Green Technological Diversification: The Role of International Linkages in Leaders, Followers and Catching-Up Countries

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Abstract

To promote a more environmentally sustainable economy, countries need to broaden their innovation activities to include green technologies. In this process, the increasing global interconnectedness and internationalisation of innovative activities underlines the growing importance of external knowledge linkages. This paper examines how different categories of countries - technological leaders, catching-up countries and follower countries - diversify into green technologies by exploiting different types of external linkages through co-inventions with international partners. The dataset covers 49 countries over a period of 40 years. The results show that it is complementary linkages, rather than external linkages alone, that facilitate related diversification in the green sector. Moreover, while complementary linkages have a significant impact on the ability of catching-up countries and followers to diversify into less complex and widely diffused green technologies, the diversification pattern of leaders is more oriented towards complex technologies in their early stages. Therefore, green technology development policies should actively promote international cooperation as it has the potential to catalyse green catching-up and foster sustainable growth.

Keywords: technological diversification, green technologies, co-inventor linkages, relatedness, catching-up

JEL: O33, Q55

1. Introduction

The development and diffusion of new low-carbon and clean technologies are crucial for achieving a global green economy (OECD, 2011b,2021; Roson and Van der Mensbrugghe, 2012; Haščič and Migotto, 2015; Fabrizi et al., 2018), which means that sustainability depends essentially on technological change (Smith, 2007; Pearson and Foxon, 2012; Dechezleprêtre et al., 2011 and 2013; Gibbs and O'Neill, 2018), a cumulative, strongly endogenous and path-dependent and iterative process (Dosi, 1988). This is causing many countries to diversify to include new economic and technological activities that are related to already existing local activities (Hidalgo et al., 2018).

This path-dependent pattern seems to be holding for green technologies (Montresor & Quatraro, 2020; Perruchas et al., 2020; Santoalha and Boschma, 2020; Moreno and Ocampo Corrales, 2022), which is raising questions about which countries have the capabilities required for the green technology transition and how those economies that lack such capabilities can be helped. Several studies show that international sources of knowledge are particularly beneficial for latecomer economies to allow catch up with the leaders in certain sectors and technologies (Malerba & Lee, 2021; Park & Lee, 2006), including clean technologies (Amendolagine, et al. 2021; Lema et al., 2020). International connectedness and access to foreign green knowledge is enabled by co-patenting (Waltz et al., 2017; Corrocher and Mancusi, 2021), R&D collaborations (Ardito et al., 2018; Marin and Zanfei, 2019), exports (Aguilera-Caracuel et al., 2012; Chiarvesio et al., 2015) and Foreign Direct Investment (FDI) (Maksimov et al., 2019; Amendolagine et al., 2021). However, international connectedness may not be sufficient to enable a full exploitation of foreign knowledge and diversification into new technological fields: of importance, also, are the environmental strategies and/or local capabilities possessed by firms/countries and the types of actor links.

Empirical research shows that access to external capabilities and foreign knowledge triggers technological diversification (Bahar et al. 2020; Santoalha, 2019; Whittle et al., 2020; Zhu et al., 2017; Miguelez and Morrison, 2022; Moreno and Miguelez, 2018). In the case of green technologies, this diversification process is supported by technological relatedness or the cognitive proximity between an existing and the new technology and the knowledge bases of firms, regions and countries (Tanner, 2015; Montresor and Quatraro, 2019; Santoalha and Boschma, 2020; Moreno and Ocampo Corrales, 2022). There is evidence, also, that the important role played by relatedness depends critically on the level of development of local capabilities. Most studies show that relatedness tends to be more important for countries/regions with low levels of economic development (Petralia et al., 2017; Moreno and Ocampo Corrales, 2022).

The present paper examines the process of green technological diversification by technology frontrunners versus technology latecomers, with a specific focus on the role of international linkages based on co-inventors. The study builds on the literature on ‘catch up’ (Malerba and Nelson, 2011) and distinguishes between established technology leaders and emerging technology users. The catch-up process can result in a leadership change and former leaders falling behind and becoming followers and latecomers catching up with the group of technological leaders (Lee and Malerba, 2017). In line with recent contributions in the 'relatedness' literature (Balland and Boschma, 2021), we focus on international linkages, measured by co-invention and green patents. Specifically, we analyse the role of international complementary linkages, that is, co-inventions related to the country’s existing knowledge domain as opposed to actual international linkages. We contend that relatedness between local and external capabilities is crucial for the process of green diversification and that external capabilities that complement local capacity are particularly conducive to diversification. This is because the absorption of external knowledge will be easier if it is related to the country’s existing knowledge base (Balland

& Boschma, 2021; Moreno and Ocampo Corrales, 2022). In particular, technology latecomers with weak innovation capabilities can be expected to benefit more from external linkages with countries able to contribute complementary knowledge. Our arguments are supported by regional evidence, (e.g., Boschma and Capone, 2015; Cortinovis et al., 2017; Xiao et al., 2018). However, it has been suggested that external linkages may mediate the role of relatedness. Also, recombinations of unfamiliar external knowledge with local knowledge can create new and unrelated technological specialisations (Miguelez and Moreno, 2018).

This applies, especially, to the technology leaders who are able to leverage their accumulated knowledge and competencies. There are two main reasons why these arguments are particularly salient to green technologies. First, green technologies are characterised by high levels of complexity and uncertainty (Barbieri et al., 2020) and existing local capabilities may not be sufficient to enable diversification into complex (and possibly unrelated) technologies. This is especially true in an economic landscape characterised by strong global interdependencies (Li et al., 2020; Yeung, 2021). Second, the public good nature of climate change amplifies the potential benefits and externalities produced by international collaborations in the development of environmental innovations. The greater tendency of countries to collaborate more frequently in relation to climate change mitigation technologies compared to other technological domains would seem to confirm this (Haščič et al., 2012; Shapiro et al., 2014; Corrocher and Mancusi, 2021). Therefore, understanding the role of international linkages in technological diversification is particularly relevant in the specific context of green technologies (Haščič and Migotto, 2015).

The present paper provides new evidence on how different types of countries - technological leaders, catching-up countries, and followers – are able to focus their innovation activities on green technological diversification, through external linkages and co-invention with international partners. We address the following research questions: What types of international co-inventor linkages promote the national green diversification process? Do these effects differ among leaders, catching-up countries and followers? Do international linkages promote a process of related or unrelated diversification?

