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THE ROLE OF TECHNOLOGICAL TRAJECTORIES IN CATCHING-UP BASED DEVELOPMENT AN APPLICATION TO ENERGY EFFICIENCY TECHNOLOGIES

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The role of technological trajectories in catching-up based development
An application to energy efficiency technologies

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Vienna, 2016

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The Role of Technological Trajectories in Catching-up-based Development. An application to Energy Efficiency Technologies

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Abstract:

We argue that the analysis level of a technological trajectory is very suitable to analyse the decisions of firms in latecomer countries with regard to the technological area that they should focus on. Technological trajectories are the main focal points along which technological innovation develops, and they are more detailed than the common sectors, like electronics of pharmaceuticals, that are used in the analysis of catching-up based growth. We present a collection of methods that has been proposed in the literature to identify technological trajectories. These methods use patent citation networks, and are applied to two separate fields in energy efficiency technologies. We identify the relevant technological trajectories, and analyse how the main countries active in these fields can be classified as either latecomer or incumbent countries. We then present a measure for how much patents from a particular country contribute to the main technological trajectories in the field, and to what extent they are derived from these trajectories. We use an explorative regression model to establish that latecomer countries tend to contribute to a lesser extent than incumbents to the main technological trajectories in the fields we investigate.

Keywords: technological trajectories, patent citation networks, latecomer innovation strategy

JEL Codes: O31, O33, O47

1. Introduction

Technology plays a large role in the economic development of nations. For countries that lag behind the economic frontier, the assimilation of foreign technological knowledge is a potential way to achieve rapid growth, or, in other words, to catch up economically (Fagerberg and Godinho 2004). In all documented historical cases of successful catch-up growth, industrialization and technological upgrading has been the central process in economic development (Szirmai and Verspagen 2015).

While the process of investing in absorption capability necessary for technological catch-up has been documented extensively (Fagerberg, Srholec, and Verspagen (2010) provide a survey of this literature), there is generally less attention to the question of which specific technological choices a country aiming to implement a catching-up strategy should make. Lee (2013) and Lee and Lim (2001) are exceptions, as they apply patents statistics to analyze the technological specialization profiles of latecomer countries.

The essence of a latecomer, or catching-up, strategy is that countries that enter a technological field relatively late can assimilate existing knowledge at a costs that is ultimately lower than what it took to develop this knowledge in the original way. Part of why this is the case is that once knowledge has been developed and exists, more or less, in the open, information on what works and what works not is available for followers to use.

However, catching-up based growth is not pure assimilation of knowledge. It also consists of adapting foreign knowledge to local circumstances, and, with increasing development levels, knowledge assimilation gradually changes in knowledge creation. This transition from assimilation to creation is the topic of the study in Lee (2013), and also in the current paper. When this transition happens, latecomer countries that have been assimilating knowledge need to make choices about the direction, or technological subfield, in which they will invest their creative efforts.

This choice is heavily influenced by the nature of the knowledge creation process, which is the topic of a different literature e.g., (Dosi 1982). Technological knowledge tends to develop along specific trajectories, which can be seen as sequences of interdependent and cumulative innovations in small (incremental) steps. The nature of these trajectories is determined by the economic and other circumstances in the specific market in which the trajectory develops. The trajectory in a specific field is the result of joint efforts by multiple firms, and possibly other actors, rather than an individual effort.

Trajectories emerge after new technological opportunities open up as a breakthrough innovation. This is a relatively rare process, which implies that latecomer countries who want to enter a specific technological field will generally face a status quo of existing trajectories that are dominated by firms from the develop part of the world. The basic choice that these countries face is to either follow the existing trajectory and try to compete with the incumbent firms, for example on the basis of low production costs, or to develop technologies in new directions. This is what Lee and Lim (2001) call the distinction between a path-following catch-up strategy and a path creation strategy. Perez and Soete (1988) have also addressed this issue, and argue that a path creating strategy is most likely to succeed in a period in which breakthrough innovations are unfolding.

Technological trajectories are hard to quantify, which makes it difficult to use the notion in quantitative studies of catching-up growth. For example, Lee (2013), which is probably the most extensive and detailed study of the process of shifting from technological assimilation to technological creation, mainly uses counts of patents by economic sector or by technological class as an indicator for the creative potential of firms in latecomer countries.

Given the importance of technological trajectories in the development of new knowledge, this may not be a very adequate way of measuring technological capabilities. For example, Verspagen (2007) identified distinct technological trajectories in a specialized field such as fuel cells, which comprises only one or several detailed technological classes. If the salient features of knowledge development occur at this level of aggregation, it makes sense to incorporate more detail into the analysis than is possible with the methods of Lee (2013). This is the goal of the current paper.

The idea of technological trajectories will be elaborated in the next section. This section will also formulate a precise research question, which is mainly explorative in nature, and which asks which strategy of technological specialization latecomer countries have followed in the particular technology fields that we study. These fields are related to energy efficiency: one case we study is the technology for power generation (electricity), and the other is technologies aimed at increasing energy efficiency for indoors use. The latter field turns out to be dominated by two topics: refrigeration/cooling/airconditioning and energy saving in computers.

There is no particular reason for focusing on these specific fields, other than that energy technologies and in particular energy efficiency technologies, are very important for sustainable development. If technological trajectories are indeed important for determining the development strategy of latecomer countries, more studies of different technological fields will be necessary to increase out insights into this question. As technological fields differ, so will trajectories, and therefore it is important to analyze a range of cases. We look at the current paper as a first step in such a research programme, both in terms of proposed methods and in terms of deriving some first and preliminary results.

After discussing the idea of technological trajectories and why they matter for development, we discuss our database in Section 3. Section 4 covers the basic methods that we employ, and which are derived from network analysis. Section 5 presents our results, and Section 6 summarizes the argument and draws conclusions.

2. Technological trajectories

Technological and scientific knowledge evolves as a result of research and development (R&D), as well as more practical activities such as learning-by-doing or learning-by-using. R&D is very much a search process, in which the knowledge that a researcher already possesses influences the nature of the search effort. In particular, R&D often takes the form of a local search process, in which incremental pieces of knowledge are added to what already exists, for example because researchers look for improvements to existing knowledge. Nevertheless, major breakthroughs that change the direction of R&D also occur, although they are not very frequent as compared to incremental improvements.

Various authors, for example, (Dosi 1982, Sahal 1981) contributing to the economic history of technology have described these processes of local search combined with occasional major breakthroughs. Dosi (1982) used Kuhn (1970) terminology and posited the idea of a technological paradigm and, within the paradigm, technological trajectories. A paradigm corresponds to a major breakthrough in knowledge development, both in the sense that it is a radical break with the past, and in terms of its reach, i.e., it affects a wide variety of R&D processes. A technological paradigm is agenda-setting, it suggests the direction of R&D efforts, and the basic approach that is used to solve technological problems. Derived from Kuhn (1970), a paradigm shift becomes more likely when an existing paradigm runs into decreasing returns, i.e., when its possibilities for technological improvement dry up.

A technological trajectory, in Dosi's terminology, corresponds to Kuhn's idea of "normal science". It is the "non-radical" development of technology within a paradigm. Multiple trajectories will normally exist within a paradigm, corresponding to different uses of the basic knowledge of the paradigm. The nature of trajectories is determined by the economic environment in which the trajectory develops. This results from the fact that researchers, engineers and practitioners respond to economic opportunities or bottlenecks when they develop the technology.

An example can illustrate the basic ideas. Steam power technology was a paradigm shift compared to water power. It was made possible by the development of the Newcomen engine, and later on the separate condenser as invented by James Watt. These inventions opened up a new range of possibilities, which were developed along many different trajectories. One of these trajectories was the use of steam power for pumping water out of mines. This lead to large and bulky steam engines, which were very powerful and fuel efficient, for example, the Cornish engine (Nuvolari 2006, 2004). Another trajectory was the use of steam power on trains. These engines were much smaller, because they had to be mobile, and as a way to generate more power with smaller size, they developed by increasing steam pressure. As a result, after a period of development, even if the basic technology was identical, steam engines used in mines looked completely different to those used on trains.

