International diffusion of climate change mitigation technologies

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Abstract

The development and diffusion of low-carbon technologies on a global scale is a fundamental condition for the success of efforts to contain the harmful effects of climate change. This article aims to provide a comprehensive overview of the development and diffusion of these technologies on a global scale. We employ an original database of climate change mitigation technologies applied by countries in a long-term perspective (1950-2020). Findings reveal that leading countries in these technologies accelerate their patenting activity but maintain a high concentration of North-North transfers. Efforts are needed to diversify global transfers to include emerging economies.

Keywords: environmental innovation, green technology, developing countries, low carbon, patent applications.

Área Temática: Economia

1 Introduction

The process of global climate change resulting from the accumulation of greenhouse gases (GHG) in the atmosphere is recognized as the foremost challenge for our society and its study is one of the main guides to the debate on sustainability. Stabilizing global GHG emissions requires the enhanced development and diffusion of a wide range of climate change mitigation technologies (CCMT) since the environmental benefits increase as these technologies are widely adopted across firms, industries and countries (Mowery et al., 2010; Pulkki-Brännström and Stoneman, 2013; Stern, 2008).

In light of this, significant efforts have been made in the last decades to investigate the development and diffusion of technologies that lower the environmental harm and address the mitigation of climate change (Barbieri et al., 2016; Hojnik and Ruzzier, 2016; Lanjouw and Mody, 1996; Perruchas et al., 2020). In general, it is shown that most CCMTs continue to be conceived and adopted by developed nations and the increase in GHG emissions from emerging economies has drawn attention to how these countries will be involved in this process, either through technology transfers or by creating their own competencies (Dechezleprêtre et al., 2011; Gonçalves Montenegro et al., 2021; Hall and Helmers, 2013; Probst et al., 2021).

The relevance of the climate challenge has led to an extensive debate about the factors that encourage or inhibit the development and diffusion of CCMT at the industry level, the firm level, and the national level. According to studies on these issues, despite two decades of strong growth, low-emissions innovation efforts have lost momentum, since low-carbon patenting rates dropped annually and public R&D budgets in low-carbon innovation have fallen after the financial crisis (Cervantes et al., 2018; Probst et al., 2021).

Although the existing literature has provided valuable attempts to provide an overview of the development and diffusion of CCMT, there is a lack of comprehensive analysis of the process of international diffusion of these technologies. This gap is perceived in terms of the time frame, updating of data and also the scope of the technologies studied. This paper shed light on this issue by providing a comprehensive overview of the development and diffusion of climate change mitigation technologies on a global scale, between 1950 and 2020. We have established an original database of green patents applied worldwide and tracked their priority patents to generate new evidence about the international diffusion of these technologies at the country level.

The remainder of this paper is structured as follows. In the second section, we review the literature dealing with diffusion of climate change mitigation using low-carbon technologies. In the third section, the data set is presented and the methods for patent analysis are introduced. The fourth section contains a description and discussion of the results and points out some limitations. Section five presents the conclusion.

2 Development and diffusion of low-carbon technologies

The emission of GHGs are typical cases of externalities, that is, they are the effect of an activity whose consequences are suffered by one or several parties other than those that control the activity that produced the externality. In an economic system, while the cost of using productive resources, such as labour and raw materials, is internalized by firms when they pay for their use, there are no economic incentives to minimize the external costs of emissions and externalities in general. When dealing with this market failure, public policies are subject to comparing the marginal benefit of a cleaner atmosphere with the equivalent marginal cost imposed on society. Accordingly, while the emissions of the most harmful gases must be strongly restricted by the high marginal costs imposed on society, the emission of gases whose elimination is more expensive must be tolerated, given the high marginal cost of reducing them.

However, the inclusion of technical change in this relationship modifies the trade-off between the marginal cost of controlling emissions and the marginal social benefits. Thus, technologies such as emission control methods and clean production tend to reduce the marginal cost of achieving a given unit of emission reduction. In other words, the introduction of technical changes makes it possible for a certain level of environmental quality to be achieved at a lower total cost to society (Jaffe et al., 2005; Johnstone et al., 2010).

Achieving the required levels of technical change is not trivial and the action of free market forces alone has produced a level of private investment in environmental technologies below the socially desired ideal. It is argued that these insufficient levels of investments are due to emergence of market failures in the process of technological invention, innovation and diffusion. The combination of this failure with the negative environmental externalities of GHGs results in what the literature so-calls the *double externality problem* (Rennings, 2000). The recognition of these market failures reveals that innovative activity does not take place in a vacuum and constitutes a more complex process than is usually considered. Hence, in the process of development and diffusion of new technologies, there is a need for efforts to learn about the new technology, acquire new equipment, and adapt the technologies to particular circumstances.

