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# The emergence of new technology-based industries: the case of fuel cells and its technological relatedness to regional knowledge bases

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## Abstract

Evolutionary economic geographers propose that regional diversification is a path-dependent process whereby industries grow out of pre-existing industrial structures through technologically related localised knowledge spillovers and learning. This article examines whether this also applies to emerging radical technologies that create the foundation for new industries. The article develops a new measure for technological relatedness between the knowledge base of a region and that of a radical technology based on patent classes. It demonstrates that emerging fuel cell technology develops where the regional knowledge base is technologically related to that of fuel cells and consequently confirms the evolutionary thesis.

**Keywords:** Evolutionary economic geography, recombinant innovation, regional branching, technological relatedness, fuel cell technology
**JEL classifications:** C23, R11, Q55
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## 1. Introduction

Discussions on the emergence of new regional industrial paths have gained renewed interest in the field of economic geography. In recent decades, the field of economic geography has experienced what has been called an ‘evolutionary turn’ (Martin and Sunley, 2006; Boschma and Martin, 2007; Essletzbichler and Rigby, 2007; Grabher, 2009; Boschma and Martin, 2010) inspired by the field of evolutionary economics (Nelson and Winter, 1982; Freeman, 1994). This turn has generated renewed interest in the question of how we can explain the emergence of new technology-based industries and their spatial manifestation as a process of regional path dependency (Martin and Sunley, 2006). Boschma and Frenken (2011) argue that technological relatedness, understood as cognitive proximity, enhances knowledge transfers and sharing from pre-existing regional activities to emerging industrial activities within regional borders.

The idea that relatedness between pre-existing economic activities has an impact on the direction of future economic development was first applied at the national level (Hausmann and Klinger, 2007; Hidalgo et al., 2007). On the basis of the mapping of the relatedness between products, Hidalgo et al. (2007) demonstrate that countries diversify through the product space by developing goods that are close to those they currently develop. Boschma et al. (2013) have shown that the process of diversification is rather driven by capabilities available at the regional (i.e. subnational) level than at national scale. Several empirical studies have provided evidence that the knowledge space of regions and cities develops along technologically coherent trajectories (Essletzbichler and Winther, 1999; Neffke et al., 2011; Boschma et al., 2013; Heimeriks and Boschma, 2013; Kogler et al., 2013; Boschma et al., 2014). Consequently, the concept of technological relatedness has become an important element in understanding the creation of new varieties and the formation of new regional industrial paths (Boschma and Frenken, 2011; Neffke et al., 2011).

This article contributes to this strand of the economic geography literature in three ways. First, it is unclear whether localisation of radically new industries, based on radical technology development, is likewise driven by technologically related knowledge spillovers from pre-existing regional economic activities. As radical technology is characterised by a high degree of discontinuity in production and marketing systems and a strong dependency on knowledge produced in R&D departments (Freeman and Perez, 1988; Freeman, 1994), some scholars (Storper and Walker, 1989) have argued that new industries experience a relative 'freedom' to locate in a large number of regions. According to Storper and Walker, locational freedom is achieved because new industries are less constrained by specific locational resources and rely to a greater degree on their own creative ability to generate or attract a supportive local environment than is the case for established industries.

The main objective of this article is to test whether the thesis of regional branching and technological relatedness can explain the emergence of radically new technology-based industries in regions and thus reduce the emphasis on spatial indeterminacy. Consequently, this article aims to investigate the relationship between the knowledge base of a given region and the localisation patterns of an emerging industry to analyse the linkages between specific local knowledge resources and the emergence of a radically new industry.

Secondly, an additional objective of this article is to expand our understanding of the character of such resources. The literature on regional branching has proposed that new industries may grow out of a single industry or be the result of combining capabilities from several industries (Frenken and Bochma, 2007; Boschma and Frenken, 2011; Frenken et al., 2012). The latter is in line with the idea of recombinant innovation (Fleming, 2001; van den Bergh, 2008) where innovations are defined as combining components in new ways (Schumpeter, 1934). This article aims to answer whether the development of fuel cell technology relies on recombinant innovation or draws mainly on a single technology field.

Thirdly, this article develops a new way of measuring technological relatedness based on the (evolving) knowledge base of a nascent technology area. The main data set is a regionalised database of patent applications filed under the Patent Cooperation Treaty (PCT) (OECD REGPAT, June 2010). Patent activity is regarded as a proxy for knowledge production, and hence serves as a measure of the competences and skills present in a sample of European regions within specific knowledge areas. A total of 12 knowledge fields that form part of the fuel cell knowledge base are identified as fuel cell–related knowledge. The same database makes it possible to measure the level of knowledge production within these 12 knowledge fields for each region over a 15-year period. Moreover, measures of related variety and the unrelated knowledge stock are also developed.

Consequently, this article investigates the presence of a portfolio of technologically related knowledge fields that jointly contribute to the knowledge base of fuel cell technology. By decomposing the availability of specific regional resources into specific knowledge fields relevant to fuel cell technology, the analysis provides a detailed measure of technological relatedness. This enables the analysis to reveal the importance of specific knowledge fields (over others) and test the importance of the presence of the variety of related technology fields.

This article focuses on the emerging fuel cell industry. A fuel cell is an electro–chemical device that generates electricity based on a chemical reaction between oxygen and hydrogen. Fuel cell technology is radical because it has the potential to replace incumbent energy technologies and as such results in technological discontinuities (Garcia and Calantone, 2002). It functions as an entirely new chemical process of energy conversion and consequently builds upon a new set of scientific and technical principles, which requires the development of a new knowledge base (Avadikyan et al., 2003; Bourgeois and Mima, 2003). Since the early 1990s, the development of fuel cell technology has gained momentum in its technical achievements and is regarded as a promising alternative to replace fossil fuel-based energy technologies in the long term. This has been a result of an increasing interest in the technology by various types of actors. In the early years of the field, these actors primarily consisted of universities and the core developers of fuel cell stacks and fuel cell systems, such as electrical battery manufacturers or new, specialised firms (Bourgeois and Mima, 2003). In later years, firms further downstream become increasingly involved in the development of fuel cell technology, mirroring a diverse range of application opportunities and markets in the stationary power, automotive and portable equipment sectors.

The article is structured as follows. Section 2 describes the theoretical conceptualisation on which the article builds, beginning with a brief distinction between incremental and radical innovation, to define the related concepts of emerging technologies and industries. Then, the processes of early industrial localisation are discussed, distinguishing between the 'window of locational opportunity' interpretation and the concept of 'regional branching'. Section 3 describes the radical character of fuel cell technology, and Section 4 introduces the data, measures of 'technological relatedness' and the model used to test the hypothesis of the article. Section 5 presents the results, and the concluding Section 6 summarises the findings and presents directions for future research.