Because R&D and technology development in general is a search process, it also runs into dead ends, or, more generally, different development directions (trajectories) have different (technological and economic) success. Firms that undertake R&D and technology development have to make choices where to direct their efforts, i.e., which trajectory to follow. Due to fundamental uncertainty, this is a process that is not fully rational, as it is impossible to predict with certainty whether a trajectory will become, or remain, successful. The choices that firms make are boundedly rational (Nelson and Winter 1977), but also influenced by beliefs and culture. But there is an important difference between the way in which technological leaders and followers make these decisions (Triulzi 2015). Technological leaders face a larger degree of uncertainty, as they tend to develop technologies that are more uncertain. Followers, on the other hand, can benefit from experience that has been accumulated in the trajectory that they are interested in, and therefore the uncertainty that they face will generally be lower.

This uncertainty translates to the level of countries, which can also be characterized as technological leaders or followers. Firms in latecomer (following) countries will generally face existing technological trajectories when they try to enter a market. They can then either try to contribute to the existing technological trajectories, or direct efforts away from these, by trying to create new trajectories, or at least new technological opportunities.

Our research question is related to this basic choice. We are interested in the latecomer countries that are making the transition from knowledge assimilation to knowledge creation, which we measure by counting the number of patents that emerge from a particular country, in a particular technology field. Those countries that are contributing in a significant way to the number of patents in the field, but have been doing so only recently, are characterized as the latecomer countries that draw our interest. Being able to identify the main technological trajectories in the field in the form of a small set of patents, we then ask how the latecomer countries relate to these trajectories. In particular, our research question is whether latecomer countries tend to contribute to the main technological trajectories at a higher or lower rate than the incumbent countries in the field.

The analysis of this research question requires the identification of technological trajectories in the fields that we analyze. This task has been undertaken by a number of qualitative (historical) and quantitative research methodologies. Patent citation networks (Verspagen 2007) are one way in which the very detailed information in patent documents can be used to do this. Although a number of technological fields have been analyzed using these methods (Fontana, Nuvolari, and Verspagen (2009), Martinelli (2010)), to our knowledge, this method has not been used so far to look at technological catching up of developing countries. We explain the method in the next section, and then undertake to apply it in Section 5.

3. Patent citation networks[1]

The notion of a technological trajectory as outlined above points to technological innovations as sequential and interrelated events that are a selective draw from a large space of potential technological development. One way that has been proposed in the literature to measure the interrelatedness between innovations is by means of patent citations.[2] Patent documents contain a detailed description of the patented innovation, as well as the name and address of the innovator and the applicant. But most importantly for the present study, patent documents also contain references to previous patents, i.e. patent citations. A reference to a previous patent indicates that the knowledge in the latter patent was in some way useful and/or relevant for developing the new knowledge described in the citing patent. This is exactly the type of interpretation that allows us to use patent citations as a tool for mapping technological trajectories. Obviously, a single patent may source knowledge from multiple previous patents. Also, citing patents may themselves become cited in the future, so that we will be able to map “chains” of ideas as they develop over time.

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[1] This section draws heavily on Verspagen (2007).

[2] The use of patent data as a technology indicator has a long tradition, but they are not, however, undisputed. Griliches (1990) provides a survey of the main advantages and disadvantages of using patent statistics. Patent statistics are an output indicator of innovation rather than an input indicator (such as R&D expenditures). Their main advantage is that patents are available for a rather long period, and provide detailed technological information. The main disadvantages are that simple patent counts do not take into account differences in the quality of innovations, that many patents do not lead to innovations (i.e. are not applied), and that the propensities to patent an innovation may differ between sectors and firms.

The set of patents and the citations between them naturally lend themselves to be viewed as a network of ideas and their relatedness. The notion of a technological trajectory suggests that within this network, several main streams (or main paths) of knowledge exist that summarize the major developments in the field. It will be the general aim of our analysis to describe these main paths of knowledge flows in the datasets that we employ. The methodology used to do this draws on Hummon and Doreian (1989) and extensions proposed by Verspagen (2007) and Liu and Lu (2012). Hummon and Doreian (1989) analyze the network of citations between scientific publications on the discovery of DNA. Their aim is to construct a "main path" through this network that corresponds to the main flow of ideas in this field as represented in the formal publications. This can also be seen as an operationalization of the idea of a technological trajectory (Verspagen 2007).

The methodology rests on a number of basic concepts from network analysis, which will be explained first. We represent a patent citation network as a collection of vertices and edges. The vertices (patents) represent pieces of knowledge that depend on each other. The edges are connections between them, in this case citations between two patents. In the particular case of citation networks, the edges are directed, i.e. they have an origin (the cited patent) and destination (the citing patent).

We represent the citation network by means of a matrix C, in which the element c_{ij} is equal to 1 if patent j cites patent i, and zero otherwise. Define the matrix C* as the symmetric matrix in which the elements are formed by taking the maximum value (in C) of below and above diagonal elements. A component in the network C is defined as a subset of patents in which for every patent i and j, a path from i to j exists in the network represented by C*. A component represents a subset of the network that is somehow connected by a complex set of relations.

The citation networks that we consider are acyclic, i.e. if a path from i to j exists in C, no path exists from j to i. This follows logically from the nature of a citation: a patent can only be cited by patents that are published after itself, but this implies at the same time that the original patent cannot cite these later patents. In the network matrix C, vertices may be distinguished into three categories: sources, sinks and intermediate points. Sources are vertices that make no citations, but are cited. Sinks are the opposite: they are not cited, but make citations. Intermediate points both cite and are cited.

The most important idea in Hummon and Doreian (1989) for our purposes is that we can use the network structure to say something about the importance of the various individual edges (citations) in the network. We use the search path count (SPC) indicator for this purpose, following Liu et al. (2013). For the patent citation c_{ij}, SPC measures the number of times that the citation lies on a path from one vertex in the network to another vertex in the network. Thus, SPC measures how often one visits a citation if all possible paths in the network are traveled.

Once a measure of the importance of the edges (SPC) is calculated, Hummon and Doreain propose to define the "main path" through a network using a heuristic algorithm. Their algorithm uses a local optimization strategy, i.e., when at a particular point at a path, it picks the outgoing edge (citation) that maximizes SPC among all outgoing ones. As recognized in Verspagen (2007) and Liu and Lu (2012), such a local search strategy does not necessarily lead to a maximum sum of SPC along the entire path. Thus, instead of Hummon and Doreain's original heuristic, we look for the path that maximizes the total sum of SPC along all of its edges. Such a path will necessarily go from a source to a sink. We call the path that is found using this procedure the top main path in the network C. The intuition behind why the top main path is of interest, is that it represents the largest flow of ideas in the network.

We follow Liu and Lu's algorithm, but apply it in the way proposed by Verspagen (2007). This means that we identify the top main path for a network matrix C_t, where C_t is defined as the subset of C that includes only rows and columns corresponding to patents dated to a year smaller than or equal to t. Hence, C_t corresponds to the citation network that reflects the flow of ideas up to and including the year t. The single top main path that results for year t is called p_t. We then merge the paths p_t for all values of t = T0…T1, where T0 is a start year that we will identify below, and T1 is the last year in the dataset. The set of all paths p_t is called the network of top main paths, and is depicted for our networks in Figure 6 and Figure 7.

As a final step of the analysis, we will take the network of top main paths and attempt to identify clusters in it. For this purpose, we use the VOS algorithm, as proposed by Waltman and van Eck (2013). These clusters will be the main unit of analysis when we look at how countries have contributed to the technological trajectory (network of top main paths).