While on a macro scale the international technology diffusion could even determine the pattern of worldwide technical change (Keller, 2001), it also relies on a number of general issues relating to micro-characteristics inherent to the technology. For instance, the greater the radicality and scope of innovation faster the speed of diffusion (Lee et al., 2003). The amount of scientific knowledge on which they are based is also a factor that facilitates the diffusion of technologies in the energy sector (Fernández et al., 2022). In this regard, complex and complementary CCMT patents tend to be more enabling for subsequent innovation, and this effect is augmented for technologies that constitute dominant designs (Nylund et al., 2021). These issues reinforce the notion that diffusion is related to technological learning and lies in the build-up of local capabilities and absorptive capacity, although it differs significantly between technologies (Huenteler et al., 2014; Li et al., 2020, 2022). In addition, the geographic proximity to the innovator also matters and is associated with an accelerated time to adoption of environmental innovations (Losacker et al., 2022).

The diffusion process is also influenced by external issues and specific needs such as the presence of clear expectations for market growth, the overcoming "lock-in" or inertia in fossil-fuel dependent systems, and the social legitimacy of political leadership to incentivize decarbonization and overcome system inertia (Wilson et al., 2020). Another factor that proved to be key determinant of technological diffusion is the long-term relationships as measured by economic integration, as demonstrated by the study on wind energy (Halleck-Vega et al., 2018).

The regulatory setting and environmental policies significantly influence the development and diffusion as studies reveal a positive relationship between domestic regulatory stringency and inflows of technologies (Dekker et al., 2012; Fabrizi et al., 2018; Johnstone et al., 2012; Lanjouw and Mody, 1996; Popp et al., 2011a). This positive relationship was also revealed by studies in different localities, such as in the case of diffusion of renewable energy technologies in France and in Sweden (Mignon and Bergek, 2016), in the European continent (Ferreira et al., 2020) and in the context of developing countries (Losacker, 2022; Pfeiffer and Mulder, 2013).

In addition, there is considerable debate about the role of intellectual property regimes (IPRs) in promoting the development and transfer of these technologies. On the one hand, intellectual property is the means of addressing the externality that results from imperfect appropriability of knowledge. On the other hand, patents may not be the ideal policy instrument for encouraging innovation in this area if they are unable to create a competitive market for technology that leads to more diffusion than would be achieved in their absence. Thus, the main debate is in the examination of the extent to which IPRs encourage or inhibit the diffusion of clean/green technologies (Allred and Park, 2007; Hall and Helmers, 2010, 2013; Ockwell et al., 2010).

Given the central role played by the government, the literature has encompassed a variety of instruments for technological diffusion and a study summarizes four categories of policies (financial, competitive, information, learning), which are affected by four different factors (culture, market access, costs, current knowledge). This variety reveals the political challenge to understand the scope and the effectiveness of different categories of policies to promote the spread of new technologies (Parmentola et al., 2020). The government is a relevant actor in this process since effective and strong policy interventions play a role in the diffusion process and without them, countries will have conventional diffusion with very similar speeds of diffusion (Davies and Diaz-Rainey, 2011).

3 Methods

Patent data are a relevant source of information on inventive activity and its statistics enable various uses, such as measuring the inventiveness of countries, regions, firms or individual inventors. In this study, patent statistics are used to measure the cross-country development and international diffusion of climate change mitigation technologies. This choice is due to the possibility of investigations that have as scope a varied group of technical fields and the availability of detailed information about the invention process: description of the invention, technological fields, and data of the inventors and the applicants.

A further advantage of patent data is the possibility to deal with comparable international aggregates through information from patent families, instead of simple patent counts. Patent families are a set of applications, filed in several countries, which are related to each other by one or several common priority documents. In this regard, our research strategy consists of identifying transnational priority patents (PPT), following the steps of relevant studies on the topic (Alkemade et al., 2015; Dechezleprêtre et al., 2017; Frietsch and Schmoch, 2010; Picci and Savorelli, 2012; Rassenfosse et al., 2013b). This method takes advantage of the possibility of the PATSTAT to provide original data on the priorities of all patent filings. As argued by scholars, transnational priority patents have advantages for the analysis of the international diffusion process, when compared to traditional indicators based exclusively on data from a small number of large offices such as the EPO, USPTO and JPO, or a combination of them, such as the case of triadic patents (Popp et al., 2011b; Rassenfosse et al., 2013b).