## 2. Theory and conceptualisation

### 2.1. Radically new regional industrial paths

Although a plethora of definitions of innovation types is used in innovation studies (Garcia and Calantone, 2002), a simple distinction between incremental and radical technological change is widely accepted to capture one main variation. Incremental innovations occur continuously and are cumulative in nature within technological trajectories (Nelson and Winter, 1982; Dosi and Orsenigo, 1988; Freeman, 1994). They occur within firms or within clusters of firms that are closely linked to one another, and hence in a geographical respect are perceived to be strongly influenced by pre-existing patterns of economic activities (Boschma and van der Knaap, 1997). In other words, incremental changes to products and processes occur where firms are located and are often driven by learning by doing and learning by using mechanisms.

Conversely, radical innovations often lay the foundations for entirely new products or processes, generating paradigmatic changes (Dosi, 1982, 1988). Radical innovations are of a discontinuous nature and are argued to spur the emergence of new industries or firms that have the potential to disrupt incumbent industries and firms. In that respect, radical innovation is generally perceived to cause discontinuity in the economic system and instability in the economic landscape (Boschma and van der Knaap, 1997). It also follows that in the early stages of radical technological innovation, uncertainty is very high (Freeman and Perez, 1988), and the technology requires years of development and improvements.

The evolution of technologies is closely related to the evolution of industries, although the two concepts also differ substantially. Whereas an emerging technology can be defined as a body of knowledge (techniques, methods, equipment and devices) (Dosi, 1984), emerging industries are defined as the early risk-taking actors that explore and exploit the possibilities of a new technological paradigm (Tanner, 2012a). Consequently, in this article an emerging industry is defined by the common set of competences and skills that make firms capable of engaging in a new technology field (Bettis, 1998; Sampler, 1998). This definition differs from prevalent definition originating from the field of industrial organisational economics, which mainly defines industries by substitutable product groups (Porter, 1980). However, it is the author's opinion that, in particularly, when we study the emergence of new technology-based industries it makes sense to define industries around technologies, and not substitutable products that often only exist as prototypes at this stage. Accordingly, it is the technology that connects firms (and universities and research institutes; Tanner, 2014) in networks with shared capabilities.

When new industries emerge based on a radical technology, it forms what is here called a radically new industrial path. This article is concerned with the spatial location of the new industrial path, and hence terms it a radically new regional industrial path. A new industry may emerge in a number of regions at approximately the same time. However, in the conceptualisation of radically new regional industrial paths, it is important to highlight that the new industry builds on radical technology development and as such is not only new to the region but also *new to the world*.

In the following, a theoretical conceptualisation of the localisation of radically new industrial paths is outlined, beginning with the notion of 'windows of locational opportunity' (WLO; Storper and Walker, 1989) and continuing with an alternative approach based on the term 'regional branching' (Boschma and Frenken, 2011).

## 2.2. Early industrial localisation through locational freedom

The discontinuous nature of radical technology has led economic geographers to argue that the spatial formation of new industries occurs relatively independently of economic structures and practices (Storper and Walker, 1989). Storper and Walker (1989) argue, based on the WLO concept[1] (Scott and Storper, 1987), that the localisation of new

1 The WLO framework emerged in the late 1980s out of an interest in explaining why old industrial regions, from the 1960s and onwards, experienced severe problems of deindustrialisation and job loss. This theoretical framework was primarily used to explain the relative spatial indeterminacy of new industries' localisation patterns and fitted well with empirical observations of new innovative regions overtaking the position of old, declining industrial regions (Scott and Storper, 1987).

industries is rather independent of pre-existing industrial structures. The presumption is that an emerging industry that bases its development on a radical technology has such unique requirements that any pre-existing locational conditions will be unlikely to satisfy these requirements (Storper and Walker, 1989; Boschma, 1997). Instead, the assertion is that when a new industry emerges, firms experience a level of 'locational freedom' to locate in a large number of places because their future depends more on their own ability to shape a supportive environment (e.g. labour skills, suppliers and buyers) than on a set of specific localised resources. Accordingly, leading firms in emerging industries are more dependent on their ability to create their own favourable locational conditions than on specific initial conditions provided by the existing settings in a region. Although Storper and Walker note that locational freedom has limits and we will not witness new industries developing in relatively unindustrialised regions (Storper and Walker, 1989), their overall argument is towards a high degree of spatial indeterminacy of new industrial localisation. Boschma and van der Knaap (1997) and Boschma and Lambooy (1999) propose a refinement of the WLO argument and contend that the spatial indeterminacy of new industries is limited to regions with useful and beneficial generic resources, such as basic knowledge provided by universities and research institutes, basic institutions and infrastructure.

However, the primary shortcoming of the WLO framework is that it devotes little attention to the possibility that new industries are linked to pre-existing industrial structures in a region as a result of regional path dependency. It is argued in this article that it is possible to increase our understanding of why new industries emerge where they do by examining the linkages between pre-existing regional knowledge bases and the emergence of radical technologies.

This is much in line with Perez and Soete's (1988) prominent paper on developing countries' ability to catch up in technology. They argue that four components influence the cost and capabilities of firms in a given country, or in this case a region, to enter a technological trajectory. The four components consist of fixed investment costs, scientific and technical knowledge, skills and experience (in management, production, marketing, etc.) and a set of locational advantages. These components are likely to vary, depending on the nature of the technology and the stage of technological evolution, understood as phases in the technology's lifecycle (Perez and Soete, 1988). During the introduction phase, which is in focus of this article, the level of scientific and technical knowledge and the level of locational advantages (externalities) are relatively high for firms to be able to enter the emerging technological trajectory, whereas the initial fixed investment costs and the experience and skills in managing, production, marketing, etc. are assumed to increase as the technology's level of maturity increases. Thus, Perez and Soete argue that it is '(. . .) absurd to assume that a firm can start with zero previous knowledge' (Perez and Soete, 1988, 466).

Perez and Soete's contribution on countries' abilities to catch up in technology can be applied to regional economies at the sub-national level and their capacity to enter into a radically new regional industrial path. In the early phase of radical technology development, two components, in particular, are of substantial importance: a minimum level of firm-bound scientific and technical knowledge within the technological knowledge base and an advantageous location near to university research and researchers that can assist in the accumulation of a new knowledge base. Consequently, it can be argued that the total knowledge base of a region, as an expression of firm-bound knowledge and other localised sources of knowledge (e.g. universities and research institutes), has substantial influence in determining which radically new regional industries will emerge within a given region.