4. Data

In order to implement the methods explained in the previous section, we will draw on data from the EPO Worldwide Patent Statistical Database (PATSTAT, 2014 April version) developed by the European Patent Office (EPO). The version of PATSTAT that we use contains more than 90 million patent documents from all the leading economies in the world[3], covering patents since the beginning of the patent system (for some countries the records date back to the 1830s). Besides patent bibliographical data, PATSTAT also provides a comprehensive and up-to-date patent citation dataset that is based on patent publication and application documents. Table 1 below lists all the PATSTAT tables used in this paper.

Table 1. PATSTAT tables used in the analysis

Name of the table	Description
TLS201_APPLN	Patent application bibliographical data
TLS202_APPLN_TITLE	Patent application title
TLS206_PERSON	Data on patent applicants and inventors
TLS207_PERS_APPLN	Links between applicants and applications
TLS211_PAT_PUBLN	Patent publication bibliographical data
TLS_212_CITATION	Citation data linking between publications, applications and non-patent literature
TLS218_DOCDB_FAM	Patent family data, based on EPO DOCDB patent family
TLS224_APPLN_CPC	Cooperative Patent Classification (CPC) data

Notes: all the tables are extracted from PATSTAT (2014 April version).

The technology fields that will be analysed below are defined in terms of the Cooperative Patent Classification (CPC), and cover several parts of the recent OECD ENV-TECH list, which describes

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[3] See also: https://www.epo.org/searching-for-patents/business/patstat.html

patent search strategies for the identification of selected environment-related technologies (Haščič and Migotto 2015). Specifically, this paper chooses two kinds of technologies from the OECD list: (1) combustion technologies under the CPC class Y02E20 in the section "climate change mitigation technologies related to energy generation, transmission and distribution" and (2) energy efficiency technology for indoors use, under the CPC classes Y02B 20 – 70 in the section "climate change mitigation technologies related to buildings". The two chosen fields are sub-classes related to energy efficiency in a larger list that covers a broad range of climate change mitigation technologies (Table 2). The use of CPC codes (or any other classification scheme) has the disadvantage that it may exclude relevant technologies that are classified under different codes. For example, it is evident that other CPC classes in the OECD ENV-TECH are also closely related to energy efficiency, for instance, "technologies for an efficient electrical power generation, transmission and distribution" under Y02E40, and "architectural or construction elements improving the thermal performance of buildings" under Y02B80. Also, the OECD ENV-TECH contains an item called fuel efficiency-improving vehicle design under the CPC classes Y02T10 / 80 – 92 in the section "climate change mitigation technologies related to transportation", which we also do not include in the analysis.

Table 2. Climate change mitigation technologies related to energy generation, transmission and distribution

Category in OECD ENV-TECH	**CPC class**	**Used in this paper**
Renewable energy generation	Y02E10	No
Energy generation from fuels of non-fossil origin	Y02E50	No
Combustion technologies with mitigation potential (e.g. using fossil fuels, biomass, waste, etc.): technologies for improved output efficiency and input efficiency	Y02E20	Yes
Nuclear energy	Y02E30	No
Technologies for an efficient electrical power generation, transmission and distribution	Y02E40	No
Enabling technologies (technologies with potential or indirect contribution to emissions mitigation)	Y02E60	No
Other energy conversion or management systems reducing GHG emissions	Y02E70	No

Climate change mitigation technologies related to buildings

Category in OECD ENV-TECH	CPC class	Used in this paper
Integration of renewable energy sources in buildings	Y02B10	No
Energy efficiency in buildings, including energy efficient lighting, heating, ventilation or air conditioning, home appliances, elevators, escalators and moving walkways, information and communication technologies, end-user side	Y02B20 Y02B30 Y02B40 Y02B50 Y02B60 Y02B70	Yes
Architectural or construction elements improving the thermal performance of buildings	Y02B80	No
Enabling technologies in buildings	Y02B90	No

Source: own elaboration based on OECD ENV-TECH list (Haščič and Migotto 2015).

In choosing a relevant classification, we searched for a group of patents which are relatively strongly connected to each other, either directly or indirectly. The reason is that the methods that we will use work within a single component of a larger network, and hence a citation network that consists of many components will never identify a common trajectory for all the components. Including a broad class, like Y02E40, that includes topics that are only indirectly related to energy efficiency will tend to generate more components, which is why we do not include this. Also, preliminary results show that the patent citation networks of fuel efficiency-improving vehicle design (Y02T10) are not well connected. On the other hand, the two technology fields that we analyse are well connected, as will be shown below.

In constructing our patent citation datasets, the first challenge is to choose a proper unit of analysis to deal with the problems of double counting and self-citation in patent data. It is very common that a firm patents the same technology with various patent authorities (countries) around the world. All the patents reflecting the same technology but documented in different patent authorities are recorded in PATSTAT separately using different IDs. Also, an invention can be represented in three levels in PATSTAT: patent publication, patent application and patent family. The relationship between them is shown in Figure 1. A patent application may cover multiple patent publications, but a patent publication can only be linked to a single patent application. A patent family is related to multiple patent applications[4], but a patent application cannot be included in multiple patent families. The PATSTAT citation dataset is based on publications and applications, which results in the problem that many citing and cited entities actually indicate the same technology, which leads to double counting.

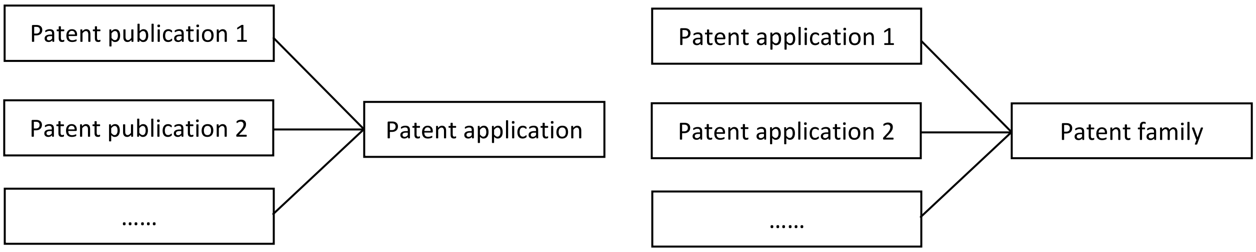

Figure 1. The relationship between patent publication, patent application and patent family in PATSTAT

The problems of double counting and self-citation (between members of a family) are solved by identifying all patent publications and patent applications in the citation dataset to their corresponding patent families and performing the analysis on patent families. The EPO has developed its own DOCDB patent family system, which is what we use, where different patent publications and patent applications representing the same technology are assigned a unique and stable ID. In the raw dataset, a patent publication can cite (1) another patent publication, (2) another patent application, or (3) non-patent literature. We do not include non-patent literature in our analysis, since it cannot be linked to any patent application or patent family. For patent citations, , we link all the citing and cited patent publications to their corresponding patent applications and only use those citation pairs under the CPC classes of interest. Then we link all the obtained citation

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[4] For example, patent applications authorized in different countries.

pairs of patent application to their corresponding DOCDB patent families.[5] We are then able to identify and remove all the self-citations and duplicated pairs in the citation dataset at family level.

Another problem is related to the timing of a patent family. Unlike patent application in the original patent bibliographical documents, DOCDB patent families do not have a specific filing date, while the temporal information greatly matters in our analyses. In this paper, we use the earliest application filing date (also known as priority date) within the same DOCDB patent family as the time indicator of the patent family. In the raw dataset, a patent publication cannot cite a patent publication or application earlier than itself. If we convert all the patent publications and patent applications into patent families, however, some “illogical” pairs where the citing patent family is earlier than the cited patent family do exist. For logical consistency, and to keep the network acyclical, we do not include these pairs. Also, we delete any citations that lead to cycles in the network when two families have the same priority date.

In the final citation dataset of energy efficiency technology related to energy generation, 18,031 citation pairs formed by 7,230 DOCDB patent families from the CPC class Y02E20 are found. We will refer to this data set as the power stations dataset. The date of cited patent family ranges from 1905 to 2012 and the citing patent family occurs for the period 1951 – 2013. For the Y02B 20 – 70 classes, which we will to as indoors energy efficiency technologies, the final citation dataset has 143,653 citation pairs containing 51,206 DOCDB patent families. The cited patent family exists for the period 1898 – 2012 and the citing patent family appears for the period 1933 – 2013.