Nevertheless, a challenge for research on patent families is to understand the motivations for applying for patents in foreign countries. Scholars argue that the internationalization of technology using the patents of non-residents is an "imperfect measure" of technology diffusion between the country that applies for the patent and the one that grants the patent (Thomson and Nelson, 1997). According to the authors, motivations for encouraging foreign patenting includes: (i) enabling the extraction of income derived from the licensing of technology from national firms; (ii) providing a guarantee to operate locally and to sell products in national markets; (iii) secure markets for exports. Regardless of the motivation, the success of foreign patenting as an international strategy depends on the understanding of the potentialities and limits of international opportunities (Beneito et al., 2018; Dang et al., 2019).

3.1 Data and sample

Our data were obtained from the World Patent Statistical Database (PATSTAT/EPO), the most comprehensive global patent database in the world. PATSTAT includes more than 100 million patent documents filed in over 80 patent offices in the world. We developed a unique database containing all patents related to Climate Change Mitigation Technologies (CCMT).

In a first step, starting from a universe of approximately 100 million patents worldwide, we selected all applications that have one or more technical fields identified as Environmentally Sound Technologies (ESTs) in the IPC Green Inventory developed by WIPO. This step resulted in a data set with 12,629,866 applications (hereafter green patents)[1]. In the second step, we

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[1] Here, a patent is perceived as "green" when it has some IPC identified by Green Inventory as EST. However, it is important to note that the determination of a green patent in an intellectual property office is more complex because it involves the technical examination of a specialist in each case.

identify the priority patent applications and establish their respective families. Hence, this set of green patents are related to 5,414,303 priority patents, or transnational priority patents, as the previous studies suggest (Alkemade et al., 2015; Picci and Savorelli, 2012; Rassenfosse et al., 2013a). From the second step, the green patents and their corresponding patent family were organized based on the year of application and the respective office worldwide.

The development of an original database aimed to overcome the absence of a source of information that enables tracking international transfers and the evaluation of diffusion of climate technologies. As observed by other authors (de Coninck and Puig, 2015; Su and Moaniba, 2017), the existing literature on technology diffusion of low carbon technologies is often exploratory in nature, restricted to case studies or focused on a specific type of technology transfer programmes (Dechezleprêtre et al., 2008; Ockwell and Mallett, 2012).

3.2 Patent classification

In view of the main existing patent classifications, this article adopts the classification by applicants and the classification by technical fields (IPC). The classification by applicants is useful in reconstructing patent portfolios of countries and enable sectoral analyzes by technical field, as well as suitable in examining the diffusion strategy of countries. This classification by technological fields has benefits such as the broad technological scope and broad temporal coverage.

There are two main classifications to identify patents related to environmental technologies, which have different levels of disaggregation and prioritize different areas of technology. The first is the *Patents in Clean-Energy Technologies* which resulted in the reformulation of the European Classification System (ECLA) to include a new section and class of patents called "IPC Y02" (Veefkind et al., 2012). The second classification is the IPC Green Inventory and developed by the WIPO by a committee of experts to enable searches for patent information related to Environmentally Sound Technologies (EST), according to the United Nations Framework Convention on Climate Change (UNFCCC).

