Technological Forecasting & Social Change 144 (2019) 25–35

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

The impact of public research on the technological development of industry in the green energy field

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ARTICLE INFO

Keywords:
Green energy technologies
Public research
Technology attributes
R&D policy
Environmental innovations

ABSTRACT

This paper, by analysing technology attributes, examines the degree to which companies build on environmental technologies generated by public research organisations (PROs) to develop the related technological solutions. Three main technology attributes have been considered: (i) the level of establishment, (ii) the scope of application, and (iii) the technological breadth. We have then developed three hypotheses about the influence exerted by these characteristics and have chosen the green energy as the field of investigation. The analysis is based on a sample of 4363 green energy patents registered by PROs at the United States Patent and Trademark Office in the 1976–2011 period. The results of a set of Tobit regression have revealed that the level of establishment, the scope of application and the technological breadth of public environmental technologies are positively related to the technological development of an industry. Hence, these findings can help advance the current debate on whether the green outputs of public research can stimulate firms to generate environmental technologies.

1. Introduction

The need to reduce human-induced climate changes, while avoiding shrinking economic growth is crucial to maintain sustainable economic growth (EC/EACI, 2011; OECD, 2012). In order to achieve this win-win effect, the development of technological solutions that favour the creation of and at the same time address environmental issues has become of foremost importance (Alkemade et al., 2011; Ghisetti et al., 2015; Mowery et al., 2010). Green energy technologies (i.e., alternative energy production and energy conservation solutions) are of utmost importance in this respect. On the one hand, since energy production and consumption account for two-thirds of the world's greenhouse-gas (GHG) emissions (OECD/IEA, 2015), "effective action in the energy sector is essential to tackle the climate change problem" (OECD/IEA, 2015: 20). On the other hand, greening the energy sector is necessary to create new business opportunities (OECD, 2012). The invention, adoption and diffusion of green energy technologies should therefore be at the core of a sustainability transition in order to replace the current dirtier technologies, improve environmental protection, and boost the economy (Benson and Magee, 2014; Geels et al., 2016; OECD/IEA, 2015).

However, market failures often hamper the capabilities of firms to capture the full economic return of their environmental R&D activities (Mowery et al., 2010), which are subject to the so-called double externality problem (Jaffe et al., 2005; Rennings, 2000; Popp et al., 2010; Hoppmann et al., 2013). In other words, environmental R&D activities lead to two types of positive externalities, that is, knowledge creation and environmental benefits; nonetheless, neither are well captured by market prices (Rennings, 2000). As a result, only a suboptimal number of green energy technologies would be generated by the industrial sector in the absence of a proper regulatory push (e.g. Jaffe and Palmer, 1997; Johnstone et al., 2012), thus making governmental intervention essential to compensate for this misalignment (Foray et al., 2012; Ghisetti and Pontoni, 2015). The recent increase in public research organisation (PRO) spending on environmentally friendly energy solutions is seen as a means to compensate for such sub-optimal investment (Albino et al., 2014; Hargadon, 2010) and may be explained by both neoclassical and evolutionary economic theories. As far as the former are concerned, the public funding of PROs (e.g., universities, public research centres, governmental organisations) may compensate for market failures and generate new technological solutions that i) would not be developed by private research alone and ii) may be of use to as many firms as possible to generate related technological advancements. Instead, as far as the evolutionary economic theory is concerned, the availability of new technologies developed by PROs would not automatically lead to the setting of the basis for the development of

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https://doi.org/10.1016/j.techfore.2019.04.007
Received 9 August 2018; Received in revised form 18 January 2019; Accepted 9 April 2019

subsequent technologies by firms. In fact, firms are often not always willing and/or able to draw on public research outcomes because of their weaker connection to market needs or a lack of firms' absorptive capacity (Cohen and Levinthal, 1990; Salter and Martin, 2001). Consequently, the degree to which firms benefit from the research efforts of PROs has yet to be fully understood (Coccia and Rolfo, 2008; Cohen et al., 2002), and this knowledge can be used to improve the effectiveness of public investments in producing research externalities for the industrial sector (Beise and Stahl, 1999; Bornmann and Marx, 2014).

The present paper aims to be part of this debate and it deals with an application to the green energy field. In fact, its focus is not on the public incentives that may stimulate private environmental R&D (R&D tax credits, R&D subsidies, etc.), as is the case for most of the existing research (e.g., Hoppmann et al., 2013), but is instead on whether and under which conditions the knowledge underlying green energy technologies created by PROs spills to firms intensively and whether it boosts a firm's contribution towards technological development.

The empirical analysis has drawn on a sample of 4363 patents registered by PROs during the 1976–2011 period at the United States Patent and Trademark Office (USPTO) and has labelled them as environmentally based on their International Patent Classification (IPC) code. The results, obtained through Tobit regressions, have revealed that the level of establishment, the scope of application, and the technological breadth of public environmental technologies all have a positive effect on the degree to which the industrial sector builds on green public knowledge for further technological development.

The remainder of the paper is structured as follows. Section 2 presents the theory and hypotheses. Section 3 outlines the methodological approach, while Section 4 shows the results. Finally, Section 5 provides the discussion, implications, limitations and future research directions.

2. Theory and hypotheses

The paper assesses whether and to what degree companies build upon the technological knowledge generated by PROs, ultimately stimulating an industry to generate new (environmental) technologies. To the best of our knowledge, this is still an underdeveloped area of research. A recent exception is that of from Popp (2017), whose contribution has shed light on the value of knowledge flows between academia, the private sector and governmental research by means of US patent data which were used to answer questions about whether quality science has been useful for future technology development in the green energy field (namely biofuels, solar and wind) and about which institutions produce the most valuable research. His findings suggest the importance of public institutions in increasing the impact (citations) on renewable energy research and in helping new energy technologies overcome barriers to their exploitation (Mowery et al., 2010).