### 2.3. Regional branching: an evolutionary approach

Frenken and Boschma (2007) use the evolutionary metaphor of 'regional branching' to illustrate that new industry emerges from the existing industrial structure within a region. Regional branching occurs either when a new industry emerges from an existing industry, or knowledge and competences from a combination of sectors and research fields are brought together and lead to the development of a new industry.

The concept of regional branching builds on two ideas from the field of economic geography. The first and foremost is that knowledge tends to spill over in spatially proximate locations, rather than globally, as shown by the literature on localised knowledge spillovers (Jaffe et al., 1993; Audretsch and Feldman, 1996; Anselin et al., 1997; Feldman, 1999; Maurseth and Verspagen, 2002). Several localised mechanisms, such as firm diversification, entrepreneurial spinoffs, labour mobility, and social networking, are argued to induce local knowledge spillovers, leading to the process of regional branching (Boschma and Frenken, 2011; Tanner, 2014). The common characteristic of these mechanisms is that they function as localised channels for knowledge transfers from existing industries and universities to the emerging industry.

Secondly, positive externalities from knowledge in a given field are more likely to spill over to third parties working in the same field (Antonelli, 2001). In other words, localised knowledge sharing and transfers are enhanced by the 'technological relatedness' between sectors (Neffke and Henning, 2008; Boschma and Frenken, 2011), where technological relatedness is understood as an appropriate balance between cognitive proximity and distance (Nooteboom, 1999).

Empirically, 'regional branching' has found support in a number of studies exploring the concept of regional path dependency in general but has received less attention in the effort to understand the 'place dependency' of radical industries (Martin and Sunley, 2006; Colombelli et al., 2014). Previous studies have revealed that regions develop along coherent industrial paths. Neffke et al. (2011) demonstrate how Swedish regions develop along a somewhat coherent industrial path on which industries have a higher probability of entering regions where the regional industrial structure is related to that industry and existing industries unrelated to the region's industry are more likely to exit. Moreover, Essletzbichler and Winther (1999) demonstrate that Danish regions develop along different technological trajectories in the food-processing industry. With respect to how radically new industries build on competences from old industries, Klepper and Simons' study (2000) demonstrates that successful television producers were experienced radio producers before entering the television industry, indicating a high level of complementarity in competences and routines between the two industries. Similarly, Boschma and Wenting (2007) confirm that technological relatedness to the regional knowledge base plays a large role in the localisation of the British car industry, and this process in particular was driven by spinoffs from related industries.

More recent studies have examined the coherent evolution of scientific and technological knowledge spaces of cities (Heimeriks and Boschma, 2013; Kogler et al., 2013; Boschma et al., 2014). Kogler et al. (2013) measure relatedness in knowledge bases of cities from 1975 to 2005 and find the highest relatedness values in smaller cities, whereas larger cities patent across a broader range of technology classes, resulting in lower relatedness values. Similarly, Heimeriks and Boschma (2013) distinguish between cities with slow and fast growth rates of scientific knowledge production within biotech and find that slow growth cities are characterised by topics that are less related to existing topics and high growth rates experience higher relatedness between current and new topics. These studies confirm that the geography of scientific and technological knowledge spaces affects the future direction of search for technical solutions.

This study focuses on the emergence of a new radical innovation. Radical innovations build on a new set of scientific and technical principles (Arthur, 2009), which break with incumbent technological trajectories and lay the seeds for the creation of new paths. Radical innovation is as such associated with the process of successfully combining unrelated technology fields (Fleming, 2001; Castaldi et al., 2014). However, once the scientific and technical principles are discovered and the new technological trajectory takes shape through the accumulation of a new knowledge base, actors draw on complementary knowledge assets from related disciplines and activities to improve the functionality of the technology. Technology fields become related either as a result of the discovery process, which can turn previously unrelated technologies into being related (Castaldi et al., 2014), because of advances made in a previously unrelated technology field or because an entire new technology field emerges, such as nano-technology.

Consequently, in this article it is expected to find that regions that enter the field of fuel cell technology have a knowledge base that, at the time of this analysis, is technologically related to the knowledge base of fuel cells. In addition, the character of the related knowledge resources is investigated. Exactly because of the recombinant nature of radical innovations, i.e. successfully combining unrelated technology fields, it is expected to find that the knowledge base of fuel cell technology spans several technology fields and that the more these knowledge fields are present in a given region the more likely is the region to enter the emerging field of fuel cell technology.

## 3. The case of fuel cell technology

This section addresses the radical nature of fuel cell technology. The classification of a technology's 'radicalness' in practice rarely satisfies the unambiguous distinction between incremental and radical innovations presented in Section 2. It is often a question of a continuum of differences rather than a clear-cut dividing line (Markard and Truffer, 2006). This is partly because of the list of dimensions, an innovation can be distinguished along, such as its potential to substitute for existing products or technologies, or its price and performance attributes. Another reason for the difficulties in classifying innovations is that the degree of 'radicalness' may vary along the value chain (Markard and Truffer, 2006). For example, a radical process technology may only affect end-users to small degree, whereas producers may have to adapt to a larger extent. In the following, the focus is on the disruptive character of fuel cell technology towards incumbent industries.

Fuel cell technologies are regarded as one of many alternatives to replace incumbent fossil fuel–based energy technologies (Brown et al., 2007). Among the positive environmental effects of fuel cells are their high fuel efficiency and that their exhaust is pure water, providing both local and global environmental benefits above the incumbent technologies (provided that the fuel is produced from renewable energy sources). Fuel cell systems are somewhat generic in the sense that they have the potential to replace batteries, oil-fired boilers and internal combustion engines (ICE), and hence are applicable in a wide range of energy-related sectors, from portable equipment, such as mobile phones and laptops; stationary power units, including back-up power units; and within the transport sector as a new means of propulsion or auxiliary power units (APU). When assessing the extent to which fuel cell technology is radical, it is therefore necessary to assess it against each type of application option and with respect to its disruptive potential along the value chain.