Our investigation of these three questions contributes to various literature strands. First, we add to research on green technological diversification and relatedness. The existing literature is focused overwhelmingly on Europe (Castellani et al. 2022; Montresor and Quatraro, 2020; Cicerone et al. 2023; Santoalha and Boschma, 2021; Santoalha et al. 2021; Barbieri et al. 2023; Moreno and Ocampo Corrales, 2022) or a few large countries such as the USA and China (Barbieri and Consoli, 2019; Ning and Guo, 2022). Our work is global in scope and includes both emerging and advanced economies. The relatedness literature also mostly neglects the significance of external linkages (Boschma, 2017; Yeung, 2021), which, apart from the notable exception of Castellani et al. (2022), applies to research on green technologies. Our work complements this body of work by focusing explicitly on international linkages and their role in explaining patterns of related or unrelated diversification. Second, our study extends existing research exploring the impact of global connectedness on countries' and regions' green growth and technological development (Marin and Zanfei, 2019; Corrocher and Mancusi, 2021; Amendolagine et al., 2021; Castellani et al., 2022), by examining the specific role of international complementary linkages. The literature has examined the role of FDI, trade and overseas R&D investments as channels of international connectedness that may stimulate green innovations and mitigation of environmental changes. However, few studies investigate the effect of international co-inventorships in the green diversification process. Most studies focus solely on renewable energies, which are just a subset of green technologies. Third, the provision of large-scale quantitative evidence from various sectors contributes to work on catch-up in green technologies. This evidence allows more generalisation of recent empirical findings from specific green sectoral cases (e.g., Lema et al., 2020) and provides insights into the differences between leader, catching-up and follower countries in terms of the impact of international connectedness on the process of green diversification.

The empirical analysis is based on United States Patent and Trademark Office (USPTO) patent data from 1975 to 2015, covering 49 countries and 250 seven-digit CPC green technologies. An entry model is used to test the relationship between international co-inventor linkages and the development of new green technological specialisations by groups of countries. To assess the type of linkages considered most influential, we apply Balland and Boschma's (2021) measure of complementarity. The results indicate that complementary linkages facilitate green-related diversification, which involves the emergence of a new green technological specialisations related to the country's existing knowledge portfolio. This supports the notion that complementary linkages lead to a path-dependent development process, which is especially pronounced in the cases of follower and catching-up countries. Our study demonstrates that leaders and catching-up/follower countries exhibit distinct patterns of green diversification. Catching-up countries and followers can achieve green technology diversification based on complementary linkages. In contrast to the case of leaders, the ability of followers to diversify into green technologies increases significantly in the presence of links to other countries with complementary capabilities. Technology leaders tend to diversify into complex technologies that are in their infancy, whereas catching-up and follower countries are likely to diversify into less complex and more well-diffused technologies. These findings suggest that green technology development policies should actively promote international collaboration in order to facilitate green catch-up and sustainable growth. In particular, followers need to pay special attention to the technological complementarity with partner countries, since this could stimulate a long-term shift in the innovation capacity of local actors and the accumulation of knowledge and competences required for sustainable growth.
The paper is structured as follows: Section 2 reviews the literature on technological diversification, the role of external linkages and green technologies. Section 3 – the empirical analysis – describes the data, the methodology and the variables used and presents the findings. Section 4 concludes the paper and suggests some directions for future research along with some implications for policy.

2. Green technology diversification and external linkages: A literature review

Diversification into green technologies is considered a priority by governments in a range of different geographical contexts (Mazzucato and Perez, 2015; Lema et al., 2020). It is seen as important for the sustainable growth of countries and regions. However, diversifying in green technologies depends on a set of demand, supply and institutional factors that vary considerably across countries. These factors are dependent, also, on the level of national technological development (Lema et al., 2020; Malerba et al., 2020; Moreno and Ocampo-Corrales, 2022) and global connectedness (Amendolagine et al., 2021 and 2023; Castellani et al., 2022). The public nature of climate change and the characteristics of green technologies means that international linkages and cross-country cooperation play a crucial role in promoting green technological developments (Haščič and Migotto, 2015; Corrocher and Mancusi, 2021).

Green technologies tend to be more complex and innovative than their non-green counterparts. They feature unique combinations of larger amounts and a larger variety of knowledge (Barbieri et al., 2020; Santoalha et al., 2021). They also have greater spillover effects that affect subsequent inventions and a wider range of technological domains (Barbieri et al., 2020). Finally, green technologies entail higher risk and more uncertainty than other types of investment since they are in the initial stages of development and do not benefit from increasing returns. The distinctiveness of the green knowledge base is supported by firm-level evidence (Cainelli et al., 2015; Ghisetti et al., 2015). This suggests that developing green technologies is a complex endeavour that not all countries are able to undertake relying solely on their domestic capabilities. Accessing foreign knowledge and building the endogenous domestic capabilities required to achieve green technology diversification often requires global connections. Connectedness to the global economy and absorption of external capabilities are significant for the green diversification process. External linkages are essential to prevent the lock-in and stagnation that can result from an inward-looking and over-embedded local innovation system (Uzzi, 1997). These external links provide access to non-redundant knowledge (Morrison et al., 2013) that complements domestic knowledge and can trigger new knowledge recombinations. These are especially relevant in the case of the diversification opportunities of latecomer countries. Their location on the periphery of the product and technology spaces means that their ability to enter core areas and catch up with the leader countries, is limited (Zhu et al., 2017). External linkages can be crucial for overcoming internal constraints and enabling diversification and simultaneous investment in local technological capabilities, at both the country and regional levels (Andersson et al., 2013; Santoalha, 2019; Whittle et al., 2020).

Research on green technologies shows that international connections are crucial for accessing green knowledge (Amendolagine et al. 2021; De Marchi et al. 2022) and promoting green technological diversification (Castellani et al. 2022). The global connectedness of middle-income countries, particularly China and India, is particularly important (Amendolagine et al. 2023). Similarly, evidence based on co-patenting indicates that emerging economies utilise this channel to obtain access to international knowledge (Corrocher and Mancusi, 2021).
However, international connectedness, on its own, is not sufficient to enable the development of green technologies. The environmental strategies and local capabilities of firms/countries and the types of actors they are connected to, are also crucial (Aguilera-Caracuel et al., 2012; Maksimov et al., 2019; Amendolagine et al., 2023; Corrocher and Mancusi, 2021).

The analysis in Balland and Boschma (2021) is particularly relevant to our study. It focuses on the knowledge complementarity of regions and highlights the importance of connections with specific individuals rather than external linkages in general. The underlying idea is that regions require a certain level of absorptive capacity to utilize external capabilities effectively (Miguelez and Moreno, 2015). Therefore, establishing connections with external knowledge sources that complement and are related to the local knowledge base can stimulate the diversification process. This is especially relevant for peripheral countries, whose local capabilities and networks are typically weaker than those in more advanced nations. This argument is supported, also, by the literature on technology catching-up. It shows that tapping into foreign knowledge can compensate for domestic gaps and pave the way to successful catching-up (Figueiredo and Cohen, 2019; Morrison and Rabellotti, 2017). Followers can benefit from connectedness to leading countries to gain access to high-quality capabilities (Malerba and Lee, 2021). Foreign technology acquisition has been important for enabling emerging economies, such as China, to overtake the leaders in various green sectors, including renewables (Lema et al., 2020).