Our contribution adds to the above work by conducting a specific investigation on the nature of the attributes of the green energy technologies developed by PROs. Since the evolutionary economic theory recognises that not all the technologies developed by the public sector affect the industrial domain (Bornmann and Marx, 2014; Coccia and Rolfo, 2008; Cohen et al., 2002), this paper attempts to understand what types of PRO technologies lead to the technological development of industry. Technologies are not all equal and, depending on their attributes, they may be more (or less) attractive to and useful for firms (see, e.g., Chen et al., 2011; Shane, 2001). Such an investigation would allow more light to be shed on how the outputs of PRO research can help the transition to more environmentally friendly R&D efforts in the industrial sector, a transition which would require high levels of investment for the development of environmental technologies and thus riskier research activities that are unlikely to be sustained by the private sector on its own (Mowery et al., 2010), given the double externality features of such research activities (Rennings, 2000).

It will be argued that, depending on the technology attributes, not only may the technologies developed by PROs be attractive to different extents to firms, but they may also facilitate the transition of firms towards more environmentally friendly research activities, hence overcoming the double externality problem. Therefore, according to the previous discussion, the main research question of this study is: *how does the research generated by PROs impact the technological development of industry in the green energy field*? In other words, we question whether the attributes of the technological knowledge generated by PROs can explain if, and to what extent, such knowledge impacts the industry technological development of industry.

The technology attributes under investigation were selected on the basis of a review of the existing literature on technology management (e.g., Chen et al., 2011; Messeni Petruzzelli et al., 2015; Nerkar and Shane, 2007; Shane, 2001; Sohn et al., 2013) and of the emerging literature on environmental technology development (e.g., Popp, 2006; Popp et al., 2010; Nemet, 2012; Guan and Yan, 2016; for a review, see Barbieri et al., 2016).

By focusing on the role of knowledge flows from PROs as a determinant of a firm's technological development, the paper contributes to the current debate on the conditions under which the outcomes of public environmental research can stimulate the generation of more environmentally friendly technologies by industry, which is becoming more and more important to promote economic growth and address environmental issues (Alkemade et al., 2011). Furthermore, an alternative perspective is provided to evaluate the societal impact of public environmental research which, although difficult for governments to undertake, is necessary to better design effective funding policies (Bornmann and Marx, 2014).

2.1. Technology attributes

Hereafter, we argue that the attributes of the (environmental) technologies created by PROs can predict whether public research will set the basis for a firm's further technological development in the case of such technology-intensive industries as the energy sector. In fact, technology attributes reflect the opportunities and knowledge base that characterise technological solutions (Shane, 2001). These attributes may explain to what degree firms build upon certain types of technologies, since they choose technologies for subsequent development on the basis of their expectations for the future and their ability to exploit them (Nerkar and Shane, 2007; Shane, 2001). Technology attributes of PRO green energy technologies reflect the public environmental knowledge and opportunities available to firms that can be drawn on for subsequent technological development. Those attributes might thus alleviate/strengthen the double externality problem, mainly by fostering (or hampering) the intentions of firms to acquire the initial environmental knowledge needed for their research activities, but not internally developed by them, given the impossibility of capturing its full value.

After reviewing the extant literature on technology management and environmental technology drivers, three attributes have been identified, namely (i) the level of establishment (Heeley and Jacobson, 2008), (ii) the scope of application (Novelli, 2015) and (iii) the technological breadth (Messeni Petruzzelli et al., 2015). The level of establishment reflects to what extent technologies are known and their underlying knowledge has been exploited; the more (/less) known and exploited the technologies are, the more established (/nascent) they can be considered (Ahuja and Lampert, 2001; Heeley and Jacobson, 2008). The scope of application refers to the extent of different domains a technology is related to, i.e., a higher scope reflects a broader set of potential applications (Gambardella et al., 2007; Lerner, 1994). Finally, technological breadth captures the extent to which the knowledge base of a technology is diversified, thus reflecting a wider search process during its development (Messeni Petruzzelli et al., 2015).

From a technology management perspective, it has been proved that such attributes may point out if and how a firm relies on related (public) technologies, for instance by explaining the likelihood of firm formation (Shane, 2001), technology selling/acquisition (Nerkar and Shane, 2007; Sohn et al., 2013) and the commercialisation of environmental technologies (Chen et al., 2011). Furthermore, some studies have revealed that the three selected attributes affect the technological impact of patents (e.g., Fischer and Leidinger, 2014; Messeni Petruzzelli et al., 2015; Sterzi, 2013) - i.e., the impact of a patent on the development of any related and subsequent patents (e.g., Ahuja and Lampert, 2001) - even in the case of green energy technologies (Nemet, 2012).

As far as the setting under examination is concerned, the development of green energy technologies involves technological knowledge that covers a long time period and/or is subject to a faster (or slower) exploitation process (Nemet, 2012), hence highlighting the need to investigate the level of establishment of PRO technologies. Furthermore, the green energy sector may affect multiple industries (e.g., transportation, waste management, and energy production) and the respective technological development may rely on multiple knowledge domains (Benson and Magee, 2014; Guan and Yan, 2016), given the complexity that characterises such solutions (Carrillo-Hermosilla et al., 2010), which are usually more distant from the traditional sectorial knowledge base (De Marchi, 2012). Accordingly, Popp and Newell (2012) outlined that alternative energy technologies are more general than dirtier technologies, serve multiple sectors and are hence cited more often than other technologies. Furthermore, clean energy innovations are found to create more knowledge spillovers than dirtier innovations (Dechezleprêtre et al., 2014), so that their inventions are more pervasive and applicable than dirtier ones. It has recently been confirmed that environmental technologies differ significantly from non-environmental ones under multiple attributes (e.g., originality, radicalness and generality), including their scope (Barbieri et al., 2018). As far as the latter aspect is concerned, the higher a patent scope is, the greater the complexity of an invention, the higher the number knowledge components it would draw upon (Lerner, 1994). Green technologies have in fact been found to draw on more dispersed technological fields and knowledge components than other technologies (Barbieri et al., 2018).