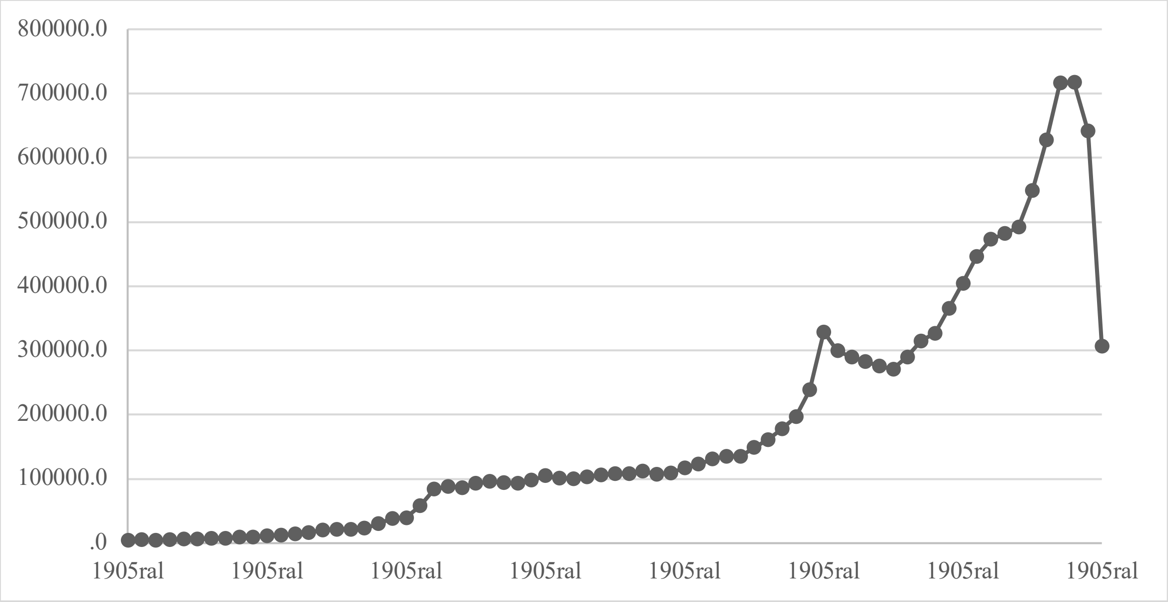
This article implements the IPC Green Inventory and this choice has two main justifications. Firstly, this classification enables a broader geographic scope and improved comparison between countries, as it is not restricted to the European classification (ECLA). Second, the IPC Green Inventory technologies have a broader scope and are not merely restricted to clean energy technologies. Furthermore, this is the main classification by which patent offices worldwide have characterized so-called green patents. In these offices, applications involving these technical fields have been examined at a faster pace than regular patent applications, using fast tracking procedures (Dechezleprêtre, 2013)

4 Results and discussion

4.1 Global patenting trend

Our study reveals an average growth of 7% in the number of priority green patents over the entire study period from 1950 to 2020. Studies have estimated growth rates of between 5,5% and 10,4%, although with different groups of technologies and periods of analysis (Probst et al., 2021). Although there are years with high growth or decrease rate, an average growth of 7% is consistent with a general trend of the inventive activity in this heterogeneous group of technology areas. Figure 1 shows a decrease in the number of applications over the last three years (2018-2020), but that is also consistent with the period required for the database to capture the updates of patent applications accumulated by the offices on a global scale.

Figure – Number of priority green patents worldwide, 1950-2020.



Similar works have detected a 6% decrease in low-carbon patenting rates between 2013 and 2017, due to decreasing fossil fuel prices, a realignment in the long-term expectations of its investors and inertia of public funding for green R&D after the financial crisis (Probst et al., 2021). However, this reduction is not observed in our estimates, since in the same period the growth rate of priority green patents increased by an average of 9%. Possible explanations for the difference in recent trends are the most up-to-date version of our PATSTAT database and also the broader coverage of our technical fields, which uses the entire IPC Green Inventory (WIPO) and not just patents under the Y02 classification (EPO).

Although our results show a more optimistic view of the growth rate of inventive activity in green patents, there are issues already reported in the literature that continue to deserve our attention. That is to say, the rate of growth of patenting is desired, but more important is the rate of international diffusion of these technologies. In line with existing studies, a characteristic of the data is the high concentration of green patents in some industrialized countries and the knowledge stock in the world distributes unequally (Probst et al., 2021; Yan et al., 2017).

Thus, the top-10 inventing countries account for 83% of global CCMT inventions. Yet, while the studies attribute the leadership in patenting to the United States, Germany and Japan, our study finds the United States, Germany, and Korea as leading countries. Therefore, policy interventions aiming to stimulate the international diffusion of green patents need to focus on these countries and their inventive activity.

Table 1 exhibit a scenario of the international diffusion of green patents from top-10 inventor countries, which accounted for applications in 59 offices around the world. Thus, it is possible to observe differences in the international coverage of applications by patent office since these countries implement different strategies for the international exploitation of their technologies. For example, while the United States, Germany and France select 3 or 4 dozen markets to explore their technologies on a global scale, other countries such as Japan, Taiwan, China, and Korea have a more focused strategy and this number of offices does not reach two dozen.