The figures below illustrate the development of the citation networks for energy efficiency technology related to energy generation and buildings respectively.[6] Figure 2 and Figure 3 show the general evolution of the networks in terms of the number of patents (vertices in the networks), also by type of vertex. Both types of technologies show similar trends in development. Before 1980s the growth of the citation networks for both types of technologies is rather slow: the curves indicating the total number of patent families, the number of sources, the number of sinks and the number of citation network components are very flat compared to those after 1980s.[7] After 1980 the development of both types of technologies takes off: all the relating curves have steep increases.

Also, in the early years, citations happen between only a small number of patent families, leading to a fragmented nature of the citation network. Figure 4 and Figure 5 document the share (in terms of the number of patents involved) of the largest citation network component in the complete networks. These shares generally remain at a low level (below 60%) and fluctuate significantly for the period until 1980. For the power stations field, from 1984 onwards the share of the largest citation network component starts to continuously increase and gradually reaches a very high level (from 63% in 1984 to 91% in 2013), and for the indoors energy efficiency field, the share of the largest citation network component smoothly grows from 79% in 1982 to 92% in 2013. The higher this share,

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[5] The source of citation data is the table “TLS_212_CITATION”. The table “TLS211_PAT_PUBLN” contains the links between patent publication and patent application. The table “TLS218_DOCDB_FAM” contains the links between patent application and DOCDB patent family.

[6] To obtain all the basic network statistics, we use the two complete citation datasets to construct sub-datasets in which all the cited and citing patent families are earlier than or equal to the corresponding year on the X axis of the figures. For example, the sub-dataset for 2012 only contains cited and citing patent families up to and including 2012. We do this for every year existing in the ranges of the citing patent families.

[7] In the early years all the curves are discontinuous because no patent families are found in some years.

the better connected is the citation network, and the better our analysis will capture general trends in the field. We therefore choose 1984 and 1982 as the start years for the analysis in the next section.

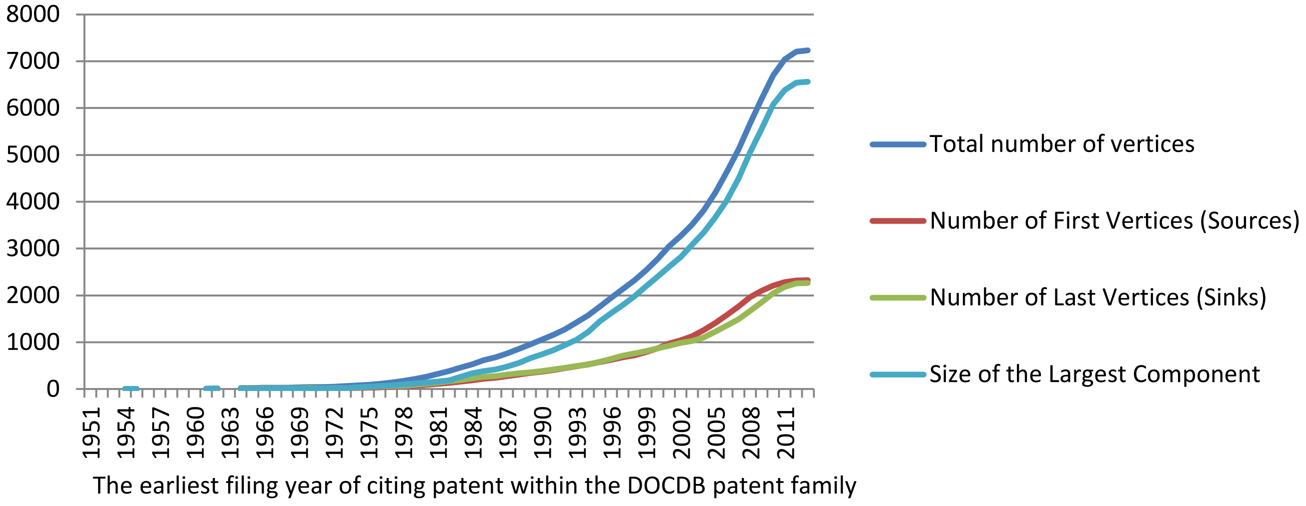

Figure 2. Development of the citation network for power stations

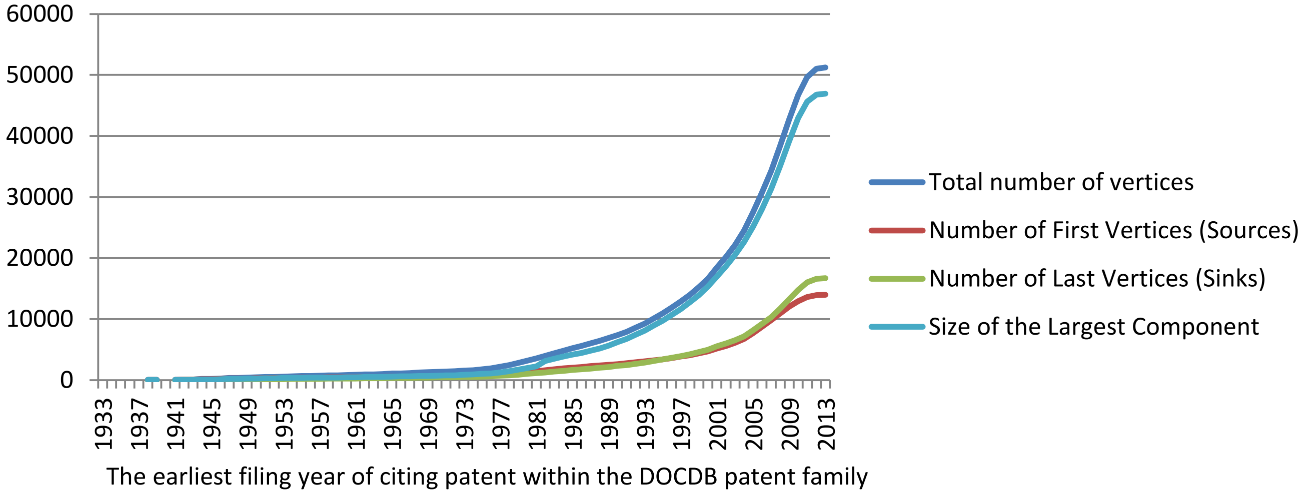

Figure 3. Development of the citation network for indoors energy efficiency technologies

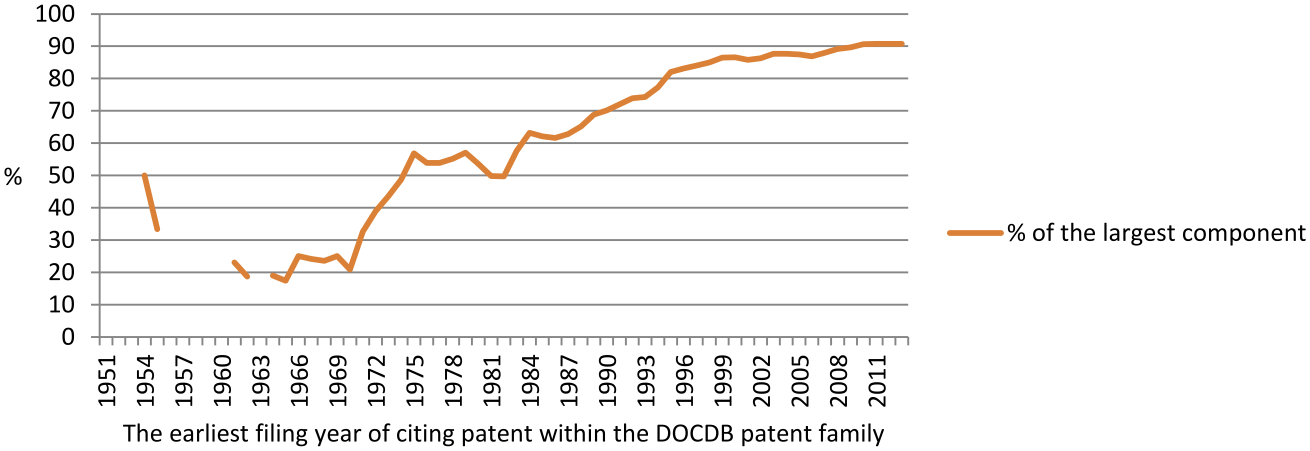

Figure 4. Evolution of the importance of the largest component in the power stations citations network