Overall, this evidence would seem to suggest the need to investigate the energy technology realm to assess the effect of the selected technology attributes on the generation of green knowledge, given the specificities and differences from standard technologies.

2.1.1. The level of establishment

Prior research suggests that established technologies may positively impact subsequent technological development, since they are more codified than novel ones, and hence require an lower level of absorptive capacity (Dosi and Nelson, 2010; Heeley and Jacobson, 2008). Thus, it is easier and more cost-effective for firms that have not developed solutions to build on established technologies with fewer risks. Second, a better understanding of a given technology provides firms with more chances to come up with useful recombinant opportunities, which may then act as a catalyst for the generation of new technologies (Fleming, 2001; Savino et al., 2015). Third, the exploitation of established technologies is legitimated more by the operating market, because customers usually consider them as more familiar (Story et al., 2014). The evidence that green energy technologies that are more radical (especially in a systemic vision) and at their initial stage are considered by firms as less reliable and/or more costly than dirtier and already established solutions (Oltra and Saint Jean, 2009) is particularly relevant for the energy sector. This perception, in turn, increases the rigidity of the energy regime, which makes the entry and switching costs of less established green energy technologies higher (Geels et al., 2016; Wainstein and Bumpus, 2016), so that, in the absence of policy stimulus (including PRO innovations), technological lock-in and path dependence may lead firms and the market to favour established (and dirtier) solutions for future economic activities (Oltra and Saint Jean, 2009). Thus, the argument is that the higher the level of establishment of a PRO technology is, the more likely it is to influence a firm's own R&D efforts in the green energy field.

According to evidence collected for "standard" technological solutions, this positive effect deteriorates after a certain threshold, as a technology loses its potential exploitability (U-shaped effect) (e.g., Capaldo et al., 2017; Ardito et al., 2016a). Notwithstanding this, we do not expect to experience any inverted U-shaped effect in the green energy realm. In fact, we argue that the energy sector faces certain specificities that make the level of establishment of PRO technologies positively and linearly supportive of the technology development of an industry. These specificities are the high path dependency of the energy sector (see, e.g., Oltra and Saint Jean, 2009) and the evidence that industrial economies have suffered from a lock-in effect pertaining to "fossil fuel-based energy systems", which were augmented by the co-evolution of technological and institutional settings that were path dependent, to the advantage of dirtier technologies (Unruh, 2000). This is what has happened, for instance, in the automotive sector, in which the persistent dominant design of the more conventional engine technology (internal combustion regime) has led to continuous and incremental improvements to this technological path in order to make vehicles greener (more efficient and sustainable), at the expense of the less established technological path of alternative engine technologies (such as electric batteries, fuel cells, or hybrid vehicles) (Oltra and Saint Jean, 2009). Consequently, the transition to greener energy technologies is less mature and needs longer, so that no detrimental effect of the level of establishment may be expected. Therefore, PROs that aim at providing research externalities to industry may have a greater chance of attracting several companies, if they continue with the initial improvement of a certain green energy technology, instead of providing completely new solutions. In this way, they help firms rely on green energy solutions that might be relevant for the future objectives of the firms, but without the necessity of making them in-house, thus limiting the influence that the double externality problem has on the engagement of firms in environmentally friendly R&D activities (Hoppmann et al., 2013). Therefore, we expect that:

H1. The level of establishment of public environmental technologies has a positive effect on the related technological development of industry.

2.1.2. The scope of application

Recent research has revealed that non-innovating companies are more likely to build on technologies with a broad scope of application than on innovating ones (Novelli, 2015). Innovative firms in fact usually fail to protect and exploit broad technologies, because they do not have the complementary assets or internal capabilities required to pursue developments across all the potential domains in a timely manner (Gambardella and Giarratana, 2013; Rosenberg and Trajtenberg, 2004). On the other hand, given the high visibility of broad technologies, many non-innovating companies may come across them during their respective search processes and focus on the domain in which they are more expert or which needs a specific contribution to solve an ongoing issue (Lee and Lee, 2010; Novelli, 2015), and hence develop follow-up inventions that substitute the original ones. This in turn implies that the broader the technological solutions developed by PROs are, the more likely firms will be to come across those solutions and build on them. In other words, the scope of a technology signals its pervasiveness, and the higher this pervasiveness is, the more likely it is that relevant innovations will be developed, as occurs in the case of General Purpose Technologies (GPTs) (Bresnahan and Trajtenberg, 1995). The literature on GPTs shows interesting patterns that can partially be extended to this context, and which support the need to analyse technology attributes in depth. GPTs are currently benefiting from the recombination of knowledge from diverse knowledge areas, and their development is being affected by the technological attributes of the knowledge they build upon (Appio et al., 2017). The analysis of a patent's attributes (of any technology) may help to discern and predict whether it could become a transformative GPT or not (Feldman and Yoon, 2011). Technology attributes themselves affect the likelihood of their sustaining (or not) the diffusion of GPTs and the effects of GPTs on subsequent long-run economic growth (Andergassen et al., 2017).

The role played by this pervasiveness may be accentuated in the (green) energy sector because it is related to multiple domains (e.g., building, transportation, waste management and energy production) (OECD, 2012). Therefore, a number of different companies can encounter a green energy technology with a broad application scope.

Furthermore, the adoption of broad PRO technologies with environmental benefits may increase the competitiveness of firms. These solutions may be sources of competitive advantage for firms who build on existing technologies to develop new ones that expand existing (environmental) knowledge bases (De Marchi, 2012) without the costs associated with their internal development and, hence, going beyond a firm's core competencies (Teece et al., 1997). Moreover, even though several companies build on the same broad environmental technology, it may still be a source of competitive advantage, since not all the companies will adopt the technology on the same market or for the same application, given its pervasive nature. This is the case, for instance, of LED lighting technologies, which are considered important solutions within the energy conservation umbrella (WIPO, 2012). In fact, these technologies have been adopted by several firms in different kinds of industries (e.g., illumination, television, computers, and car manufacturing) to develop more energy efficient products, whose launching would have been hampered (or prevented) without the R&D programmes of some PROs, such as "LED lighting facts" by the US Department of Energy.[1] The foregoing discussion supports the hypothesis that:

H2. The scope of application of public environmental technologies has a positive effect on the related technological development of industry.