In addition to the significance of international and interregional connections, the crucial role of relatedness in the development of green technologies is confirmed by an increasing number of studies, such as Montresor and Quatraro (2020), Cicerone et al. (2023), Santoalha and Boschma (2021), Santoalha et al. (2021), Barbieri et al. (2023), Moreno and Ocampo Corrales (2022), Barbieri and Consoli (2019), and Ning and Guo (2022). This body of work provides an extensive examination of the factors driving technological diversification and indicates that local capabilities, embedded in actors based in countries, regions and or cities, are crucial determinants of technological diversification (Boschma and Martin, 2007). Empirical research supports this claim and highlights the path-dependent nature of diversification and the principle of relatedness (Hidalgo et al., 2018). Economies tend to diversify into new economic activities that are related to existing capabilities. However, although diversification in related technologies is often the norm, countries occasionally may deviate from this pattern and develop completely new, unrelated technologies (Boschma and Capone, 2015; Petralia et al., 2017; Pinheiro et al., 2018, 2021). Although unrelated diversification is a less common and more risky undertaking, it potentially is lucrative. It helps to avoid lock-in (Saviotti and Frenken, 2008), enables significant shifts in local capabilities (Neffke et al., 2018) and is associated with radical innovation (Castaldi et al., 2015). Several papers specifically examine green technologies in European regions. Santoalha and Boschma (2020) confirm that relatedness plays a profound role in the process of green technological diversification, and one that is more important than political support. Montresor and Quatraro (2020) found that having links to both green and non-green pre-existing knowledge, facilitates green technological diversification. Similarly, Barbieri et al. (2023) map the green and non-green capabilities in EU regions and show that the former rely on the latter. In terms of relatedness, Santoalha et al. (2021) suggests that relatedness plays a more significant role in development of non-green as opposed to green specialisations. This somewhat intriguing result implies that green diversification may depend more on the combination of knowledge domains that are further apart. Moreno and Ocampo-Corrales (2022) demonstrate that relatedness plays a crucial role in determining regional specialization in renewable energy technologies compared to other green technologies. This effect is particularly pronounced in regions with low levels of economic development. Ning and Guo (2022) extend their study by examining the moderating effect of relatedness; they found a curvilinear relationship with innovation in China. Perruchas et al. (2020) analysed a sample of 63 countries, including both emerging and advanced economies, and confirmed the significant role of relatedness in green technological diversification and specialisation. They suggest, also, that complexity does not hinder this process.

Building on the previous discussion of the importance of global connectedness and recent work on relatedness for green diversification, we argue that being involved in external linkages could shed light on the more infrequent, riskier, but more profitable unrelated diversifications (Pinheiro et al. 2018). External linkages may work to mediate the role of relatedness. External knowledge is often technologically distant and unrelated to local knowledge. Combining local and external knowledge may therefore create opportunities for new forms of knowledge recombinations (Miguelez and Moreno, 2018). The existence of international linkages could reduce the role of relatedness and enable more varied forms of diversification. Recent studies would appear to support this view. Zhu et al. (2017) demonstrate that international trade and FDI in Chinese provinces support unrelated diversification. Similarly, Elekes et al. (2019) in a study of manufacturing firms in Hungarian regions, found that foreign-owned firms induce more unrelated diversification than do domestic firms. Neffke et al. (2018) show that firms relocating from outside the region foster new activities. Choudhury and Kim (2019), Miguelez and Morrison (2021), and Di Iasio and Miguelez (2022) demonstrate the effect of migrant inventors on promoting diversification in respectively firms, regions and countries. Moreno and Miguelez (2018) show that extra-regional knowledge is important in EU regions, particularly for spurring breakthrough innovation while Castellani et al. (2022) found that green FDI in EU regions tends to favour, mainly, related diversification. However, Castellani and colleagues note, also, that unrelated specialisations emerge if the FDI has a strong R&D component.

The literature explores the impact of international linkages and relatedness on green diversification, but mostly in the case of advanced economies and, particularly, European countries. This paper represents an advancement; it combines perspectives and examines the effects of technological relatedness and international linkages. It investigates the contribution of external linkages for both related and unrelated green technological diversification in technological leader countries, catching-up countries and follower countries - and across a large set of green technologies. Building on existing research, we examine the relationship between external linkages and relatedness to determine whether a country's international connections encourage unrelated diversification, which involves exploring new technological domains not yet developed domestically. Promoting the growth and diffusion of green technology relies on international partnerships (e.g., co-patenting) related to green technology developments (Waltz et al., 2017). Green innovations often require the combination of knowledge from different fields and actors across countries (Noailly and Dyfisch, 2015; Barbieri et al., 2020; Corrocher and Mancusi, 2022). Understanding diversification patterns, enabled by international technological collaborations in green technologies, can determine how developing countries that are behind the technology frontier are able to engage in research into and dissemination of these technologies. To investigate this we examine how much the type of partner (connection) matters in terms of knowledge and technology complementarity and how external linkages interact with relatedness in explaining the process of green diversification.

We are interested, also, in whether the relationship between external linkages and relatedness varies across different countries. We evaluate the influence of these two factors in the process of green catching-up by followers and the consolidation of green leadership by leaders. The notion that green specialisation is associated with distinct patterns and international linkages, is consistent with the extensive literature on green catch-up (Fu and Zhang, 2011; Binz et al., 2020; Dai et al., 2020; Corrocher et al., 2021). The literature suggests that leadership in green technologies varies over time and across technological domains. Some latecomers have leapfrogged and have overtaken the traditional leaders (Dechezleprêtre et al., 2013; Haščič and Migotto, 2015; Corrocher et al., 2021). However, followers often lack the knowledge, skills and resources required for large-scale production and distribution. In this case, international partnerships with foreign players are crucial to enable the benefits of cooperation and development of green technologies (Shapiro, 2014; Haščič and Migotto, 2015; Zhu et al., 2017). It is assumed that follower countries gain significant advantages from collaborative complementary connections. Leaders' exploration of new technological specializations is often linked to emerging technologies. Leaders are able to leverage their established capacities and accumulated knowledge to enable innovative and revolutionary technology activities. For these countries, external complementary linkages may promote unrelated diversification. We address the question of whether the effects of external linkages and the relationship between linkages and relatedness differ among leaders, catching-up countries and followers.

3. Data, Variables and Methods

3.1. Data sources

The empirical analysis is based on PATSTAT patent data from 1975 to 2015. The PATSTAT database includes patents registered at national patent offices. To ensure consistency, we selected patent applications to the USPTO. selected patents that were applied for at the United States Patent and Trademark Office (USPTO) to ensure a more consistent quality in patent filing. This also provides better representation of emerging economies.[1] The analysis is conducted at the country level. We used

[1] We recognise that this approach is conservative since it focuses on high-quality patents and does not allow us to control for national differences in incentives, which are significant when analysing international linkages in new green technologies. However, analysing the whole PATSTAT dataset of national patent office patents would also introduce biases and, especially, in the case of green patents since several emerging economies (e.g., China) offer strong incentives for domestic

fractional counting, based on the applicant country code, to assign patents to one or more countries. Our focus is on green technologies, which are in the Y02 Cooperative Patent Classification (CPC). This class includes technologies that control, reduce or prevent anthropogenic greenhouse gas emissions, as defined in the Kyoto Protocol and the Paris Agreement. It also includes technologies that enable adaptation to the adverse effects of climate change. The Y04S classification includes systems that integrate technologies related to power network operation, communication, or information technologies to enhance the generation, transmission, distribution, management or usage of electrical power. These classes are further divided into more detailed subclasses, at the 7-digit level of disaggregation covering 250 technologies (such as wind energy, Y02E10/7). We identified patents that included at least one of the specified green technologies and grouped the data according to non-overlapping three-year intervals. This resulted in 14 distinct periods between 1975 and 2015. The final dataset comprises 447,700 green patents from 49 countries.[2] Countries are classified as: leaders, followers or catch-up countries. Green innovation leaders are countries with a consistent top ranking for total patents over the period of analysis. The leaders include the US, Japan, Germany, France and South Korea. Catch-up countries are those that, although their ranking has improved, have yet to join the group of leaders. The list of countries includes China, India, South Korea, Taiwan, Russia, Singapore, Mexico, Hong Kong and South Africa.[3] This selection of countries represents both established and emerging players in the clean tech field. The remaining countries are considered followers.