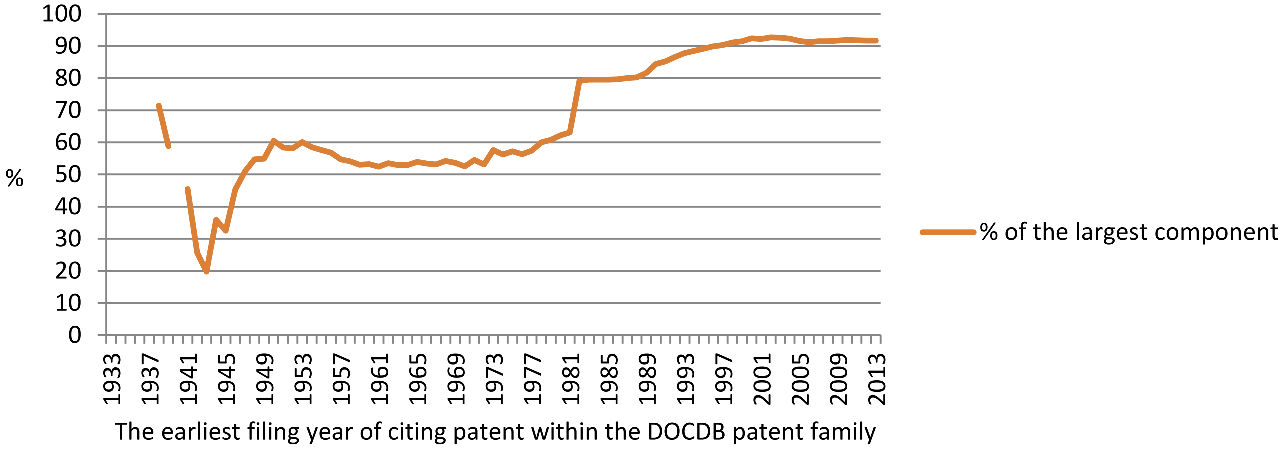

Figure 5. Evolution of the importance of the largest component in the indoors energy efficiency citations network

5. Results

We will separately analyze the two particular groups of technologies in the field of energy efficiency that were introduced above. The cases are chosen to provide a certain degree of diversity. One case, broadly speaking the technology of power stations and power plants, is a scale-intensive technology that requires large investments to be applied. The other group of technologies, broadly speaking those that are aimed at increasing energy efficiency for indoors use, in homes and offices, has much smaller scale, but also much larger variety. In the main trajectories that we will present and analyze below, for example, we find two major groups of technologies: refrigeration and heat pumps, and power efficiency in computers.

For each of those technology fields, we will use the methods explained above to identify the main paths in the technology field, which we will take as an indication of the most important technological trajectories that developed over time. We will start by discussing these results for the two fields. We will then revert back to the entire patent datasets for the fields (the identified trajectories are a subset) and look at the role of different countries over time.[8] We will try to identify leaders (in time) and latecomers, at the country level. Finally, we will analyze how individual countries relate to the technological trajectories (main paths), and what role the timing of the technological efforts (i.e., whether they are latecomers or early players) plays a role in thus relationship. We will use both a forward perspective and a backward perspective. The forward perspective asks into which parts of the main path a country's patents feed, while the backward perspective asks from which parts of the main path the country's patents are derived.

5.1. Power stations

In the dataset for the power station technology 6,563 are connected to each other by citations (i.e., they form a network component) in the final year 2013. We use this component for our analysis, i.e., we ignore the small number of patents (roughly 9%) that are outside this component. Table 3 shows the number of patent families and the age of the patents in this component, by country. We count the number of inventors by country, and because a patent family can have more than a single inventor, the total number exceeds the number of patents in the sample. We include in the analysis only countries that have more than 50 patents (an admittedly arbitrary threshold), which yields the countries listed in the table. Together, these countries account for 55% of all inventors in the sample. Of the remaining 45%, 41%-points are inventors for which the country is not listed in the database.[9]

The US and Germany are the largest countries in this technology field. Together, they account for 32% of all patents. The other countries in the table are either European or Asian. Many of the Asian countries are characterized as latecomers. This is done on the basis of two indicators for the age of the patents from a country. The first indicator is the average year of the patents in the country, the other the year of the oldest patent for a country. The average is 1999 for the entire sample, while the earliest patent is from 1908. Thus, despite the fact that the database goes back more than a century, the majority of patents is less than 20 years old.

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[8] In this section, when we speak about "patents", we generally mean "patent families".

[9] In many cases, the unlisted inventors will be the same ones that are listed in other members of the family, hence the problem of unlisted nationalities is less serious than it seems on the basis of the 45%.

The countries that can be characterized as latecomers in terms of industrialization and catching-up are Korea, India and China, where the last two are clearly second-tier catching-up countries. In line with this characterization, their average patent is from 2005 or later. The other countries are all early industrializers, although some of them (e.g., Italy, Austria) have average patents from years that are close to that of Korea.

Table 3. Number of patents and age for power station technology, by country

	Av year	Min year	n
All	1999	1908	10262
USA	1999	1908	2134
Germany	1999	1962	1123
Japan	2001	1973	617
Switzerland	2001	1960	310
France	2002	1966	306
United Kingdom	2001	1965	238
Sweden	1998	1949	128
Korea	2006	1996	119
Italy	2003	1968	113
Canada	2002	1976	111
Netherlands	1999	1967	99
India	2008	1992	90
Finland	2000	1981	89
Austria	2002	1952	58
Israel	1999	1978	57
China	2005	1986	56

Table 4 presents the clusters in the top main paths group of patents in the power stations field. There are 214 patents in the top main paths since 1984, which is the year in which we start the analysis (this is also the year in which the largest component of the citation network become substantial). The VOS clustering algorithm that we apply divides this group into 13 clusters. The 214 patents are also spread over 2 separate components. Figure 6 displays a graph of the network of all top main paths over the period 1984 – 2013, including an indication of the clusters. The table also gives an indication of the age of the patents in a cluster, with minimum, average and maximum year of the group of patents in the cluster.

[insert Figure 6 about here]

The technological trajectory in this field shows a dynamic evolution over time. At the end of the period, in 2013, the top main path consists of two separate branches and a core. But over time, other branches have been present, which disappeared before 2013. The two final branches are labeled Branch A and Branch B in the table and figure. They have clear technological characterizations. Branch A corresponds to a trajectory of oxygen combustion, a technique where a higher concentration of oxygen than is found in normal air is used to burn fuel. Branch B corresponds to a trajectory of a combined cycle, which means that gas or steam is used twice, at different pressures, to generate energy. These two branches emerged around the same time, as shown by the oldest age of patents in the clusters (1996 and 1997), but on average the patents in Branch A are younger (2006) than in Branch B (2002). The core of the network, which includes the single source patent from 1949, includes patents on gasification of fuel. This can be considered as the most basic technology in the trajectory, from which all other sub-branches emerged. The core contains mostly older patents, with average year equal to 1979, i.e., pre-dating the average year of all patents in the sample by a full 20 years.