2.1.3. *The technological breadth*

Technologies resulting from wide searches are more likely to be understood by companies operating in different industries (Banerjee and Cole, 2010). This indicates that more companies may build on solutions with higher technological breadth. Accordingly, environmental technologies, such as energy ones, are multi-faceted in nature (Markard et al., 2012) and are more systemic than standard innovations (Carrillo-Hermosilla et al., 2010). Consequently, they may serve to spur further technological advancements. Moreover, the various companies that attempt to build on technologies with a high technological breadth may benefit from a large pool of potential links and associations between various knowledge domains, and this may in turn lead to more opportunities for knowledge recombination (Maggitti et al., 2013) and, hence, more chances of contributing to technological development (Fleming, 2001; Messeni Petruzzelli et al., 2015). Such recombinant opportunities are particularly relevant to allow firms to build on green energy technologies. Green energy technologies, based on multiple knowledge domains, are more likely to set the basis for future technological developments (Benson and Magee, 2014; Nemet, 2012) and thus they have a higher impact as they may be used to solve diverse technological problems while addressing environmental concerns (Ardito et al., 2016b). The work of Noailly and Shestalova (2017), who pointed out that renewable energy patents in general broadly serve external knowledge development, is an interesting example, as one-third of their citations came from technology fields other than power generation. More specifically, the authors established what external technology fields build most on the knowledge developed within the renewable energy field and found interesting specificities: *solar* patents are mainly cited for semiconductors, thermal processes and apparatus, and civil engineering; *wind* patents for electrical machinery, engines, pumps and turbines, mechanical elements and transport; *storage* patents for electrical machinery; *waste* and *biomass* for basic material chemistry, chemical engineering and environmental technology patents.

It may be expected that those PROs that combine more knowledge domains during their environmental research processes will find solutions of a higher impact on the technological development of industry. In addition, in the same way as for the development of environmental technologies, these benefits have been observed from an open innovation mode. In fact, the breadth of external knowledge sourcing has been found to positively influence the rate of adoption of those solutions (Ghisetti et al., 2015), since relying broadly on multiple knowledge sources provides firms with valuable knowledge flows which are later transformed into actual environmental technologies. This is especially true for green energy technologies, for which the lack of external knowledge sourcing in R&D has been found to be a detrimental barrier to their subsequent adoption and exploitation (Rennings and Rammer, 2009). Therefore, we hypothesise that:

H3. The technological breadth of public technologies has a positive effect on the related technological development of industry.

3. Data and methodology

3.1. *Industry setting*

The green energy field is a suitable field to test the proposed hypotheses for many reasons. First, although PROs are usually set up to provide scientific knowledge, their roles as technology providers has gained increasing importance in this specific context (Albino et al., 2014; Oltra et al., 2012). Second, patents are widely used to identify and examine green energy technologies (Guan and Yan, 2016; Nemet, 2012; Popp, 2017; Veugelers, 2012). Moreover, patent data allow several attributes of patented inventions to be identified and the degree to which they have impacted subsequent technological developments to be established (Kaplan and Vakili, 2015; Messeni Petruzzelli et al., 2015; Nerkar and Shane, 2007). Patent citations have also been discussed to obtain a good indication of knowledge transfer among inventors (Jaffe et al., 2000). Finally, many governments have changed their intellectual property policies to increase incentives for public research patenting (e.g., the Bayh-Dole Act). Consequently, the rate of PRO patenting has increased (Sterzi, 2013), especially in the green energy field (Albino et al., 2014; Hargadon, 2010). Therefore, patents can be considered as a reliable information source to conduct the present research.

3.2. *Data collection*

We first detected technologies developed by PROs in the green energy field by looking into patents registered at the USPTO and by labelling them as environmental on the basis of the IPC codes pertaining to the "Alternative energy production" and "Energy conservation" technology fields, as defined in the IPC Green Inventory (WIPO, 2012). All the patents related to the following macro categories: Bio-fuels; Fuel cells; Harnessing energy from manmade waste; Hydro energy; Wind energy; Solar energy; Geothermal energy; Other productions or uses of heat, not derived from combustion, e.g. natural heat and Using waste heat all belong to the first category. Those patents related to the following macro categories: Storage of electrical energy; Power supply circuitry; Low energy lighting; Thermal building insulation, in general and Recovering mechanical energy all belong to the second category. All the patents that matched our search criteria, but were not registered by a research organisation or were applied for after 2011, were excluded to allow enough time for the patents to be cited (e.g. Katila, 2002). Finally, websites, reports and other additional sources were

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[1] See http://www.lightingfacts.com/About.

scrutinised to distinguish between patents registered by private and public research organisations. This procedure yielded a final sample of 4363 patents that had only been developed by PROs during the 1976–2011 period. The final sample included patents by PROs established in diverse countries, such as the US Department of Energy, the French Commissariat à l'énergie atomique et aux énergies, the National Research Council of Canada, the Indian Council of Scientific and Industrial Research, and the Taiwanese National Tsing Hua University, which are also among the most patent-intensive public organisations in the world.