3.2. *Dependent variable*

Our interest is in the emergence of new specialisations in green technology, which is our dependent variable. First, we compute Revealed Technological Advantage (RTA) to capture the country's relative technological specialisation. This index is derived from the Revealed Comparative Advantage index, conventionally used to measure national comparative advantage in trade (Balassa, 1965). RTA is used in studies on technological diversification to compare patent shares in a specific technological domain to total patents (Boschma et al., 2015; Rigby, 2015). An RTA of 0 indicates that the country has no patents in a particular patent class, while an RTA of 1 indicates that its share in a particular technology is the same as its share in all other patent classes, that is, no specialisation. A value above 1, indicates that the country is specialised in a particular technology, that is, its share in that technology is higher than its share in other technologies.

$$RTA_{c,i}^{t} = \frac{patents_{c,i}^{t} \Big/ \sum_i patents_{c,i}^{t}}{\sum_c patents_{c,i}^{t} \Big/ \sum_c \sum_i patents_{c,i}^{t}}$$

RTA takes the value 1 if country *c* has a larger share of green patents in a specific technological class *i* in period *t* than the world average (average of the 49 countries included in the analysis), and 0

patenting in green-related fields, which result in an exponential growth in patent numbers. Recent evidence suggests that the innovative potential of these patents is questionable (Eberhardt et al., 2016). Therefore, it can be argued that using PATSTAT data for international comparisons may overestimate the performance of these countries, potentially leading to biased findings.

[2] Countries were selected based on their patenting activity. We consider countries with at least 100 patent applications over the period of observation and countries that patented in at least 9 out of 14 periods. Appendix Table A1 lists the countries in the sample.

[3] More specifically, catch-up countries are those whose patenting numbers improved by at least 10 ranks between period 1 and period 14. We used different country classifications to check the robustness of our results which are reported in the appendix (see Appendix Tables A10 to A18).

otherwise.[4] The occurrence of a new specialisation is identified if country *c* is specialised in green technology *i* in period *t+1,* but not in in period *t.*

3.3. Independent variables

Our covariates refer, specifically, to relatedness density, international co-inventor linkages and linkage complementarity. Relatedness density is used frequently to measure national technological capabilities (Boschma et al., 2015; Hidalgo et al., 2007). It captures the degree of relatedness between a specific technology and the country's existing technological portfolio. We constructed this variable by computing co-occurrence of pairs of technology mentioned in patent documents which provides the degree of relatedness between each of the 250 green technology classes. We then normalised technology co-occurrences using cosine similarity and, to obtain the relatedness density measure, we calculated the closeness of each technology to the country's technology portfolio. Related density ranges from 0 to 100. Where 0 indicates absence of technologies related to technology *i* in country c during period *t* and a 100 indicates the presence of all the technologies related to *i* in country *c*:

$$relatedness.density_{i,c,t} = \frac{\sum_{j \in c, j \neq i} \phi_{ij} X_{ci}}{\sum_{j \neq i} \phi_{ij}} * 100$$

where ϕ_{ij} refers to the relatedness between technologies *i* and *j* established by the co-occurrence analysis, and X_{ci} is a dummy variable that takes the value of 1 if country *c* has relative technological advantage in technology *i* (RTA>1).

Next, we examined international linkages, based on information on co-inventors' locations (Balland and Boschma, 2021; Le Gallo and Plunket, 2020; Whittle et al., 2020). Using the patent documents, we retrieved the adjacency matrix A_{cs}, which presents countries in rows and columns. Each matrix element represents the number of co-inventor ties of country *c* with country *s* (excluding self-loops). We then summed the matrix elements to obtain the total number of international linkages of country *c*.

4. Empirical findings

4.1. Descriptive analysis

Figure 1 depicts green patent growth from 1975 to 2015 and shows that growth accelerated after period 8 (1996-1998), driven, mostly, by the leader countries. It shows a decline after 2010, which also appears to be induced by the leaders, while the number of new green patents by followers remain fairly stable.

[4] This threshold is set higher than 1 because, in line with the traditional trade literature (Balassa, 1965) and the relatedness literature (Rigby, 2015), it indicates that a country developed a specialisation in a specific technological domain. However, it is fair to argue that technological capabilities could be built also when countries have a share of patents in each domain lower than the average (so their RTA will be slightly lower than 1). For this reason, in this study, we also check the robustness of our results to different thresholds (see Tables A6 – A9 in the Appendix)

Figure 1 – Number of green patents by group of countries

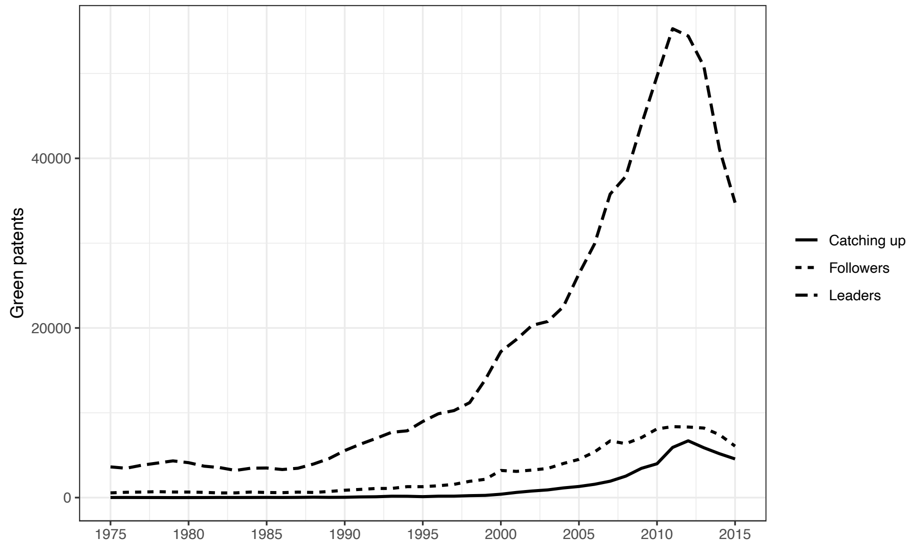

Figure 2 depicts the number of new green technological specialisations from period 2 to period 14. The increased entry observed, is driven by followers, with a more stable pattern among the leaders and catching-up countries. Leaders account for 80% of green patents applied for between 1975 and 2015, but for only 17% of total entries. Figure 3 maps entries in period 2 (1978-1980) and period 14 (2013-2015). Apart from leaders such as the US and Japan, in period 14 compared to period 2, most nations have achieved a significantly higher number of new green technology entries. This is especially noticeable for the emerging economies of Brazil, China and India. However, Australia and the UK also record substantially increased entry numbers.