The chemical process of energy conversion that occurs in a fuel cell is radically different from those of most incumbent energy technologies, which fuel cells could replace. The disruptiveness of fuel cell technology is most obvious in the case of fuel cell vehicles or combined heat and power systems, in which case incumbent firms need to accumulate an entirely new knowledge base to master the new technology (Hellman and van den Hoed, 2007). Several studies have illustrated the disruptive challenges fuel cell technology has placed on the automotive industry, as the core competences in the automotive industry are technologically centred on the ICE and the skills associated with the mechanical moving parts of this type of engine. Van den Hoed (2007) and Steinemann (1999) demonstrate that most firms in the automotive industry use a collaborative strategy to acquire competences from new entrants in the fuel cell area. New entrants in the emerging fuel cell field have either previously been suppliers of the automotive industry or transitioned into the fuel cell field because they have technologically related resources they can build upon, for example firms from the chemical industry or material science (Tanner, 2014). The latter illustrate the potential threat of the replacement of conventional suppliers of combustion engine components to the automotive industry. Similarly, Markard and Truffer (2006) assess the introduction of fuel cell technology in stationary power supply as a radical innovation with a high degree of novelty that would substantially affect every component of the value chain. This is primarily because the development of fuel cell technology requires a broad range of novel competences, which incumbent electric utilities do not possess.

A final example that, to some degree, also reveals fuel cell technology's disruptive potential is batteries. Although batteries exhibit a certain degree of overlap in competences with fuel cell technology because batteries also build on scientific and technical principles of electrochemistry, fuel cell technologies may, in some cases, have the potential to render battery competences obsolete, for example, where fuel cell systems may replace batteries in portable equipment (e.g. hearing aids or laptops) or in smaller vehicles (golf carts, forklifts or utility vehicles). In other cases, batteries and fuel cell technologies compete to replace incumbent technologies (e.g. APU for telecommunication networks in lieu of diesel generators), yet in other cases, batteries and fuel cell technology complement one another, as in hybrid fuel cell electric vehicles.

In summary, fuel cell technology is perceived as a radical innovation because it builds on a complex knowledge base (Dibiaggio and Nasiriyar, 2009) that is new to incumbent industries and firms. Consequently, the competencies of incumbents are at risk of becoming obsolete, provided that fuel cell systems succeed in reaching markets.

## 4. Method, data and the model

The intangible nature of knowledge clearly makes it difficult to measure its quantity (or quality for that matter) in any direct manner (Foray, 2004). Patent statistics are a widely used approach in quantitative studies to assess levels of competences for different units of analysis (see e.g. Patel and Pavitt (1997) for large firms and Zucker et al. (2007) for regions). The limitations of using patent data to measure knowledge production have also been widely criticised, although the critique has primarily concerned the use of patents to measure innovation (Pavitt, 1985; Griliches, 1998).

Using patent applications as a measure of knowledge production will always be an imperfect measure for several reasons. First, patents are codified knowledge, whereas a high proportion of knowledge produced in firms, universities and research institutes is tacit. Following Patel and Pavitt (1997), however, the two forms of knowledge are complementary rather than substitutes because tacit knowledge is necessary to understand and absorb information from patent applications, and vice versa. Secondly, many instances of knowledge production with scientific and technical content are not recorded in patent applications (Pavitt, 1985). Thirdly, using the count of patent applications tends to obscure variations in the quality of knowledge covered by patents (Zucker et al., 2007). Nevertheless, for the purposes of this study, patent applications are considered the most appropriate measure, given their relative homogenous, detailed and consistent recording of knowledge production.

### 4.1. Data

The OECD, REGPAT database, June 2010, is the main data source used. This database is a comprehensive attempt to regionalise patent applications filed under the PCT at the international level designated to the European Patent Office. A general reason for selecting PCT applications is that they are considered to contain the least country-based bias, as they represent international patent applications.

For the specific case of fuel cell patenting, the PCT data set is preferable for two reasons. First, as in other fields, patenting is a widely used strategy for firms to protect their knowledge assets in the fuel cell field (Avadikyan et al., 2003; Arechavala-Vargas et al., 2009). Because of the technology area's immaturity and the immense uncertainty regarding its future prospects, firms that have invested heavily in this new technology are extremely concerned with protecting their knowledge. Because of the technology's early stage of evolution, firms often lack ready products (applied knowledge) or skills in manufacturing; technological knowledge is their principal asset.

Secondly, as firms within the fuel cell industry regard themselves as global players,[2] it is appropriate to assume that they use the PCT system when applying for patents, as this provides them with the opportunity to simultaneously seek patent protection for an invention in each of a large number of countries (Arechavala-Vargas et al., 2009).

The OECD REGPAT database[3] is a regionalisation of addresses of both applicants and inventors into two hierarchical territorial levels: territorial level 2 (TL2) and territorial level 3 (TL3).[4] In this study, the sample of analysis refers to 251 NUTS2 regions across Europe, which corresponds to TL2. All patent data used are based on the

2 The author's own interviews with fuel cell stack and system developers and from Arechavala-Vargas et al. (2009).

3 The OECD REGPAT database covers 42 countries, 30 of which are OECD members.

4 TL2 is the most aggregated level, and consists of 335 regions and corresponds for most EU countries to the NUTS 2 classifications. In the case where TL2 does not directly correspond with NUTS2, data have been summarised based on the TL3 classifications. For Denmark, NUTS1 was used since the structural reform of 2007 has created inconsistency in the continuity of the data series.

inventor's address, as this is considered to be closest to the place of invention, and priority year, as this is considered to be closest to the time of invention.

Figure 1 depicts the distribution of fuel cell patenting across European regions in three 5-year periods: 1992–1996, 1997–2001 and 2002–2007. Patent counts are divided into three categories based on natural breaks in the data series to minimise value differences between data within the same category. The maps clearly reveal how fuel cell patenting activities increase during these years and diffuse across Europe. In the first period, only few regions with few patents appear, whereas in the latter period most regions in Europe have engaged in fuel cell patenting activity. However, the maps also reveal that certain regions dominate fuel cell patenting, particularly regions in southern Germany, the Ile de France and Rhône-Alpes in France, Lombardy in Italy and Denmark.[5] It is beyond the scope of this article to examine these regions in detail (see Tanner, 2014, for a more detailed study of regions highly active in fuel cells and their individual diversification patterns into fuel cell industry).