Table 4. Clusters in the top main paths graphs of the power stations field

Cluster as labeled in figure	description	Period (min – average – max)
Cluster 2 (Core)	Gasification of fuel, mainly companies from USA and Germany	1949 – 1979 – 1993
Cluster 13 (Branch A final path)	Oxygen combustion, started by companies from USA, France and Norway, last part Hitachi (Japan)	1997 – 2006 – 2013
Cluster 8 (stable part of Branch B final path)	Combined cycle, mostly companies from Japan (Mitsubishi) and USA	1996 – 2002 – 2010
Cluster 7 (non-stable part of Branch B final path)	Hybrid fuel and solar, frequency stabilization, heating, cooling, moisturization, mostly companies from USA	1994 – 2000 – 2006
Cluster 12 (non-stable part of Branch B final path)	Cogeneration, mostly companies from Korea and Japan	2001 – 2005 – 2007
Cluster 4 (early dead end)	Load control, combined cycle, mostly companies from Japan and USA	1973 – 1982 – 1990
Cluster 1 (dead ends)	Combined cycle, gasification, mainly companies from Germany and USA	1977 – 1986 – 1992
Cluster 3 (dead ends)	Use of biofuels, using fuel cells, mainly companies from USA	1977 – 1985 – 1994
Cluster 5 (dead ends)	Using waste as fuel, companies from Finland, Germany	1986 – 1992 – 1996
Cluster 9 (dead ends)	Combined cycle, companies from Germany, USA	1996 – 2000 – 2006
Cluster 6 (mostly fringe)	Reducing CO2 emissions, mainly companies from USA	1992 – 1998 – 2006
Cluster 10 (disconnected dead end)	Fuel burners, combustion, mainly companies from USA	1962 – 1986 – 1996
Cluster 11 (disconnected dead end)	Oxygen combustion, fuel injection, mainly companies from USA and France	1996 – 2001 – 2005

Cluster 4 is an early branch that turns into a dead end (by which we mean that it disappears from the top main path before 2013). This branch is present in the network from 1984 until 1991, but the oldest patent in this cluster is from 1973, and the average year of patents in the cluster is 1982, i.e., only slightly (3 years) younger than the core (Cluster 2). Technological topics in Cluster 4 are load control and the combined cycle.

There are other dead ends, some of which are closely linked to Branch B of the network. The latter clusters are indicated as non-stable parts of Branch B, and they comprise the clusters 7 and 12. When they appear, these branches are linked to the stable part of Branch B. Their technological characterization is different, however, from the patents in the stable part of Branch B. In cluster 7,l we find technologies that combine solar energy with turbines, and in Cluster 12, we find cogeneration technologies (generating electricity and useful heat at the same time).

Another dead end is formed by clusters 10 and 11, which together from a separate component in the network of top main paths (see Figure 6). This is a branch that appears for only three years in the top main path (1996, 2002 and 2006), and which is concerned with the combustion process itself, in the form of oxygen combustion, fuel injection, and the design of burners. The other dead ends in the network are Clusters 1, 3, 5 and 9. Cluster 6 contains many patents that do not form a real trajectory over time, but which are fringe patents that appear for only one or two years in the network of top main paths.

Besides a coherent technological content, the clusters can also be characterized by the country of origin of the companies that are active in them. Many companies, across most of the clusters, are from the US, but some clusters are dominated by other countries. Germany plays an important role in the core cluster, together with the US, which is the same in Cluster 1, and Cluster 9. Japanese companies play an important role in both branches A and B, as well as in Cluster 12, a non-stable part of Branch B, where also Korea plays an important role (and the US is more absent than usual). Finnish companies play an important role Cluster 5, with technologies aimed at using waste from the paper industry.

5.2. Indoors energy efficiency

The second field that we consider is a much less homogenous technology. In fact, it is a collection of relatively independent technologies, which share that they are used indoors to save energy. The total number of patent families in the largest component in this field in 2013 is 46,951 (8% is left out). Table 5 shows the number of inventors in patent families by countries. Because the dataset has more observations, we are able to apply a higher threshold of patents to include countries in the table, and as a result we have more countries. The threshold is 100 patents, but we left out Russia, which has 101 patents, because Russian patents were assigned to the Soviet Union up to around 1991.

The US is again the largest country in terms of patents in this field, followed by Japan and Germany. The next largest countries are three latecomer countries: Korea, Taiwan and China. The average year in which patents were filed is 1999, which is identical to the power stations field. Besides Korea, Taiwan and China, we also have India, Singapore and Hongkong as latecomer countries. But also Israel and Spain have rather late years for the average patent.

Table 5. Number of patents and age for indoors energy efficiency technology, by country

	Av year	Min year	n
All patents	1999	1898	73060
USA	2001	1898	15392
Japan	2002	1968	6824
Germany	1999	1912	5050
Korea	2005	1980	2794
Taiwan	2007	1982	1858
China	2008	1991	1849
France	1997	1932	1848
United Kingdom	2002	1920	1597
Netherlands	2002	1938	1465
Canada	2003	1969	982
Sweden	1997	1925	738
Italy	2003	1957	661
Switzerland	1996	1909	658
Austria	2001	1967	552
India	2007	1989	551
Finland	2002	1971	513
Israel	2004	1979	437
Spain	2004	1978	236
Belgium	2003	1965	217
Australia	2002	1974	200
Denmark	2000	1967	200
Singapore	2004	1988	199
Hongkong	2003	1980	182

Figure 7 presents the network of top main paths since 1982. There are two separate components in this network, one that corresponds to refrigeration and heat pumps, and the other to energy saving in computers. We find 14 clusters using the VOS algorithm, of which 6 are in refrigeration, and the other 8 in the computer part. Each of these two components develops in a more or less linear fashion, with one founding cluster, a number of intermediate clusters and a number of final clusters that correspond to the state of the art. The clusters are presented in Table 6. Cluster 1, in which patents going back, on average, to 1928, is the foundational cluster for the refrigeration component. This cluster is concerned with absorption cooling, as used in home and industrial refrigerators. Cluster 6 is the last cluster (state of the art) in this group, which deals with more complex and methods for cooling, which have applications in airconditioning rather than refrigeration. Cluster 4 is a dead end in this development, while Cluster 5 is an intermediate stage which includes GAX cooling.

[insert Figure 7 about here]

Cluster 7, with patents that on average go back to 1968, is the foundational cluster in the computer part of the graph. This cluster is concerned with electrical circuits in general. The foundational cluster, through a number of other clusters, develops into three clusters at the end of the period: 12, 13 and 14. Of these, Cluster 12 deals with power management systems, while Clusters 13 and 14 deal with CPUs, in particular multicore CPUs.

Table 6. Clusters in the top main paths graphs of the indoors energy efficiency field

Cluster as labeled in figure	description	Period (min – average – max)
Cluster 1 (refrigeration, old)	Absorption refrigeration	1906 – 1928 – 1937
Cluster 2 (refrigeration, old)	Absorption refrigeration	1943 – 1955 – 1967
Cluster 3 (cooling & heating)	Heating & cooling, heat pumps, mainly companies from US and Japan	1970 – 1984 – 1991
Cluster 4 (pumping & storing heat)	Storing & pumping heat, absorption refrigeration, mainly companies from Germany, France and US	1980 – 1986 – 1991
Cluster 5 (heat pumps, GAX absorption)	Heat pumps, GAX absorption, mainly US companies and individuals	1990 – 1993 - 1997
Cluster 6 (triple-effect absorption cooling, airco)	Triple effect absorption cooling, efficiency, mainly US companies	1996 – 2001 – 2006
Cluster 7 (electrical circuits)	Electrical circuit (peak) regulation	1925 – 1968 – 1989
Cluster 8 (cpu & memory)	CPUs, memory, computer related power management, almost exclusively US companies	1992 – 1995 – 2000
Cluster 9 (computer power management)	Computer power management, mainly US companies	1993 – 2002 – 2007
Cluster 10 (cpu & memory bus)	CPU clockspeed, memory bus, mainly US companies	1997 – 2001 – 2005
Cluster 11 (storage and CPU)	Storage, clockspeed, mainly US companies	2006 – 2008 – 2009
Cluster 12 (power management systems)	Computer power management systems, many US companies with foreign inventors	2003 – 2007 – 2011
Cluster 13 (multicore and energy consumption)	Energy consumption of CPUs, multicore, many US companies	2008 – 2009 – 2010
Cluster 14 (multicore and energy consumption)	Energy consumption of CPUs, multicore, many US companies	2008 – 2009 – 2010

5.3. How countries relate to the technological profiles

We now come to the final stage of the analysis, which consists of investigating the way in which countries' technological efforts (patents) relate to the technological trajectories that were identified in each of the two fields. To analyze this, we ask, for each patent in the dataset (largest component) whether a path exists from that patent to one of the patents on the network of top main paths, or vice versa, i.e., from a patent on the network of top main paths to any other patent. The first of these perspectives, i.e., from a patent to the network of top main paths, is called the forward perspective, while the latter (from the network of top main paths to a different patent) is called the backward perspective. The forward perspective asks to which part (e.g., Cluster) of the trajectories a patent (and its inventor country) contribute, while the backward perspective asks from which part (Cluster) it is ultimately derived.