Figure 2 – Entry of new green specialisations by country groups

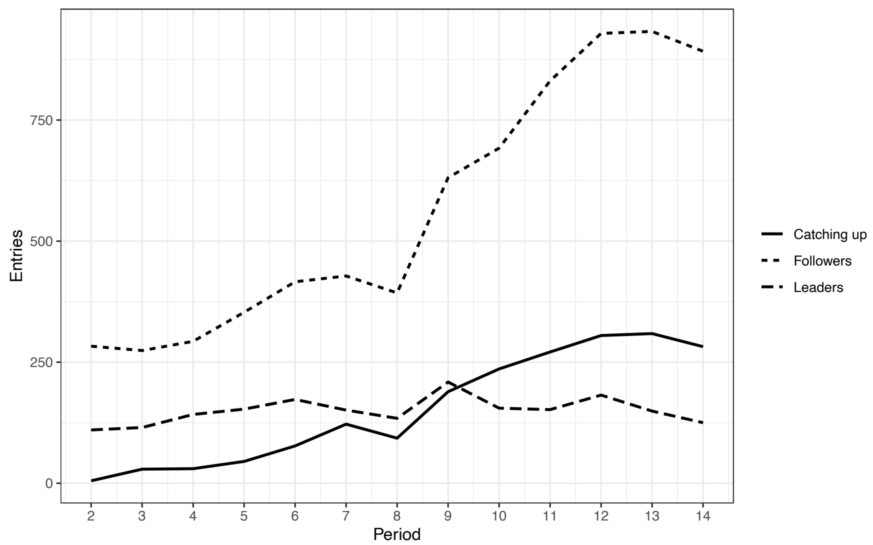

Figure 3 – Entries in period 2 (1978-1980) and in period 14 (2013-2015)

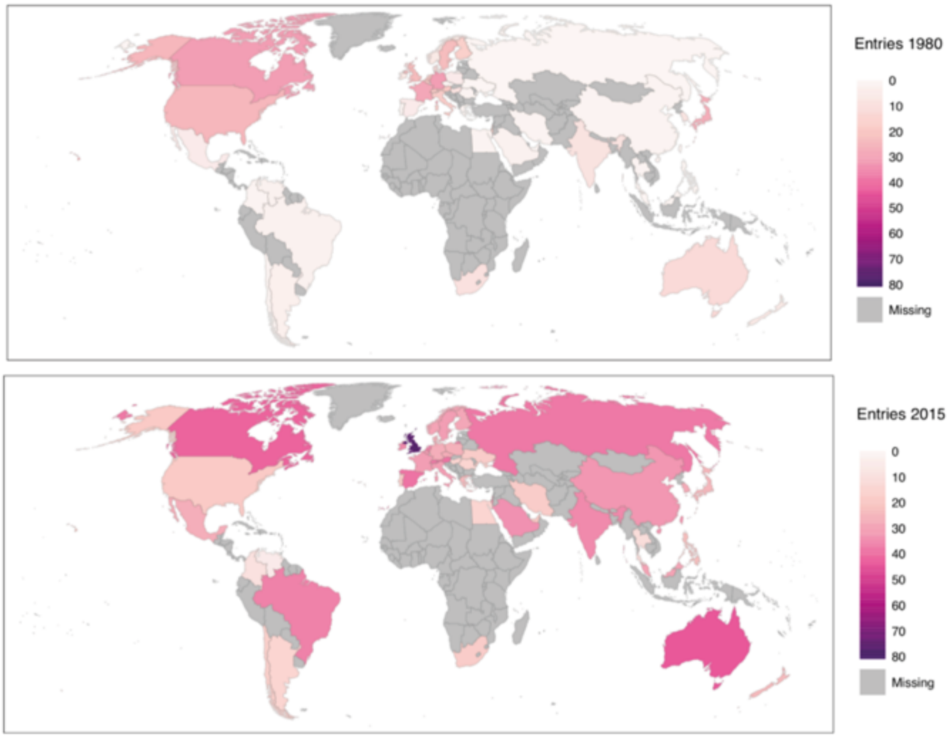

Figure 4 shows that the number of international co-inventor linkages is in line with the number of green patents depicted in Figure 1, with similar dynamics among leaders, catching-up countries and followers. In our estimates, we weight the number of linkages by the number of green patents to obtain the number of linkages per patent and time period for a given country. Figure 4 shows also that, on average, followers and catching-up countries have more linkages per patent than the leaders.

Figure 4 – Co-inventor linkages

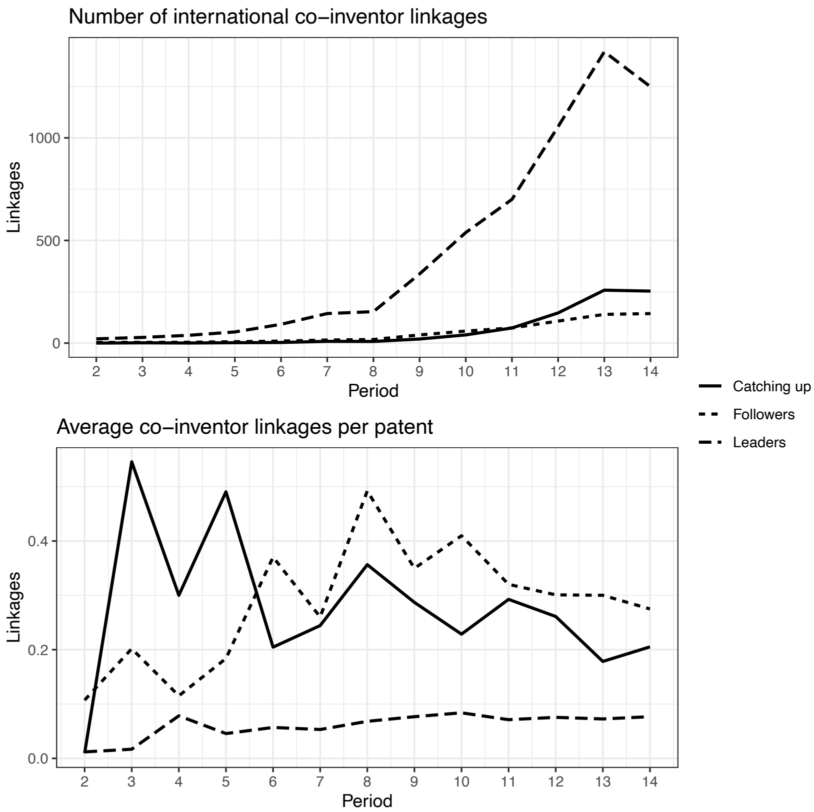

Figure 5 depicts the development of complementary linkages over time. In line with the trends in number of patents and linkages, the number of complementary linkages mostly increased significantly over time, although with a drop in the most recent period.