### 4.2. Identifying the knowledge base of fuel cell technology

The primary interest is to define and measure (i) fuel cell knowledge production for a given region in a given year, (ii) the knowledge base of fuel cell technology, defined as a set of knowledge fields that appear to be technologically related to fuel cells, (iii) the frequency of each of the fuel cell–related knowledge field relative to all non–fuel cell knowledge production for a given region in a given year and (iv) the related variety of fuel cell knowledge fields for each region in each given year

To identify the fuel cell knowledge base, all patents classified in accordance with the International Patent Classification (IPC)[6] system covering fuel cell technology were extracted from the data set. This was done rather narrowly by using IPC-main groups (7-digits), H01M008 ('Fuel cells, manufactures thereof'). The analysis focuses on the period 1992–2007; 1992 is the year in which the main patenting (and development) activity in fuel cells began in earnest, and 2007 is the latest complete year in the database. For this period, the dataset contains 8572 fuel cell patent applications defined by IPC-code H01M008. This article concentrates on the regional dynamics of fuel cell development in Europe, and therefore restricts its analysis to patent applications filed by inventors localised in a sample of 251 European regions[7], totalling 2429 patent applications.

To measure the knowledge base of fuel cell technology, the set of knowledge fields that together form the technological knowledge base of fuel cell technology has

5 The data reveal no signs of spatial autocorrelation. Moran's I has been calculated and it is statistically significant but very low (−0.004).

6 The IPC is a hierarchical category system developed by the World Intellectual Property Organization (WIPO) for classifying patents and patent applications. Patents cover a broad area of technology fields, and each field can be further divided into subtopics until a reasonable level of specialisation is achieved. The classification consists of five hierarchical levels: sections (A – H), classes (three digits), subclasses (four digits), main groups (seven digits) and subgroups (nine digits).

7 Because of the lack of some regional data or because of the inconsistency in the continuity of the data series, only the number of regions from the following countries are included: Austria: 9, Belgium: 11, Switzerland: 7, Czech Republic: 8, Germany: 38, Denmark: 1, Estonia: 1, Spain: 15, Finland: 5, France: 22, Greece: 13, Hungary: 7, Ireland: 2, Iceland: 1, Italy: 21, Lithuania: 1, Luxembourg: 1, Latvia: 1, the Netherlands: 12, Norway: 7, Poland: 16, Sweden: 8, Slovakia: 4, and the United Kingdom: 35. Two Italian autonomous regions and French Guadalupe have been dropped.

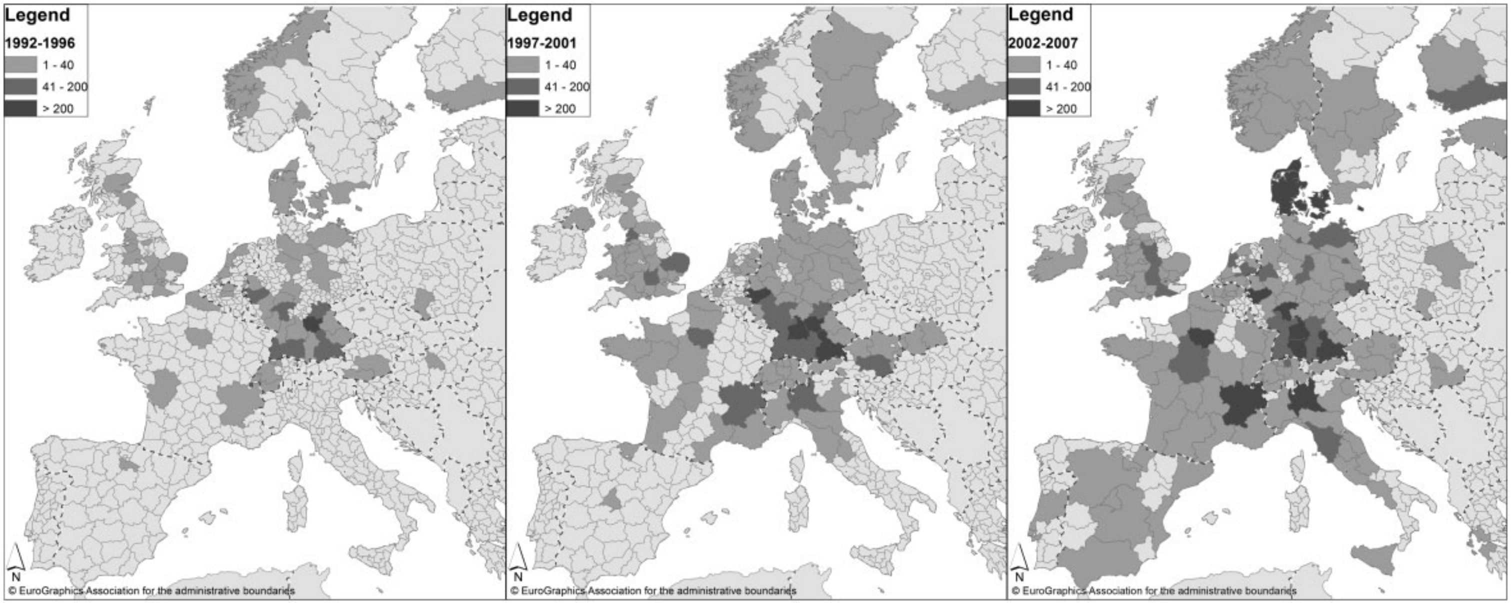


**Figure 1.** Distribution of fuel cell patenting across European regions in three different periods, *Source:* Own mapping based on OECD REGPAT June 2010.

been identified. These are identified by IPC-codes that are co-classified with the European sample of fuel cell patent applications. A patent application is often assigned more than one IPC-code, reflecting every knowledge field the patent covers. These knowledge fields are all involved in the generation of fuel cell knowledge. Therefore, there is a good reason to assume that knowledge fields (IPC-codes) that are co-classified with fuel cell patent applications form part of the fuel cell knowledge base.[8]

The co-classified knowledge fields are aggregated at the level of subclasses (4 digits).[9] This indicates that 312 of 628 possible IPC subclasses are co-classified with the IPC-code for fuel cells. However, a number of the 312 IPC subclasses only appear a few times over the period considered. Thus, to keep the analysis relatively simple, only IPC subclasses with a share >1 pct. (percent) have been included as forming part of the fuel cell knowledge base.

Table 1 provides a description of the 12 knowledge fields and their relevance for fuel cell technology.

The identification of the fuel cell knowledge base simultaneously provides the identification of the knowledge fields that are technologically related to the emerging fuel cell industry. The level of knowledge production within each of these 12 areas for each given region and year serves as the independent variable and is described in greater detail in the following section.