We are particularly interested in the clusters that appear, in Figure 6 and Figure 7, as parts of the network that are present at the end of the period. These clusters embody the most recent technological trajectories in their field, and therefore are a good reference to assess how latecomer countries relate to the main technological trajectory in the fields that we investigate. Thus we focus on Clusters 13 and 8 (Branch A and B) for the power stations field, and on Clusters 12, 13 and 14 for the computer energy efficiency field. We ignore the refrigeration field, as there are generally very few patents with forward linkages to this trajectory in the dataset. Fort the computer technology field, we merge the three clusters under consideration, because they appear as parts of the same technological direction, and because on their own they are not involved in many forward linkages. The two clusters in the power stations field are considered as separate cases.

Our main variable of interest for the research question whether latecomer countries tend to contribute to the main technological trajectories at a higher or lower rate than the incumbent countries in the field, are the forward linkages. These measure whether the patents of a country lead into the main technological trajectory. Because latecomer countries, by definition, have the majority of their patents concentrated towards the end of the period, we measure the forward linkages for the period 2008 – 2013. For a particular technological trajectory (cluster or group of clusters) and a particular country, the forward linkages variable measure which fraction of patents in the period 2008 – 2013 have a forward linkage to at least one patent on the technological trajectory.

We will use this variable as the dependent in a simple regression analysis. The aim is not to estimate a theoretical model aimed at identifying causation, but instead simply to explore the nature of the correlations. The main independent variable of interest is an indicator for the timing of a country's technological effort in the field. For this purpose, we use the average year in Table 3 and Table 5, from which we subtract 1995 (1996 is the minimum value found in the tables). If this variable has a positive (negative) sign in the regression, then latecomer countries tend to have a higher (lower) proportion of their total patents with forward linkages to the main technological trajectory.

We include two control variables. The first is a measure for the vested interest that a country has in the main technological trajectories. We measure this as the backward linkages for all clusters in the relevant field. For the power stations technology, this is the sum of all backward linkages for all clusters (1-13). This means that for the two separate clusters that are used as dependent variable, this variable is identical within a country. For the computer energy efficiency field, this is the sum of backward linkages to clusters 7 – 14 in Table 6. The backward linkages indicator is measured over the entire period, including the pre-2008 years, to reflect the entire history of a country in the field. Another control variable is the number of patents that a country has, in the period 2008 – 2013. Finally, we include intercept dummies for two of the three technology fields. We express all variables, except the two dummies, in natural logs. In the regression, we cluster the error terms by country. Because we have 9 cases where the dependent variable is zero (before taking logs), the number of observations is 46 (there are 55 cases in Table 3 and Table 5).

Table 7. Regression results for forward linkages

	Coefficient	t-value	significance
ln(year)	-1.50	(3.52)	***
ln(backward)	1.24	(3.27)	***
ln(number patents)	-0.12	(0.81)	
Dummy Branch B	2.56	(3.69)	***
Dummy Branch A	2.57	(3.88)	***
Constant	-1.52	(0.99)	

*** indicates significance at 1% level or better.

Table 7 presents the regression results. The year and backward linkages are significant. The number of patents is not. The two dummies for the power stations clusters are also significant. The year has a negative sign, which indicates that latecomer countries tend to contribute less, proportionally, to the main technological trajectories in the field that we analyze. The number of backward linkages has a positive sign, which adds to this effect: those countries with large vested interests in the dominant technological trajectories are also the ones with strongest forward linkages, i.e., they contribute in the strongest way to the further development of the trajectory. The insignificance of the number of patents suggests that economies of scale do not play a major role, beyond what is already related to the backward linkages. The two dummy variables for Branch A and B are positive, which indicates that forward linkages are higher in the power station field than in the computer energy efficiency field. This is in line with the more scattered nature of the indoors energy efficiency field.

What do the results tell us about the technological choices of latecomer countries in the technological fields that we analyzed? Latecomer countries tend to contribute less (proportionate to their number of patents) to the main technological fields. This could be an indication of the technological choices made by the firms in these countries. These firms may have assessed that competition is too strong in the dominant technological trajectory, and hence that it is better to search for new opportunities in a different direction. But it may also be a reflection of the technological capabilities of the firms in these countries. Citations are also often used as a measure of the quality of a patent (Lee, 200X). Because only citations can link a patent (forward) to a technological trajectory, receiving few citations will tend to decrease the forward citations. Thus, our regressions have little to say about the causal mechanisms behind the observed tendency of a negative relationship between forward linkages and the year variable.

6. Conclusions and discussion

This paper has looked at the role of technological trajectories in the dynamics of technological catch-up. It has focused on a small number of countries that contribute significantly, in terms of the number of patents, to technological developments in two fields related to energy efficiency: energy efficiency in power stations and energy efficiency in indoors use, in particular computers and refrigeration. We identified a number of main technological trajectories in each of these fields, and were able to specify which specific technological issues were dealt with in these trajectories, as well as which firms were involved. We were also able to put an average date (year) on the patents of the countries in the fields, thus enabling us to measure the extent to which a country is a latecomer. Our database includes China, Korea, India, Taiwan, Singapore and Hongkong as countries that are traditionally seen as catching-up economies in the postwar period, e.g., (Fagerberg and Godinho 2004).

Our findings indicate that latecomer countries tend to contribute to the main technological trajectory in the fields under investigation in a less strong way than incumbent countries. By this we mean that the average year of the patents from a particular country is correlated negatively, in a multiple regression framework, to the forward linkages of that country's patent. The forward linkages measure which fraction of a country's patents (in the 2008 – 2013 period) is linked by forward citations to the main technological trajectory in the field. This is lower for latecomer countries. This tendency is reinforced by the tendency that countries with vested interests in the main technological trajectory also tend to have higher forward linkages. The vested interests are measured by backward linkages, which is a measure for which fraction of a country's patents is linked to the main technological trajectory by backward citations.

Our results do not tell us anything about the causal mechanisms that can explain the observed correlations. Our research question is explorative, and first of all asks whether the notion of technological trajectories is relevant for the study of technological capabilities in latecomer countries. This question is answered affirmative: we are able to identify technological trajectories that make sense from a technological point of view, and there is a systematic tendency of latecomer countries to be related to these trajectories in a different way than incumbent players. Thus, the concept of technological trajectories seems a useful one for studying technological choices in latecomer countries, as in (Lee (2013)).

For this to become a useful research area, we need more research, in at least two forms. First, we need more cases, for a wide variety of technological fields. The methods explored here can be applied, and possibly refined, to different fields in a more or less direct fashion. Second, we also need more research, empirical and theoretical, on how firms in latecomer countries deal with technological trajectories. For this question, patent data alone are probably not enough. Patent data, including citations, can tell us many things about the structure of a technological field, but very little about the motivations of firms to search in particular technological directions. In order to understand how firms in latecomer countries or in incumbent countries, contribute and relate to technological trajectories, this is the key process that we need to analyze.