Figure 5 – Average complementary linkages by country groups

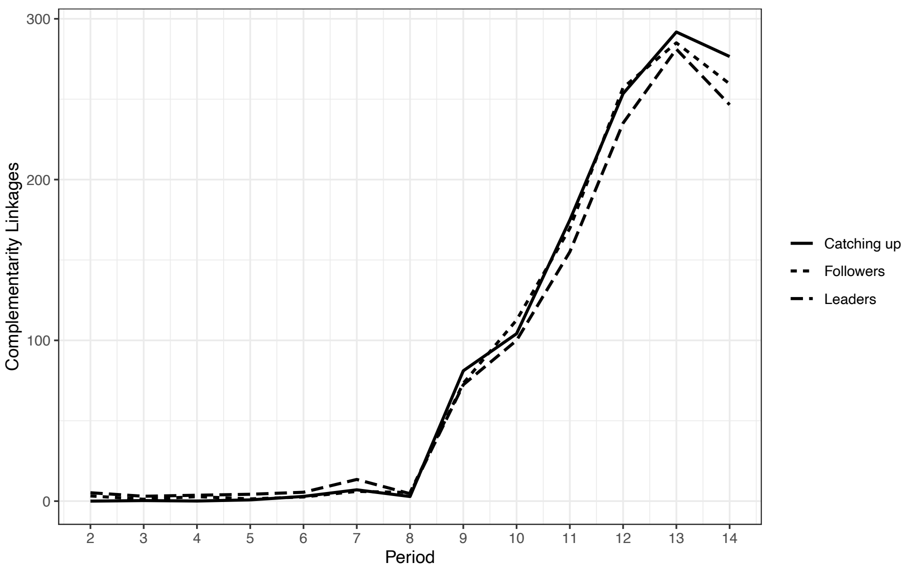

Table 1 presents summary statistics of all the variables; Figure 6 present the correlation matrix.

Table 1 – Summary statistics

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Entry	163,333	0.07	0.25	0	0	0	1
Linkages	163,333	0.26	0.41	0	0.05	0.3	6
Compl. linkages	163,333	90.87	219.04	0	0	65.8	2,686
Relatedness density	163,333	13.92	24.92	0.00	0.00	17.60	100.00
Tech. complexity	163,333	-0.002	0.91	-2.69	-0.60	0.47	2.72
Class size	163,333	3,757.14	8,878.62	1	154	3,302	69,138
Share growth	163,333	0.01	0.26	-4	0	0	6
GDP per capita	126,469	20,641.68	18,415.71	197.07	5,991.32	30,325.85	106,749.00
HHI	163,333	0.13	0.24	0.00	0.01	0.12	1.00

Figure 6 - Correlation matrix

	Entry	Linkages	Compl. linkages	Relatedness density	Tech. complexity	Class size	Share growth	GDP per capita	HHI
Entry	1	-0,05	0,04	0,14	-0,15	0,07	0,02	0,08	-0,12
Linkages	-0,05	1	0,01	-0,14	0	0	-0,01	-0,08	0,35
Compl. linkages	0,04	0,01	1	0,13	0,12	-0,1	0,01	0,19	-0,17
Relatedness density	0,14	-0,14	0,13	1	-0,07	0,05	0,02	0,28	-0,27
Tech. complexity	-0,15	0	0,12	-0,07	1	-0,41	-0,02	0	0
Class size	0,07	0	-0,1	0,05	-0,41	1	0,01	0	0,01
Share growth	0,02	-0,01	0,01	0,02	-0,02	0,01	1	0,02	-0,02
GDP per capita	0,08	-0,08	0,19	0,28	0	0	0,02	1	-0,29
HHI	-0,12	0,35	-0,17	-0,27	0	0,01	-0,02	-0,29	1

4.2. Regression model

To assess the probability that a country will develop a new green technological specialisation, that is, will diversify in green technologies,[5] we estimated a linear probability model (Balland et al. 2015; Petralia et al. 2017)[6]:

$$Entry_{i,c,t+1} = \alpha + \beta_1 linkages_{c,t} + \beta_2 compl.linkages_{i,c,t} + \beta_3 relatedness.density_{i,c,t} + CV + \gamma_i + \delta_c + \theta_t + \varepsilon \quad (1)$$

[5] In line with the literature, we refer to country level 'diversification' as a process involving the country specialising in a technology that is new to that country. This addition of a *new* specialisation, indicates diversification of the country's technology portfolio.

[6] As discussed in Boschma et al. (2015), there is an ongoing debate about the appropriateness of Linear Probability (LP) or binary (e.g., logit) models. Boschma et al. argue that one reason for using an LP model is that the presence of too many zeros in the dependent variable could result in lack of estimation consistency (King and Zeng, 2001), which occurs in empirical work on technological diversification. Another reason is interpretability, because coefficients are more easily interpreted in terms of elasticities (Battey et al. 2019). However, we checked our results using alternative methodologies (see Appendix Tables A2-A5).

Our binary dependent variable $Entry_{i,c,t+1}$ measures whether the country enters a new specialisation and is lagged by one period. The main independent variables are number of co-inventor linkages (i.e., *linkages*) to other countries and number of linkages with related technological fields (i.e., *complementary*). Inclusion in the model the technological relatedness density variable (i.e., *relatedness density*), which, also, in interacted with both linkage variables, controls for the effect of local capabilities. CV is control variables. Our model also includes technology (γ_i), country (δ_c) and time (θ_t) fixed effects.

4.3. Regression results

Table 2 presents the estimates of the various econometric models including our variables of interest: external linkages and complementary linkages and their interactions with technological relatedness. Since scales vary widely, all the variables of interest are standardised to enable better coefficient comparison.[7]

The linkages variable is not statistically significant when included in the model either on its own (Column 1) or along with complementarity linkages (Column 3). However, the coefficient of complementary linkages is highly statistically significant and positive. These results suggest that, compared to external linkages, complementary linkages are more beneficial for diversification into new green technologies.

Since the coefficient of variable *linkages* is statistically insignificant, we focus on complementarity linkages and their potential to mediate the role of relatedness. In Column (4), *complementarity linkages* are interacted with *relatedness density*, which results in a positive and statistically significant effect. This suggests that external capability complementarity promotes the development of related green technologies. Therefore, in with countries specialised in related technologies will promote a similar direction of diversification and reinforce the role of relatedness. Column (5) presents the interaction between relatedness density and linkages. Although on their own, linkages are not statistically significant the interaction term reveals a significant and negative coefficient. This suggests that countries with international co-inventor linkages will be more likely to diversify into new green technologies that are relatively unrelated to their existing capabilities. Therefore, on their own, linkages could diminish the importance of relatedness, potentially allowing for deviation from a given technological development path. However, complementary linkages are likely to reinforce the effect of relatedness.