It is important to stress that our empirical design selected the patents, developed by PROs, which had been taxonomised as belonging to the green energy field in existing classifications as belonging to the green energy field, as detailed before, and not those firms or, more generally, the population of actors belonging to the energy sector. In other words, our definition of the green energy sector was driven by the patents (which constitute our unit of analysis) and not by the actors active in the energy sectors. This implies that, on the one hand, it has not been possible to perfectly overlap the evidence obtained from looking at aforementioned patents with the evidence regarding the status quo and the overall evolution of the sustainability of the energy sector, which is discussed elsewhere, for instance in recent ad hoc reports (EEA, 2018). On the other hand, we have not restricted our analysis on the subsequent technological development of the sector to actors who necessarily belong to this sector, i.e. we have looked at the industrial use of those patents, generated by PROs, that have been labelled as being related to the green energy field, regardless of whether the user of those patents is connected to the energy sector or not.

3.3. Variables

3.3.1. Dependent variable

Forward citations have been widely considered as a proxy for the impact of patents on subsequent technological developments (Arts et al., 2013; Kaplan and Vakili, 2015; Messeni Petruzzelli et al., 2015). In fact, "external citations indicate that other players have internalised part of the knowledge underlying the original invention and succeeded in building on it" (Novelli, 2015: 494). In line with this reasoning, the citations received by the patents in the sample were analysed to assess whether they had been referenced by patents developed by companies, in order to test whether PRO patents have had an impact on the technological development of the related industry. In other words, we identified the citing patents for each patent in our sample and to whom they belong. Once the owners of the citing patents had been identified, a distinction was made between those registered by firms and those registered by other types of assignees, such as universities and research organisations, single inventors and financing institutions. Finally, after checking the company names, the dependent variable (*IndustryTechDevelopment*) was built as follows:

$$IndustryTechDevelopment = 1 - \sum_F \left(\frac{C_{FP}}{C_P}\right)^2,$$

where C_{FP} indicates the number of times firm F cited focal patent P, while C_P is the total number of citations of patent P from patents owned by firms. This is a Herfindahl-type index, which is based on the generality index proposed by Trajtenberg et al. (1997). Unlike Trajtenberg et al.'s (1997) generality index, this measure does not account for the diverse technological classes of the citing patents; it instead considers the diverse firms that own the cited patents. The rationale behind this index is that the greater the variety of firms that own the cited patents is, the higher the impact of the PRO patent on the technological development of the industry.

This variable may alternatively be computed as a simple count of diverse firms that own at least one patent which cites a PRO patent. However, in this way, the actual degree to which the PRO patent affects the industrial sector would not emerge. This can be understood by considering the following example: let a patent receive 15 citations equally distributed among patents owned by companies A, B and C, and let a second patent also receive 15 citations, but 13 of them are from patents owned by company A, one citation is from company B, and one citation is from company C. The first invention actually has a wider impact on the industry than the second one, which mainly has an impact on company A. In addition, if we adopted a count measure, its value would be the same for the two patents (three). On the other hand, the Herfindahl index, *IndustryTechDevelopment*, would have amounted to 0.88 for the first invention and 0.24 for the second invention. The latter would better characterise the diverse impact of the two inventions, but the former would reflect a wider impact.

Furthermore, although this study covers a long period of time and there may be a bias towards older patents, in terms of forward citations, we are confident that our measure is still reliable for the following reasons. First, the most recent patents in our sample were filed for in the year 2011, with forward citations collected until the beginning of 2017. Hence, we have captured all the received citations for at least five years after the patent applications, which is considered the time span when patents obtain most of their citations (e.g., Griliches, 1987; Katila, 2002; Nooteboom et al., 2007). Second, our models include time-period effects to account for systematic intertemporal differences (see Section 3.3.3).

3.3.2. Independent variables

The first independent variable measures the extent to which a technology is established (*Established*). It is computed as the natural logarithm of the number of a patent's backward citations. The logarithmic transformation was adopted to correct for skewness and kurtosis.[2] The rationale behind this measure is based on previous studies that argued that the higher the citations made by a focal patent are, the higher the level of establishment (e.g., Ahuja and Lampert, 2001; Ardito et al., 2016a; Nerkar and Shane, 2007; Ziedonis, 2007). In fact, since a technology is often the result of a cumulative process over a technological trajectory (Dosi, 1982; Dosi and Nelson, 2010), it can be assumed that patents that refer to a large number of previous patents reflect inventions with a stronger link to a well-established technological paradigm (Dornbusch and Neuhäusler, 2015; Martinelli, 2012). Conversely, a small number of backward citations signal that a patent is disconnected from previous technical solutions, thus highlighting its novel nature (Ahuja and Lampert, 2001; Ziedonis, 2007). Second, according to the literature in this field, the scope of application (*Scope*) was operationalised as the number of different three-digit US classes assigned to each patent by USPTO (Lerner, 1994; Novelli, 2015). Finally, in order to assess the breadth of the technological base upon which a patent was built (*TechBreadth*), Trajtenberg et al.'s (1997) originality index was adopted (see also Arts et al., 2013). This index is computed through a Herfindahl index, which highlights the degree of diversification, in terms of technological classes, of the patents upon which a focal patent is based (i.e. the backward citations). Specifically:

$$Technological\ breadth = 1 - \sum S_{ij}^2,$$

where S_{ij} refers to the fraction of patents cited for patent i that belong to the three-digit US class j out of n technological categories assigned to the patents by USPTO.

3.3.3. Control variables

Several control variables were included to improve the reliability of our analyses. First, the scientific nature of the knowledge underlying a patented technology (*Scientific*) was accounted for by counting the

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[2] The skewness and kurtosis values before the logarithmic transformation were 7.78 and 93.81, respectively. After the logarithmic transformation, they decreased to zero and three, respectively.