### 4.3. The dependent variable: fuel cell knowledge production

The dependent variable in the analysis is fuel cell knowledge produced in given regions at given times. It is measured as fuel cell patenting activity (FCpt) under the PCT and defined as above (all patent applications with an IPC-code of equal to H01M008, 'Fuel cells and manufactures thereof'). The patents are ascribed at the regional level using a non-fractional count. In the OECD REGPAT database, the fractional count takes into consideration that several inventors with different regional residences may be responsible for the invention in each patent application, and hence only ascribes a fraction of each patent application to the specific region in which the inventor resides. It is argued, however, that knowledge is a non-divisible asset, and because the purpose of this article is to measure knowledge production at the regional level, non-fractional counts have been used, i.e. in the event that multiple inventors from different regions are responsible for a patent application, the same patent application is assigned to each of the regions involved.

As fuel cells remain an immature technology, the number of FCpt for some regions is small, particularly in the early period. Therefore, FCpt is calculated as the sum of three consecutive years for each region for each year in the period 1992–2007. In this way, the

8 An identification of the fuel cell knowledge base based on a patent citation analysis rather than co-classification has been calculated for comparison. On the basis of the 8572 fuel cell patents recorded in 1992–2007, the OECD Citations Database, December 2010, made it possible to identify 28,434 cited patents and their respective IPC-subclasses. The top 12 IPC-subclasses are identical to those identified based on the co-classification approach, except for IPC class B60L: 'Propulsion of electrically propelled vehicles', which is included in the citation analysis and not in the co-classification analysis. Further, the order of the knowledge fields (sorted by share) is nearly identical in the two approaches.

9 As all patents and patent applications are classified with IPC-codes at the subgroup level (nine digits), some co-classifications fall within the same subclass (four digits). If this is the case, the subclass is only counted once.

**Table 1.** Twelve knowledge fields that together compose the knowledge base of fuel cell technology in the years 1992–2007

| IPC | IPC name | Knowledge field | Relevance for fuel cells | Share[a] |
|---|---|---|---|---|
| H01M | Processes or means, e.g. batteries for the direct conversion of chemical energy into electrical energy | Conversion of chemical energy into electrical energy | This is obviously one of the core knowledge fields in FC development because converting chemical energy into electrical energy is the key function of fuel cells | 24.8% |
| B01J | Chemical or physical processes, e.g. catalysis, colloid chemistry; their relevant apparatus | Catalysis and colloid chemistry | The fuel cell contains both anode and cathode catalysts; the anode catalyst breaks down the fuel into ions and electrons, and the cathode catalysts turns the ions into water or carbon dioxide | 10.1% |
| C01B | Non-metallic elements; compounds thereof | Non-metallic elements | Non-metallic elements refer to the production, separation, purification, etc. of hydrogen or oxygen and the preparation hereof | 9.5% |
| B01D | Separation | Separation | Separation refers to the process of separating the ions and electrons in the anode, for example with ion-exchange materials as adsorbents | 6.8% |
| C25B | Electrolytic and electrophoretic processes for the production of non-metals, apparatus thereof | Electrolytic processes | Electrolytic processes are the inversed reaction of what occurs in the fuel cell. In electrolysis, electricity generates gaseous products, e.g. hydrogen | 4.1% |
| C08J | Working-up; general processes of compounding; after treatment not covered by C08B, C08C, C08F, C08G or C08H | Processes of compounding | Moulding and processes of compounding of conductive polymers are important in the production of membranes | 3.7% |
| H01B | Cables, conductors, insulators, selection of materials for their conductive, insulating or dielectric properties | Cables, conductors, insulators | That fuel cells generate electricity makes electrical conductors, conductive materials, cables, insulators, etc. central to the development of fuel cells | 2.6% |
| C08G | Macromolecular compounds obtained by means other than reactions only involving carbon-to-carbon unsaturated bonds | Macromolecular compounds (double/triple bond) | Macromolecular compounds are relevant for PEMFC, in which the electrolyte consists of a polymer (macromolecular) membrane. The chemical process in producing the polymer in C08G contains carbon-to-carbon double/triple bonds | 2.5% |
| C08F | Macromolecular compounds obtained by reactions only involving carbon-to-carbon unsaturated bonds | Macromolecular compounds (single bond) | Identical to C08G, except that the production of the polymer (membrane) relies on a different chemical process, namely, carbon-to-carbon single bonds | 1.9% |
| C08L | Compositions of macromolecular compounds | Compositions of macromolecular compounds | C08L is in line with C08G and C08F also only relevant to PEMFC, and this class refers to the composition of the macromolecular compound | 1.9% |
| C04B | Lime, magnesia, slag, cements, compositions thereof, e.g. mortars, concrete or like building material, artificial stone, ceramics | Ceramics, materials | Ceramics are primarily used in solid oxide fuel cells that have a ceramic (solid oxide) electrolyte | 1.6% |
| G01N | Investigating or analysing materials by determining their chemical or physical properties | Analysing materials | The chemical and physical processes occurring in the heart of the fuel cell involves testing and measuring, as well as analysing the effects of various materials. This is particularly important during the development stage | 1.2% |

[a]The share indicates how large a proportion of the total co-classifications belongs to the specific knowledge field.
*Source:* Own calculations based on OECD REGPAT June 2010.

model also accounts for the time required for fuel cell–related knowledge to be absorbed and utilised in the generation of fuel cell knowledge.[10]

### 4.4. Independent variables: technological relatedness and related variety

The independent variables are measures of fuel cell–related knowledge for each region. On the basis of the knowledge base of fuel cell technology (the 12 knowledge fields identified in Table 1), two measures of regional assets in fuel cell–related knowledge fields are calculated. The first measure of fuel cell technological relatedness (FC-TR) essentially consists of 12 measures indicating the occurrence of knowledge production within each of the identified knowledge fields for each region and year. It is calculated for all non–fuel cell patent applications, i.e. all fuel cell patent applications are withdrawn from the database before aggregating the frequency of patent applications within the selected IPC subclasses. Two further steps were taken in preparing the FC-TR measures. As regions differ in their total level of knowledge production (all patent applications filed under the PCT regardless of IPC-codes), a first step was taken to make the FC-TR comparable by relating the knowledge produced within each of the 12 knowledge fields to the total patent activity of the region. This approach is intended to control for the substantial differences that exist between the regions' levels of knowledge production, which could explain the differences in levels of fuel cell knowledge production.[11] Secondly, following Zucker et al. (2007), the figures were computed by cumulating counts for all previous years and discounting by 20% annually to reflect knowledge depreciation.