The results for the control variables show a positive and significant coefficient of *relatedness density*, but show, also, that technological complexity impedes the development of a new green specialisation. These findings are consistent with evidence showing that counties are constrained by existing technological paths and tend to avoid the most complex technologies (Boschma, 2017). The Herfindhal Hirschman Index (HHI) has a negative sign, which confirms previous findings that diversification is less likely in the case of more complex technologies (Petralia et al., 2017). The negative sign of the GDP variable is also as expected and indicates that, as countries become richer, the likelihood of diversification decreases. This reflects the fact that richer countries are already innovating in many different technological domains, while less economically advanced countries have more scope for diversification. Finally, the positive coefficient of *share_growth* indicates that diversification is more likely in those domains displaying the fastest growth.

[7] Variables are standardised by subtracting from it their sample means and dividing them by their standard deviation.

Table 2 –Determinants of green diversification – all countries

	Dependent variable:				
	Entry				
	(1)	(2)	(3)	(4)	(5)
Linkages	-0.001		-0.001	-0.001	-0.003**
	(0.001)		(0.001)	(0.001)	(0.001)
Compl. linkages		0.003***	0.003***	0.002**	0.003***
		(0.001)	(0.001)	(0.001)	(0.001)
Relatedness density: Compl. linkages				0.002***	
				(0.001)	
Relatedness density: Linkages					-0.004***
					(0.002)
Relatedness density	0.014***	0.014***	0.014***	0.014***	0.013***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Tech. complexity	-0.026***	-0.026***	-0.026***	-0.026***	-0.026***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
GDP per capita	-0.004*	-0.004**	-0.004*	-0.004*	-0.003*
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
HHI	-0.007***	-0.008***	-0.007***	-0.008***	-0.008***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Share growth	0.002***	0.002***	0.002***	0.002***	0.002***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Class size	1.317	1.358	1.345	1.172	1.337
	(1.047)	(1.047)	(1.047)	(1.049)	(1.047)
Constant	0.385	0.398	0.394	0.347	0.391
	(0.284)	(0.284)	(0.284)	(0.284)	(0.284)
Observations	126,469	126,469	126,469	126,469	126,469
R^2	0.063	0.063	0.063	0.063	0.063
Adjusted R^2	0.060	0.060	0.060	0.060	0.060
Note:	*p<0.1** p<0.05***p<0.01				
	Includes Country, Technology and Period Fixed Effects.				

Table 3 presents separate regressions for leaders, catching-up countries and followers. Column (1) shows the full model from Table 2 which acts as the benchmark. In the case of leaders, the coefficients of the variables 'linkages' and 'complementary linkages' are not statistically significant (Column 2). In the cases of follower and catching-up countries, the coefficients of complementary linkages are positively associated with green diversification (Columns 3 and 4). However, linkages remain statistically insignificant. In these countries, external knowledge is particularly important if it is related to local capabilities. This is consistent with the idea that, in the early stages of development, countries tend to search for knowledge that is close to their existing knowledge and does not require high levels of absorptive capacity (Petralia et al. 2017; Perruchas et al. 2020). It is interesting to observe that technological complexity has different effects for leaders compared to catching-up/follower countries. The coefficient of technology complexity is negative for catching-up countries and followers, suggesting that these countries find it more difficult to adopt and develop complex technologies, compared to leaders which are more likely to specialize in complex technologies due to their strong knowledge endowments. This result supports the notion that complex technologies may provide higher value and, thus, a greater incentive for countries with strong knowledge bases to search and innovate (Lerner, 1994). The relationship between the size of the technological class and diversification differs between leaders and catching-up/follower countries. It supports the idea that leading countries have already taken advantage of the technological opportunities in large classes which are already widely dispersed while catching-up countries and followers benefit from the greater opportunities for technological recombination characterising small technological classes.

Table 3 – The determinants of green diversification by group of countries

	Dependent variable:			
	Entry			
	all	leaders	catching-up	followers
	(1)	(2)	(3)	(4)
Linkages	-0.001	-0.009	0.005	-0.001
	(0.001)	(0.028)	(0.003)	(0.001)
Compl. linkages	0.003***	0.004	0.003*	0.003***
	(0.001)	(0.003)	(0.002)	(0.001)
Relatedness density	0.014***	0.011***	0.015***	0.010***
	(0.001)	(0.002)	(0.002)	(0.001)
Tech. complexity	-0.026***	0.030***	-0.037***	-0.033***
	(0.001)	(0.004)	(0.003)	(0.001)
GDP per capita	-0.004*	-0.011	-0.022***	0.001
	(0.002)	(0.014)	(0.007)	(0.002)
HHI	-0.007***	-0.166***	-0.012***	-0.001
	(0.001)	(0.039)	(0.004)	(0.002)
Share growth	0.002***	0.004**	0.004**	0.001
	(0.001)	(0.002)	(0.002)	(0.001)
Class size	1.345	-0.008***	0.011	2.174**
	(1.047)	(0.002)	(0.053)	(1.017)
Constant	0.394	0.063	0.012	0.621**
	(0.284)	(0.045)	(0.039)	(0.276)
Observations	126,469	16,384	21,248	88,837
R^2	0.063	0.044	0.091	0.076
Adjusted R^2	0.060	0.028	0.079	0.073

Note: *p<0.1** p<0.05***p<0.01. Includes Country, Technology and Period Fixed Effects.

Tables 4 and 5 introduce the interaction term between linkages, complementary linkages and relatedness density. This provides information on the direction of the diversification process - related or unrelated. The findings indicate a different effect among country groups. Table 4 shows that external linkages among catching-up and follower countries with complementary capabilities tend to favour more related diversification. The positive coefficient of the interaction term suggests that complementary linkages result in path dependence. However, leading countries seem to benefit from complementary linkages as potentially enabling path-breaking outcomes. The negative interaction term indicates that leading countries with complementary linkages are more likely to develop new green technological specializations that are unrelated to their existing technology set. Table 5 shows that, on their own, linkages are significant for green diversification by catching-up and follower countries, shown by the negative interaction term between relatedness density and linkages (Columns (3) and (4)).

Table 4 –Determinants of green diversification by country groups (compl. interaction)

	Dependent variable:			
	Entry			
	all	leaders	catching-up	followers
	(1)	(2)	(3)	(4)
Linkages	-0.001	-0.011	0.004	-0.001
	(0.001)	(0.028)	(0.003)	(0.001)
Compl.linkages	0.002**	0.024***	0.001	0.002**
	(0.001)	(0.006)	(0.002)	(0.001)
Relatedness density: Compl.linkages	0.002***	-0.015***	0.006***	0.005***
	(0.001)	(0.003)	(0.002)	(0.001)
Control Variables	Yes	Yes	Yes	Yes
Observations	126,469	16,384	21,248	88,837
R^2	0.063	0.045	0.091	0.076
Adjusted R^2	0.060	0.029	0.079	0.073

*Note:**p<0.1** p<0.05***p<0.01. Includes Country, Technology and Period Fixed Effects.