number of patent references to non-patent documents (Narin et al., 1997). Since this variable was skewed and kurtotic, a logarithmic transformation was also used.[3] Second, a dummy variable that assessed whether a patent had been jointly developed by several organisations was included (value one) (*Joint*) (Messeni Petruzzelli et al., 2015). Third, we controlled for the number of patent claims (*Claims*) (Novelli, 2015; Reitzig, 2004). Fourth, we accounted for the number of inventors (Singh, 2008) who had been involved in the invention process (*TeamSize*). Fifth, since a patent may attract the attention of companies, whether it has been published in other patent offices or not, and whether the innovating organisation has been willing to pay renewal fees or not, we took into account the number of patent offices (besides USPTO) where the patent had been registered (*PatFamily*) (Reitzig, 2004) and whether the patent renewal fees had been paid at least once (*Renewal*) (Fischer and Leidinger, 2014). Sixth, we distinguished between PROs from universities, governmental organisations (e.g., the U.S. Department of Energy) and other public research centres (e.g., national research councils), each of which was represented by a dummy variable. Thus, we included two dummies (*dummy PRO*) to control for the different types of PRO, with the "University" PRO being the benchmark. Seventh, we also included dummy variables to control for relevant time period effects (*dummy period*). Time fixed effects were considered for 1976–1987, 1988–1997, 1998–2002 and 2003–2011, and the latter was considered as the benchmark. Eighth, we added a dummy variable to assess whether a PRO that owned a patent was US based (value one) in order to control for a potential country bias (*dummy US*). Finally, we included a dummy variable that took on the value of one if a patent was an "Alternative energy production" technology (*dummy AEP*), and zero in the case it referred to an "Energy conservation" technology.

3.4. Model specification

Since our focus has been on the technology attributes of an invention, the unit of analysis of this study is a single patent. Specifically, *IndustryTechDevelopment* has been operationalised through a Herfindahl index, which takes on continuous values, ranging from zero to one. Given the double bounded nature of this variable and its non-normal distribution, it falls into the category of limited dependent variables (LDVs) (Long, 1997). Therefore, we employed a Tobit regression (see, for example, Banerjee and Cole, 2010; Köhler et al., 2012). This type of regression is in fact suitable when the dependent variable is limited to a range of values and is not normally distributed (Long, 1997). Conversely, other types of regressions (e.g., OLS) cannot account for the nature of LDVs and tend to estimate incorrect parameters (Long, 1997; Wiersema and Bowen, 2009; Wooldridge, 2012). Furthermore, the bias in the fixed effect estimates, due to the "incidental parameter problem", is attenuated in the case of Tobit models (Greene, 2004).

4. Results

Tables 1 and 2 show the descriptive statistics and pairwise correlations, respectively. According to Table 2, the correlations are essentially low, with the exception of 0.66 for Technological Breadth and Establishment, but the maximum variance inflation factor for each model is below two, hence signalling the absence of severe multicollinearity issues (Cohen et al., 2013).

Table 3 presents the results of the Tobit regression. Model 1 is the baseline model, which only includes the control variables. Models 2–4 are the partial models, each of which contains one of the three independent variables. Model 5 is the full model. Model 1 reveals that PRO green energy patents have a wider impact on the industrial sector if the number of claims is high ($\beta = 0.008$, $p < 0.01$), and if they are owned by several organisations ($\beta = 0.057$, $p < 0.10$), have been renewed at least once ($\beta = 0.244$, $p < 0.01$) and the PRO is US based ($\beta = 0.110$, $p < 0.01$). The opposite effect can be ascribed to the reliance on basic research ($\beta = -0.081$, $p < 0.01$), team size ($\beta = -0.011$, $p < 0.05$), and the development of an "Alternative energy production" technology ($\beta = -0.246$, $p < 0.01$). Model 2 tests H1 and suggests that the level of establishment is positively related to *IndustryTechDevelopment* ($\beta = 0.114$, $p < 0.01$), according to H1. In line with H2, Model 3 reveals that the scope of application has a positive impact on the technological development of an industry ($\beta = 0.027$, $p < 0.01$). Finally, Model 4 supports H3, in that the coefficient of *TechBreadth* is positive and significant ($\beta = 0.296$, $p < 0.01$). We added the squared term of the independent variable under analysis to establish robustness for each partial model. No squared terms resulted significant, thus confirming the initial hypotheses (see Models 2a, 3a, and 4a). The full model also corroborated the results of the partial models. In addition, we measured the patent scope considering the number of diverse sub-classes instead of the number of different three-digit IPC classes. All the hypotheses continued to be supported in this case.

5. Discussion and conclusion

Boosting the development of green energy solutions by the private sector is pivotal for policymakers in order to simultaneously improve economic growth and environmental benefits (Hoppmann et al., 2013; Rennings, 2000). The aim of public research is to correct market failures (e.g., the double externality problem) while hampering private environmental R&D efforts, yet PROs often fail to achieve this goal (Balachandra et al., 2010). Furthermore, it has been pointed out that green technologies differ substantially from non-environmental ones, both as far as their nature and their impacts are concerned, not only because of their "double externality" nature, but also because they are more complex and have a greater and more pervasive impact on the subsequent related inventions (Barbieri et al., 2018).

Therefore, the present paper has been aimed at understanding under which conditions the research outcomes of PROs influence the technological development of an industry in the green energy sector. To do so, the attributes of PRO technologies (i.e., the level of establishment, the scope of application, the scientific nature, and the technological breadth) have been analysed.

A Tobit regression, which was conducted on a sample of 4363 patents registered by PROs during the 1976–2011 period, and which were classified as "Alternative energy production" or "Energy conservation" technology fields, revealed that the level of establishment, the scope of application and the technological breadth had a positive effect on the degree to which many companies will build on PRO research outcomes, thus supporting our conjectures. Considering that "understanding the impact of public research on industrial R&D is central to understanding the innovation process itself" (Cohen et al., 2002: 1), these results provide relevant theoretical and policy implications.

5.1. Theoretical implications

From a theoretical perspective, this research has investigated a novel and understudied set of antecedents (i.e., technology attributes) that may help explain when the outcomes of public R&D efforts in the green energy field provide externalities for the industry sector. To the best of our knowledge, prior research has widely investigated the policy incentives that foster private R&D activities (e.g., public subsidies) (e.g., Hoppmann et al., 2013; OECD, 2012), but negligible efforts have been devoted to examining situations in which the results of public research have an impact on the industrial sector by explicitly focusing on the same nature of the technological results as this research.