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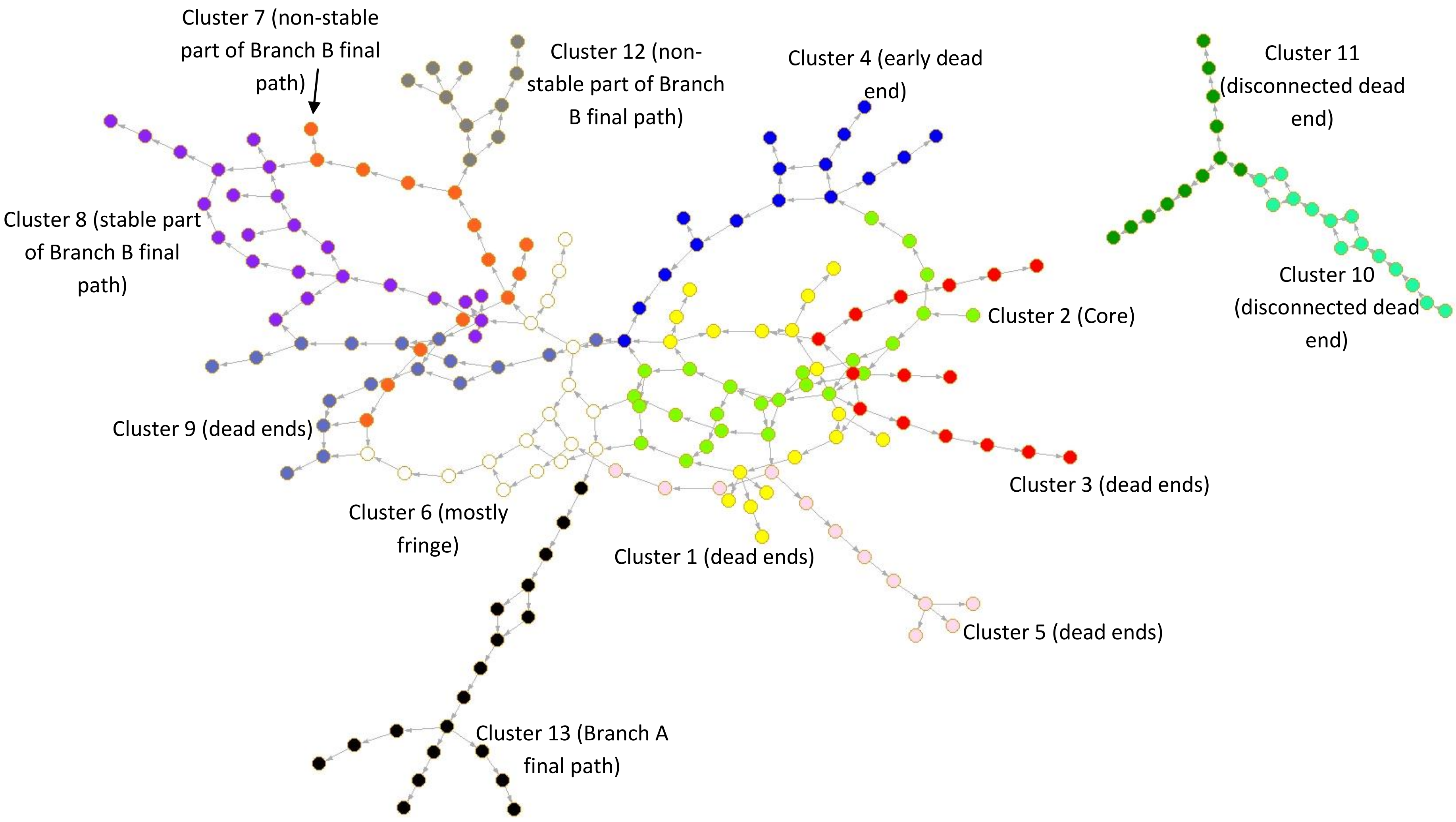

Figure 6. Top main paths, 1984 - 2013, power stations field, colors indicate 13 VOS clusters

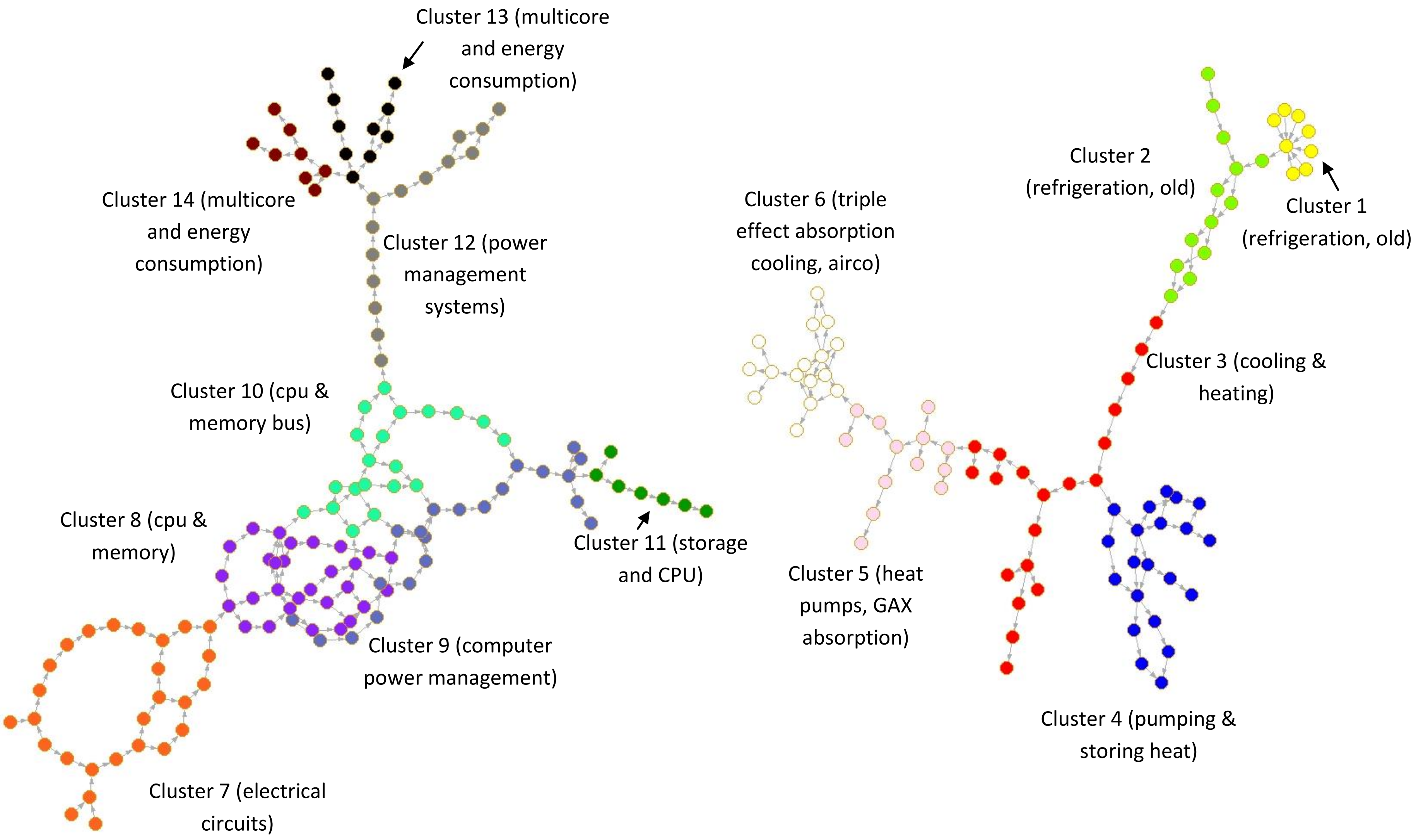

Figure 7. Top main paths, 1984 - 2013, indoors energy efficiency field, colors indicate 14 VOS clusters

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