Table 5 –Determinants of green diversification by country groups (link. interaction)

	Dependent variable:			
	Entry			
	all	leaders	catching-up	followers
	(1)	(2)	(3)	(4)
Linkages	-0.003**	-0.004	-0.002	-0.003**
	(0.001)	(0.029)	(0.004)	(0.001)
Relatedness.density: Linkages	-0.004***	-0.015	-0.015**	-0.004**
	(0.002)	(0.015)	(0.006)	(0.002)
Compl. linkages	0.003***	0.004	0.003*	0.003***
	(0.001)	(0.003)	(0.002)	(0.001)
Control variables	Yes	Yes	Yes	Yes
Observations	126,469	16,384	21,248	88,837
R^2	0.063	0.044	0.091	0.076
Adjusted R^2	0.060	0.028	0.079	0.073

*Note:**p<0.1** p<0.05***p<0.01. Includes Country, Technology and Period Fixed Effects.

To test the robustness of our results, we conducted three checks. Firstly, we estimated our models using a logit regression. This dichotomous representation of our dependent variable and use of count data (i.e., patents) suggest this choice. The results show that the linkage variable is statistically insignificant in all the logit regression specifications. However, the results for complementary linkages and interactions with relatedness density confirm the findings from the linear probability model (see Appendix Tables A2-A5). In the second robustness check, we repeated the analysis using a different RTA threshold, specifically 1.5. The results for RTA greater than 1.5 are consistent with the original findings (see Appendix Tables A6-A9). Finally, we assessed the stability of entry events and recalculated the dependent variable to include only the first entry of a technological specialisation, disregarding subsequent entries after an exit. This analysis confirms the original findings. Appendix Tables A10-A18 present the various classifications for leading, catching-up and following countries.

5. Discussion and Conclusion

Climate change is a global problem that calls for coordinated global efforts. Among the most relevant efforts is the development of technologies that carry environmental benefits or address environmental issues directly. Countries must shift their innovation activities towards green technologies, which highlights the need to understand what drives green technological diversification.

The literature on technological diversification focuses primarily on local capabilities. However, recently, interested has shifted towards the role of external factors. This paper examined this aspect by investigating the relationship between international co-inventor linkages and the process of green technological diversification, for 49 countries between 1975 and 2015. Specifically, we examined how complementary linkages and their interaction with relatedness density affect this process. As globalisation increases, green innovation increasingly becomes a collaborative effort. Our descriptive evidence shows that international collaboration of inventors developing green technologies has increased more than overall patenting. Therefore, linkages to external capabilities and the capacity to absorb knowledge produced elsewhere play an increasing role in diversification. Furthermore, our study demonstrates that the role of external linkages varies depending on national characteristics. The diversification patterns and diversification drivers may differ significantly depending on the country's innovation capacity (Petralia et al., 2017; Zhu et al., 2017; Balland and Boschma, 2021; Xiao et al., 2018).

The empirical analysis produced four sets of results. The first set indicates that a country is more likely to develop a new green technological specialisation if it engages in technological collaborations (i.e., co-inventor linkages) with countries that bring complementary capabilities for this green technology. Although international linkages may aid diversification in catching-up countries, what matters is the type of connection. This supports the notion that external linkages can allow escape from lock-in and stagnation caused by an overly embedded local innovation system (Uzzi, 1997). The second set of results indicates that complementarity linkages reinforce the role of relatedness and support the development of new green technological specialisations that are strongly related to the country's existing set of capabilities. These findings are consistent with Balland and Boschma's (2021) investigation of interregional linkages and complementarity among European NUTS2 regions for technological diversification. The third set of findings indicates that catching-up countries and followers are the main drivers of our results. While green diversification benefits significantly from complementarity for followers, leaders' diversification does not seem to rely on either linkages or complementarity. These findings support the arguments in Zhu et al. (2017) regarding developing countries, and in Balland and Boschma (2021) in relation to peripheral areas. Catching-up and follower countries, which have fewer endogenous capabilities than leaders, benefit from co-inventor linkages to other complementary countries. Leaders tend to enter new technological specialisations that are complex and non-mature, since they have the ability to leverage existing capabilities and accumulated green knowledge to explore innovative and radical technological fields. In addition, external linkages can stimulate the emergence of new technological specialisations that are unrelated to existing local capabilities. The mediating role of relatedness varies depending on the level of the country's development. External complementary linkages can encourage unrelated diversification in leaders, while in catching-up and follower countries, linkages, on their own, can lead to unrelated diversification. These findings suggest a different pattern of diversification among different types of countries.

Our empirical analysis indicates that policy interventions should actively promote international collaborations. Countries, such as China, that developed rapidly and have become leaders in various green technologies, achieved this by utilising a range of public instruments (Altenburg and Assmann, 2017; Mazzucato, 2018). Access to foreign technologies played a significant role in the toolboxes of these policymakers, particularly in the early stages of the green industries (Lema et al., 2020; Binz et al., 2020). Although the effectiveness of each policy measure may vary depending on the specific green technology (Binz et al., 2017), a crucial lesson for policymakers in developing countries is that collaborating with foreign strategic partners can accelerate the process of green diversification. Increased international linkages can be achieved by offering incentives such as R&D-related fiscal incentives or innovation grants that are conditional on the establishment of international collaborations for innovation activity. Also, education policies could emphasise exchange programmes with foreign countries and promote socio-cultural diversity to support inventors search for collaborators from abroad. Attracting returnees from academia and the business community could be an effective strategy for accessing frontier knowledge and exploiting social and professional networks in distant markets. In addition, investment in up-to-date and solid information and communication technology infrastructures, including 5G, is essential for international collaborations. Although face-to-face interaction is important for effect collaboration, virtual collaborations are increasing in order to reduce the carbon emissions caused by travel, and are becoming more effective due to improved technologies. These strategies would benefit both innovation leaders and followers by creating more international linkages. The findings serve, also, as a warning to policymakers in developing countries. Foreign partnerships can be beneficial under certain circumstances. Policymakers must remember that countries need internal capabilities in order to absorb foreign knowledge. Policies aimed at developing these capabilities have proven crucial for countries, such as China, that are trying to catch up technologically (Lema et al., 2020). Also, when searching for foreign strategic connections, it is important to target partners with complementary knowledge.

This study identifies potential areas for future research. It focuses on co-inventor linkages and technological complementarity among countries, but other types of linkages, such as trade, migration, FDI and multinationals, can also be effective. Also, different facets of complementarity, such as historical, lingual, cultural and institutional complementarity, could be explored. The importance of examining the relationship between linkages and the development of green products or green occupations should not be overlooked when diversifying beyond green technologies. It is crucial to consider the different roles played by linkages and complementarity in green development for various country groups, including emerging, latecomer, developing and lagging countries. It would be useful, also, to investigate the impact of climate change in developing countries with limited capabilities. Finally, future research on linkages and green diversification could benefit from sub-national analysis since the influence of connections may be particularly relevant for regions, which are smaller than nations and tend to specialize in fewer industries and technologies. Regions need to tap into distant and heterogeneous knowledge to increase their technological diversification in green domains and should aspire to a more prominent role in a broader set of domains. Existing evidence focuses on Europe and the advanced economies. But extending the analysis to catching-up countries would provide additional insights into the importance of external linkages.

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