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[3] The skewness and kurtosis values before the logarithmic transformation were 11.57 and 254.98, respectively. After the logarithmic transformation, they decreased to 0.68 and 2.72, respectively.

Table 1
Descriptive statistics.

	Mean	Std.	Min	Max	Description
IndustryTechDevelopment	0.287	0.350	0.000	0.972	Modified generality index (Trajtenberg et al., 1997), with a focus on the owners of citing patents instead of their technological classes.
Established	1.759	0.966	0.000	5.505	# backward citations.
Scope	2.043	1.100	1.000	10.00	# different three-digit US classes.
TechBreadth	0.3861	0.299	0.000	0.9158	Originality index (Trajtenberg et al., 1997).
Scientific	1.434	1.375	0.000	6.982	# citations to non-patent documents.
Joint	0.121	0.327	0.000	1.000	1 if a patent is owned by more organisations, 0 otherwise.
Claims	14.793	11.337	1.000	99.00	# claims.
TeamSize	2.971	1.938	1.000	24.00	# patent inventors.
PatFamily	1.391	1.333	0.000	5.000	# patent offices, besides the UPTO, in which the patent is also published.
Renewal	0.678	0.467	0.000	1.000	1 if the patent has been renewed, 0 otherwise.
Dummy US	0.540	0.498	0.000	1.000	1 if a patent is owned by a US PRO, 0 otherwise.
Dummy AEP	0.786	0.410	0.000	1.000	1 if a patent is in the "Alternative energy production" technology field, 0 otherwise.

$n = 4363$.

Table 2
Pairwise correlations.

	1	2	3	4	5	6	7	8	9	10	11	12
1-IndustryTechDevelopment	1											
2-Established	0.119*	1										
3-Scope	0.067*	−0.006	1									
4-TechBreadth	0.113*	0.666*	0.150*	1								
5-Scientific	−0.239*	0.047*	0.148*	−0.011	1							
6-Joint	−0.084*	−0.002	0.078*	−0.017	0.207*	1						
7-Claims	0.075*	0.169*	0.126*	0.141*	0.221*	0.020	1					
8-TeamSize	−0.163*	−0.024	−0.011	−0.022	0.123*	0.206*	0.002	1				
9-PatFamily	−0.141*	−0.035*	0.133*	−0.032*	0.314*	0.169*	0.156*	0.119*	1			
10-Renewal	0.129*	0.027	0.027	0.007	0.057*	0.010	0.120*	0.024	−0.013	1		
11-Dummy US	0.209*	0.099*	0.019	0.040*	0.125*	−0.100*	0.077*	−0.181*	−0.254*	0.035*	1	
12-Dummy AEP	−0.053*	−0.176*	0.104*	−0.202*	0.145*	0.127*	−0.087*	0.014	0.090*	−0.057*	0.116*	1

$n = 4363$.
* $p < 0.05$.

We have revealed that investigating the role of technology attributes is relevant to assess the impact of public environmental research on the technological development of an industry, in particular with reference to the green energy field, which has been at the core of academic (e.g., Barbieri et al., 2016; Hoppmann et al., 2013) and political debates (OECD, 2012; OECD/IEA, 2015). These technologies present distinctive features with respect to standard technologies, and hence call for ad hoc investigations. Moreover, their role has been proved to be central to move towards a low-carbon society (Benson and Magee, 2014; Nemet, 2012). Notwithstanding this, these studies have not provided insights about the potential influence of technology-level factors, such as technological attributes, to explain whether green energy technologies, developed by PROs, have an impact on the subsequent research and technological activities of firms.

Moreover, among the few studies that have examined the results of public research in promoting R&D initiatives related to the private sector (e.g., university-industry-government collaborations and Spin-off creation) (e.g., Bruneel et al., 2010; Dornbusch and Neuhäusler, 2015), very few of them have narrowed the level of analysis to the technology level (e.g., Shane, 2001), which, instead, has been proved to be pivotal to understand innovation phenomena and the impact of developed technologies (e.g., Chen et al., 2011; Nerkar and Shane, 2007). In the same way, studies that have examined public-private knowledge transfer have mainly focused on firm/university characteristics, modes of knowledge transfer and proximity dimensions (e.g., geographic) (Agrawal, 2001; Azagra-Caro et al., 2017; Lindelöf and Löfsten, 2004). However, except for in the work of Bekkers and Bodas Freitas (2008), knowledge specific characteristics (e.g., codification) have been undervalued; additionally, whether these knowledge characteristics help firms improve their innovation processes has remained unclear. These arguments help to point out the relevance of our contribution, which refines earlier works on the influence of public research on the industrial sector by offering empirical evidence about the role of technology attributes.

Finally, this study also contributes to the discussion on "where" to measure the influence of a (green) technology. In fact, a technology may influence the technological landscape in which R&D efforts succeed within or beyond a technological, geographic or institutional domain (see, for example, Ardito et al., 2016b; Messeni Petruzzelli et al., 2015). In line with this perspective, our results highlight when (green) technologies belonging to the public domain have an impact on the industrial sector. These results may be added to the literature on research evaluation (e.g., Bornmann and Marx, 2014; Lyall et al., 2004). This literature claims that measuring the societal benefits of public research is still a complex task, and we believe our approach may have provided further insights on how to measure the societal impact of public research, in light of its influence on achieving sustainable goals.

5.2. *Policy implications*

From a policy perspective, we have provided guidance on how governments can allocate public funds to develop green energy technologies in order to play a relevant role in the technological development of an industry. We advise policymakers that the attractiveness of such public technologies is not the same for all companies. Therefore, when it is relevant to produce research externalities for the industrial sector, policymakers should design funding schemes that are devoted specifically to developing explicit types of technical solutions. In turn, it is important that PROs receive clear indications regarding the R&D outcomes they are expected to produce. Therefore, we suggest that policymakers should invest in strengthening their networks with corporate executives in the green energy field to obtain a better

Table 3
Results of Tobit regression (with robust s.e.).