Table 1 – List of top-10 green patent applicants, patents offices and concentration

Country	Number of offices	Patent office HHI index
Switzerland	29	0,2863
China	13	0,6500
Germany	41	0,4507
France	35	0,4803
United Kingdom	28	0,5445
Japan	18	0,2998
Korea	12	0,8974
Sweden	22	0,3412
Taiwan	15	0,3738
United States	48	0,7850

In addition to the number of offices, the international diffusion undertaken by the top-10 countries can also be examined from the point of view of the concentration of patenting activity. This index reflects the degree of dispersion of the green patents across different offices and varies between 0 and 1: $\sum_{i=1}^{n} \alpha_i^2$, where α_i is the share of green patents applied in the office i in the country stock of patents. The higher the index, the more concentrated the application of patents from that country in offices worldwide and, therefore, the less likely the diffusion of technologies on a global scale. Therefore, we conclude that Korea, the United States and China have a very concentrated patenting internationally when compared to Sweden, Japan and Switzerland.

The implication is that CCMT's international diffusion process would depend not only on the scale of patenting, but also on diversification into patent offices worldwide. In other words, the application of green patents in an increasing number of offices around the world is a necessary but not sufficient condition for international diffusion of these technologies, because the growth in the number of applications may be concentrated in industrialized countries. Instead, there needs to be a more dispersed distribution across patent offices that reaches countries and regions with the highest potential growth in GHG emissions in the future.

The international diffusion of technologies is a two-way process, and its understanding is enhanced by including the perspective of countries with a lack of competencies in CCMT and the greatest potential for economic growth and GHG emissions. Some relevant cases from these countries are Brazil, Russia, India, China, and South Africa. These countries have significant differences in many aspects, but they have in common a great potential for growth in the same way that they need many technologies to decarbonize their economies.

In this regard, it is shown that patent offices in these countries received green patents applied by 36 different countries. However, China is the main destination for green patents and receives patents from 31 offices around the world. Despite this, efforts are being made to examine whether this increase in foreign patent applications has translated into more opportunities for China to access and obtain new technology from foreign countries (Cai et al., 2020; Dominguez Lacasa and Shubbak, 2018; Yu, 2017).

For other emerging economies, the number of countries that received green patent applications is approximately one third of the amount observed in China, namely: Brazil (10), Russia (11), India (9), China, and South Africa (8). On the one hand, these estimates show a change in the scenario of a historically high concentration of climate technology transfers between developed countries previous reported by Dechezleprêtre et al. (2011). On the other hand, there are several opportunities to be explored in technology transfer from cooperation with major emerging economies but also with less prominent developing countries (Halleck Vega and Mandel, 2018).

CDM projects have been too concentrated in large emerging economies and that developed countries should put a stronger weight on the positive externalities in terms of technology transfer of cooperating with less prominent developing countries

For developed economies, but especially for emerging ones, the development and diffusion of low-carbon technologies could be enhanced when environmental technology policies are integrated into national sustainable development strategies. Therefore, the main drive to the development and diffusion of these technologies may not be climate change itself or environmental quality standards, rather, the main guide could be the growth and economic development resulting from the transition to a low carbon economy.

5. Conclusion

In this article, we used a unique data set on climate change mitigation technologies applied by countries in a long-term perspective (1950-2020). In more detail, we provide a comprehensive overview of the development and diffusion of these technologies on a global scale, focusing on emerging economies with high potential for GHG emissions. From a set of approximately 100 million patents worldwide, we have established a data set with 12,629,866 green patents. Then, we identify 5,414,303 priority patent applications and tackle their respective families. These green patents and their corresponding patent family were organized based on the year of application and the respective office worldwide.

Findings reveal a growth rate of 7% per year in applications of these technologies. This long-term perspective demonstrates that low-carbon technologies have been applied for some time, but more needs to be done to effectively shift the direction and pace of invention towards accelerating its diffusion in emerging economies.

It is also found that leading countries in these technologies, such as the United States, accelerate their patenting activity but maintain a high concentration of North-North transfers. These governments need further promote collaborative North-South platforms that include researchers, companies and public research, with an emphasis on those countries and regions that will need a transition to a low carbon economy.

Despite a growing diversification in the origin of transfers in emerging economies, the main flow of applications is towards China. It is necessary that the other emerging economies are more substantially included in the international flows of knowledge of low carbon technologies. Furthermore, it is essential that emerging countries build technical, financial and human skills capacity in order to help them further develop and deploy these technologies.

As expected, this study has limitations that must be recognized and considered in future research. Specifically, our study is based only on patent data and as such are imperfect measures for evaluating the development and diffusion of these technologies. The results of the present study need to be combined with new evidence that confirms or rejects them. Additional research that examines the conditions of other emerging economies and with great potential for emissions seems to be an important research question.

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