The second measure of FC-TR is a related variety measure (FC-REL), which is introduced to capture the recombinant nature of a radical innovation. Because the fuel cell knowledge base spans over a wide range of technology fields, it is of great interest to test whether a higher variety of related fields results in higher probability for fuel cell knowledge production. FC-REL is calculated based on a normalised Herfindahl index. The Herfindahl index indicates the variety of knowledge that is technologically related to fuel cell technology in a given region and given year. The normalised Herfindahl index ranges from 0 to 1, where 0 indicates no variety and 1 indicates full variety across all 12 knowledge fields.

Moreover, the stock of fuel cell–unrelated knowledge (FC-UNREL) has been measured to include an indication of the total level of knowledge production in a region. FC-UNREL has been measured as all patents, except fuel cell patents and fuel cell-related patents.

A population measure was included to control for the size of the region, as it is assumed that larger regions will generate more knowledge. Population is measured as log to total number of inhabitants.

10 Running the model with single year values for fuel cell patenting gives very similar results. Only the significance of two technology fields is interchanged; so 'Ceramics, materials' are positively significant in the model with the sum of three consecutive years and not in the model with single year count; in this model the variable 'Processes of Compounding' is positively significantly related to fuel cell knowledge production.

11 It is not possible to control for the total level of patenting by including it as a control variable, as this generates multicollinearity in the model and risks biasing the results. A 'variance inflation factor' (VIF) analysis of the data set indicated that the variable 'total patent count' exceeded the value 10. Kutner et al. (2004) advocate for a critical threshold of VIF = 10 to qualify multicollinearity.

**Table 2.** Fuel cell knowledge and fuel-cell-related knowledge variables: correlation statistics ($n = 2236$)

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 Fuel cell patenting | – | | | | | | | | | | | | | | | | | |
| 2 Fuel cell patenting (consecutive three years) | 0.83 | – | | | | | | | | | | | | | | | | |
| 3 Conversion of chemical energy to electrical energy | 0.56 | 0.60 | – | | | | | | | | | | | | | | | |
| 4 Catalysis and colloid chemistry | 0.43 | 0.47 | 0.54 | – | | | | | | | | | | | | | | |
| 5 Non-metallic elements | 0.49 | 0.49 | 0.55 | 0.76 | – | | | | | | | | | | | | | |
| 6 Separation | 0.53 | 0.63 | 0.64 | 0.78 | 0.69 | – | | | | | | | | | | | | |
| 7 Electrolytic processes | 0.39 | 0.39 | 0.43 | 0.49 | 0.46 | 0.47 | – | | | | | | | | | | | |
| 8 Processes of compounding | 0.34 | 0.37 | 0.44 | 0.83 | 0.62 | 0.67 | 0.45 | – | | | | | | | | | | |
| 9 Cables, conductors, insulators | 0.32 | 0.37 | 0.39 | 0.37 | 0.35 | 0.45 | 0.31 | 0.33 | – | | | | | | | | | |
| 10 Macromolecular compounds (double/triple bond) | 0.36 | 0.39 | 0.45 | 0.81 | 0.59 | 0.65 | 0.50 | 0.85 | 0.32 | – | | | | | | | | |
| 11 Macromolecular compounds (single bond) | 0.28 | 0.30 | 0.36 | 0.83 | 0.58 | 0.59 | 0.40 | 0.87 | 0.27 | 0.78 | – | | | | | | | |
| 12 Compositions of macromolecular compound | 0.31 | 0.34 | 0.43 | 0.83 | 0.63 | 0.63 | 0.47 | 0.92 | 0.36 | 0.86 | 0.90 | – | | | | | | |
| 13 Ceramics, materials | 0.45 | 0.54 | 0.58 | 0.65 | 0.67 | 0.71 | 0.40 | 0.55 | 0.39 | 0.55 | 0.50 | 0.56 | – | | | | | |
| 14 Analysing materials | 0.46 | 0.50 | 0.54 | 0.58 | 0.57 | 0.64 | 0.35 | 0.40 | 0.36 | 0.48 | 0.35 | 0.42 | 0.65 | – | | | | |
| 15 FC-REL | 0.13 | 0.14 | 0.17 | 0.20 | 0.22 | 0.22 | 0.15 | 0.20 | 0.18 | 0.20 | 0.17 | 0.20 | 0.22 | 0.10 | – | | | |
| 16 FC-UNREL | 0.55 | 0.63 | 0.65 | 0.67 | 0.68 | 0.78 | 0.42 | 0.56 | 0.47 | 0.60 | 0.50 | 0.58 | 0.76 | 0.78 | 0.21 | – | | |
| 17 Population | 0.19 | 0.22 | 0.29 | 0.32 | 0.38 | 0.35 | 0.25 | 0.21 | 0.23 | 0.23 | 0.19 | 0.26 | 0.43 | 0.41 | 0.09 | 0.40 | – | |
| 18 Total patent count | 0.56 | 0.63 | 0.67 | 0.73 | 0.71 | 0.82 | 0.45 | 0.62 | 0.47 | 0.66 | 0.56 | 0.64 | 0.79 | 0.83 | 0.21 | 0.97 | 0.43 | – |

*Note:* All correlations are significant $p < 0.001$.

Furthermore, a lagged-dependent variable (LAG-FC) was included to account for the effect of fuel cell knowledge produced in previous years. The lagged-dependent variable was constructed analogously to the FC-TR measure, i.e. cumulated counts for all previous years and discounting by 20% annually to reflect the depreciation of fuel cell knowledge.

Table 2 presents the variables in a correlation matrix. All of the variables have positive correlations. Some knowledge fields have high correlation coefficients (>0.80). For example, ‘processes of compounding’ (8) is correlated with both types of macromolecular compounds (10 and 11) and compositions of macromolecular compounds (12), which all belong to the same IPC class at the three-digit level. Variance inflation factors (VIF) were calculated to estimate the potential effect of multicollinearity. The VIF revealed two variables with values > 10 (which is the standard threshold indicating multicollinearity; Kutner et al. (2004)): total patent count (VIF = 39.20) and the knowledge field ‘compositions of macromolecular compounds’ (IPC: C08L) (VIF = 11.67); consequently, these variables were dropped.