	Model 1	s.e.	Model 2	s.e.	Model 2a	s.e.	Model 3	s.e.	Model 3a	s.e.	Model 4	s.e.	Model 4a	s.e.	Model 5	s.e.
Established			0.114***	0.010	0.114***	0.010									0.095***	0.013
Established2					−0.008	0.009										
Scope							0.027***	0.009	0.067**	0.027					0.020**	0.009
Scope2									−0.007	0.005						
TechBreadth											0.296***	0.032	0.355***	0.108	0.096**	0.041
TechBreadth2													−0.081	0.141		
Scientific	−0.082***	0.009	−0.081***	0.009	−0.079***	0.009	−0.084***	0.009	−0.085***	0.009	−0.080***	0.009	−0.079***	0.009	−0.082***	0.009
Joint	0.057^{+}	0.032	0.047	0.032	0.047	0.032	0.052	0.032	0.050	0.032	0.049	0.032	0.049	0.032	0.042	0.032
Claims	0.008***	0.001	0.007***	0.001	0.007***	0.001	0.008***	0.001	0.008***	0.001	0.007***	0.001	0.007***	0.001	0.006***	0.001
TeamSize	−0.011*	0.005	−0.011*	0.005	−0.010^{+}	0.005	−0.011^{+}	0.005	−0.011*	0.005	−0.011*	0.005	−0.011*	0.005	−0.010^{+}	0.005
Family	0.012	0.008	0.014^{+}	0.008	0.014^{+}	0.008	0.010	0.008	0.010	0.008	0.014^{+}	0.008	0.014^{+}	0.008	0.012	0.008
Renewal	0.244***	0.022	0.230***	0.021	0.228***	0.021	0.244***	0.022	0.244***	0.022	0.241***	0.022	0.240***	0.022	0.232***	0.021
Dummy PRO	Included		Included		Included		Included		Included		Included		Included		Included	
Dummy period	Included		Included		Included		Included		Included		Included		Included		Included	
Dummy US	Included		Included		Included		Included		Included		Included		Included		Included	
Dummy AEP	Included		Included		Included		Included		Included		Included		Included		Included	
Constant	−0.470***	0.039	−0.679***	0.044	−0.679***	0.044	−0.510***	0.041	−0.552***	0.049	−0.605***	0.042	−0.609***	0.043	−0.717***	0.046
Log Pseudolikelihood	−2612.57		−2550.48		−2550.49		−2607.51		−2605.98		−2569.26		−2569.10		−2543.11	
F statistic	221.94***		215.33***		215.33***		208.45***		194.54***		215.73***		201.75***		191.70***	
Multiple Squared Correlation	0.382		0.401		0.401		0.384		0.384		0.395		0.395		0.405	

$n = 4363$.

$^{+}$ $p < 0.10$.

** $p < 0.05$.

*** $p < 0.01$.

understanding of their technology needs. In this way, the environmental and business requirements may be better matched and there will therefore be more chances for governments to supply relevant green energy technologies to the industrial domain, in order to set the basis for their future research activities.

More in detail, we have found that green energy technologies that are more established are more likely to have an impact on the technological development of an industry. Although it may appear that this result suggests policymakers should disregard more basic research, we advocate that PROs should instead focus on both basic and applied research. In other words, PROs should continue refining a technology until it reaches a level that may be understandable and usable by companies, without necessarily limiting their efforts to the creation of a new solution. This may also help to overcome the double externality problem that private research activities have to face by reducing knowledge leakage and uncertainty. Whether a policy can be designed accurately to this aim, is certainly hard to say. However, we retain that technological knowledge generated by PROs (be it more established or less established) can affect the technological development of an industry at two stages (early and mature), and both stages should be stimulated in an appropriate way. On the other hand, sustaining only more established – and mature – technologies, may come at the price of not witnessing a rise in future radical advancements, which may even serve future economic growth by serving as GPTs. Accordingly, the scope of application and technological breadth were both revealed to be core attributes that help make green energy technologies more usable by firms. This implies that green technologies that can readily be applied to diverse domains or which are grounded on a knowledge base that enables several recombinant opportunities will likely spread more easily to multiple companies. Therefore, policymakers are advised that developing more pervasive green solutions or green solutions that are based upon broad innovation activities will sustain the related technological development of an industry.

5.3. Limitations

Some limitations of the current study could not be solved and have been left for future research. First, although the use of patents to capture technology development is widely diffused, especially in the green energy field (Albino et al., 2014; Hoppmann et al., 2013; Popp, 2006), some inventions have not been patented and/or are not patentable. Hence, direct interviews with companies and policymakers would help to close this information gap and would allow the additional characteristics of technologies (e.g., operational complexity) that cannot be captured through patent measures to be scrutinised. Second, in this research, we have only focused on the role of technology attributes, given the limited attention they have received, to analyse the impact of public research. However, we acknowledge that organisational- and environmental-level factors might moderate the technology-level relationships between the attributes of PRO technologies and the technological development of an industry, and this aspect would require multilevel analyses. Third, although the energy sector has been considered particularly relevant for this research, other green domains could also be investigated to ensure the generalisability of the results. Fourth, a properly designed counterfactual impact evaluation could be an important future extension of the work. It could be aimed at testing whether PRO knowledge would have a greater/less impact on the green energy field than knowledge created elsewhere (and by how much). The current design does not allow such a test to be conducted. Finally, from a purely environmental viewpoint, the analysis and its findings do not necessarily imply a positive environmental impact. In other words, it is not known whether the technology attributes under study positively affect the technological development of an industry at the cost of creating technological lock-ins that hamper the uptake of cleaner technologies. However, this kind of investigation is beyond the scope of the current contribution and deserves further ad hoc investigations.

Acknowledgment

The scientific output expressed does not imply a policy position of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use which might be made of this publication.

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