixed effects. Robust standard errors in parentheses with *** p<0.01, ** p<0.05, * p<0.1. The dependent variable is the total number of citations received by invention.

Table 8 Results by sector: environmental use

	Processing	Gaseous and liquid fuels	Lubricants	Drilling
Environmental	-0.192***	-0.140***	-0.330***	-0.228***
	(0.00859)	(0.00948)	(0.0287)	(0.00970)
Family size	0.0161***	0.0178***	0.0157***	0.00807***
	(0.000305)	(0.000576)	(0.000677)	(0.000369)
Granted	0.0310***	0.0531***	0.102***	0.0490***
	(0.00705)	(0.00877)	(0.00846)	(0.00447)
Constant	2.414***	1.732***	0.0905	2.144***
	(0.153)	(0.201)	(1.000)	(0.158)
Observations	39,493	29,294	29,004	92,493

Note: all estimations include patent office, filing year and type of applicant fixed effects. Robust standard errors in parentheses with *** p<0.01, ** p<0.05, * p<0.1. The dependent variable is the total number of citations received by invention.

Table 9 Multilevel logit: exclusive use

	INNER	MIXED	OUTER
Citing:			
Granted	-0.194***	0.0535***	0.113***
	(0.00724)	(0.00664)	(0.00709)
Family size	-0.0297***	-0.00176***	0.0215***
	(0.000737)	(0.000497)	(0.000556)
Cited:			
Exclusive	1.938***	-0.886***	-1.503***
	(0.00611)	(0.00636)	(0.00754)
Granted	0.0966***	0.0120*	-0.110***
	(0.00748)	(0.00691)	(0.00724)
Family size	0.0104***	-0.00725***	-0.00189***
	(0.000501)	(0.000504)	(0.000482)
Constant	-1.361***	0.535*	-1.523***
	(0.308)	(0.293)	(0.303)
Observations	661,482	661,482	661,482

Note: all estimations include patent office, sector, filing year and type of applicant individual effects. Robust standard errors in parentheses with *** p<0.01, ** p<0.05, * p<0.1.

Table 10 Multilevel logit: exclusive and environmental uses

	INNER	MIXED	OUTER
Citing:			
Granted	-0.194***	0.0540***	0.111***
	(0.00724)	(0.00664)	(0.00710)
Family size	-0.0303***	-0.00188***	0.0220***
	(0.000739)	(0.000498)	(0.000559)
Cited:			
Exclusive	1.900***	-0.895***	-1.473***
	(0.00618)	(0.00642)	(0.00759)
Environmental	-0.579***	-0.113***	0.401***
	(0.0163)	(0.0110)	(0.0110)
Granted	0.0964***	0.0119*	-0.110***
	(0.00749)	(0.00691)	(0.00725)
Family size	0.0102***	-0.00733***	-0.00163***
	(0.000503)	(0.000504)	(0.000482)
Constant	-1.280***	0.554*	-1.600***
	(0.308)	(0.293)	(0.303)
Observations	661,428	661,445	661,412

Note: all estimations include patent office, sector, filing year and type of applicant individual effects. Robust standard errors in parentheses with *** p<0.01, ** p<0.05, * p<0.1.

Table 11 Multilevel logit: citing environmental uses

	(1)	(2)
Citing:		
Granted	0.176***	0.182***
	(0.0154)	(0.0154)
Family size	0.00625***	0.00583***
	(0.000900)	(0.000925)
Cited:		
Exclusive		-0.749***
		(0.0205)
Environmental	3.124***	2.953***
	(0.0133)	(0.0137)
Granted	-0.0779***	-0.0800***
	(0.0158)	(0.0159)
Family size	-0.0252***	-0.0288***
	(0.00131)	(0.00134)
Constant	-4.839***	-4.598***
	(0.885)	(0.888)
Observations	661,482	661,482

Note: all estimations include patent office, sector, filing year and type of applicant individual effects. Robust standard errors in parentheses with *** p<0.01, ** p<0.05, * p<0.1.

Table 12 Multilevel logit: citing environmental uses by sector

	Processing	Gaseous and liquid fuels	Lubricants	Drilling
Citing:				
Granted	0.210***	0.223***	0.220***	0.104***
	(0.0237)	(0.0281)	(0.0735)	(0.0331)
Family size	0.0106***	-0.00969***	0.00904	-0.000864
	(0.000967)	(0.00220)	(0.00630)	(0.00322)
Cited:				
Environmental	2.111***	3.120***	3.508***	4.372***
	(0.0211)	(0.0245)	(0.0757)	(0.0265)
Granted	-0.0964***	-0.00326	-0.0165	-0.107***
	(0.0243)	(0.0278)	(0.0757)	(0.0358)
Family size	-0.0290***	-0.0144***	-0.0362***	-0.0161***
	(0.00190)	(0.00240)	(0.00698)	(0.00332)
Constant	-5.266***	-3.735***	-7.344***	-4.527***
	(1.058)	(1.088)	(1.338)	(1.177)
Observations	134,477	77,684	79,788	366,974

Note: all estimations include patent office, sector, filing year and type of applicant individual effects. Robust standard errors in parentheses with *** p<0.01, ** p<0.05, * p<0.1.