## 4.5. The model

The analysis is performed on a balanced panel data set comprising the years 1992–2007 and 251 European NUTS2 regions. As the dependent variable is a running aggregate of three consecutive years and a lagged-dependent variable has been included, the panel covers only 13 three-year periods and independent variables for the years 1993–2005. Most of the regions have a relatively low count of FCpt, whereas a smaller tail has much higher counts. FCpt is clearly a limited dependent count variable, which suggests

**Table 3.** Fuel cell knowledge variables: descriptive statistics (172 NUTS2 regions, $n = 2236$)

| | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|
| List of variables | | European NUTS2 regions | | |
| Fuel cell patenting | 1.36 | 4.68 | 0 | 82 |
| Fuel cells (FCpt) (consecutive three years) | 4.61 | 13.21 | 0 | 166 |
| FC TR | | | | |
| Conversion of chemical energy to electrical | 1.96 | 4.99 | 0 | 63 |
| Catalysis and colloid chemistry | 11.81 | 25.34 | 0 | 265 |
| Non-metallic elements | 3.50 | 7.45 | 0 | 76 |
| Separation | 8.98 | 16.24 | 0 | 178 |
| Electrolytic processes | 0.60 | 1.95 | 0 | 39 |
| Processes of compounding | 5.41 | 14.21 | 0 | 183 |
| Cables, conductors, insulators | 1.60 | 3.98 | 0 | 73 |
| Macromolecular compounds (double/triple bond) | 8.22 | 21.39 | 0 | 205 |
| Macromolecular compounds (single bond) | 8.27 | 25.76 | 0 | 543 |
| Compositions of macromolecular compounds | 8.60 | 22.00 | 0 | 379 |
| Ceramics, materials | 3.58 | 7.06 | 0 | 73 |
| Analysing materials | 22.60 | 40.43 | 0 | 500 |
| FC-REL | 0.71 | 0.21 | 0 | 1 |
| FC-UNREL | 248.49 | 409.64 | 0 | 3513 |
| Population | 2,092,832 | 1,593,828 | 263,056 | 11,400,000 |
| Total patent count | 300.92 | 489.53 | 1 | 3915 |

that the appropriate model is a count model such as the Poisson or negative binomial model, following Hausman et al. (1984). While the Poisson model requires the variance of the dependent variable to equal its mean, the distribution of FCpt reveals clear overdispersion (8.675)—a violation of the mean-variance equality restriction. This suggests the use of the negative binomial model that allows for heterogeneity on the mean.

To control for unobserved heterogeneity, we estimate the model with fixed effects. Introducing fixed effects in the model builds on the assumption that there are some time-independent regional effects that correlate with the explanatory variables, for instance, geographical features and access to resources and the rest of the world. Moreover, a Hausman test (1978) confirmed our choice of fixed over random effects. The fixed effect estimator has another consequence for the model because it only includes groups (regions) with FCpt values > 0. Thus, the model drops 79 groups (regions), and the analysis is performed on the remaining 172 regions.[12] Each variable (see the list of variables in Table 3) is, therefore, measured for each year in the period 1993–2005 for each of the remaining 172 regions; hence $n = 13$ years × 172 regions = 2236.

12 NUTS2 codes for the 79 regions that the model drops because of an absence of fuel cell patenting activity are: AT32, AT34, BE34, BE35, CZ02-CZ08, ES11-ES13, ES53, ES62, FI13, FI1A, FR21, FR83, GR11-GR14, GR21, GR22, GR24, GR25, GR41-GR43, HU21-HU23, HU31, HU32, IE01, ITC2, ITD1, ITD2, ITF2, ITF4-ITF6, ITG2, NL11, NL23, NL34, NO07, PL11, PL21, PL31-PL34, PL41-43, PL51, PL52, PL61-PL63, PT11, PT15, PT18, SE21, SE33, SK01-SK04, UKF3, UKJ4 and UKK3.

## 5. Results

Table 4 presents the results of the negative binomial regression with fixed effects. Model 1 includes the lagged-dependent variable and population, Models 2 and 3 include all identified technologically related knowledge fields from Table 1 and Models 4 and 5 exclude knowledge fields that have been eliminated following a manual, stepwise, forward regression. Models 3 and 5 also include the fuel cell-related measure (FC-REL) and the measure for fuel cell-unrelated knowledge stock (FC-UNREL).

Model one confirms that the lagged-dependent variable is positively correlated with the level of fuel cell knowledge production. However, the size of the region as measured by population reveals no significant relationship. The significance of the controls is confirmed in the remaining models, that is Models 2–5.

Model 4 is the result of a stepwise, forward regression approach in which variables are retained when $p < 0.05$ and dropped when $p > 0.2$. This approach is used to increase the understanding of how individual knowledge fields influence fuel cell patenting.[13] The analysis began with Model 1, and knowledge fields were introduced individually beginning with the field with the highest co-classification share (Table 1). Model 4 confirms the results of Model 2, except that the technology field of 'separation' is dropped because its *p*-value exceeds 0.2. The technology field of 'catalysis and colloid chemistry', which is significant and shows a negative relationship to fuel cell knowledge production in Model 3 is also dropped in Models 4 and 5 because of a *p*-value that exceeds 0.2. The regression diagnostics suggests that Model 4 exhibits better fit than Model 2 and Model 5 better fit than Model 3 because the Akaike information criterion (AIC) and the Bayesian information criterion (BIC) are lower. The following results are interpreted based on the significant relationships revealed in Models 4 and 5.

Consequently, all four models confirm positive and significant relationships between five of eleven technology areas and fuel cell patenting at the regional level. The technology fields 'conversion of chemical energy into electrical energy', 'cables, conductors, insulators', 'macromolecular compounds (double/triple bonds)', 'ceramics, materials' and 'analysing materials' all have a positive and significant association with the production of fuel cell knowledge. All of these knowledge fields are central to the functioning of fuel cells: the first two refer to the main processes that occur in the core of the fuel cell, namely, chemical processes of energy conversion comprising conductive materials. 'Macromolecular compounds (double/triple bonds)' and 'ceramics, materials' are important for two different types of fuel cells: proton-exchange-membrane fuel cells (PEMFC) and solid oxide fuel cells where the electrolyte is made of ceramics, respectively. The last positive and significant knowledge field, 'analysing materials', primarily refers to the determination of the materials' physical and chemical properties and makes the developers capable of monitoring and assessing any technological progress.

Six knowledge fields exhibit no significant relationship with the production of fuel cell knowledge. The knowledge fields of 'catalysis, colloid chemistry', 'non-metallic elements', 'separation', 'electrolytic processes', 'processes of compounding' and 'macromolecular compounds (single bond)' reveal no significant relationship. For

13 It was not possible to perform more complex sensitivity analysis (as e.g. reviewed by Hamby (1994)) because these are not available for the negative binomial regression for panel data command (xtnbreg) in Stata.

**Table 4.** Regression results of negative binomial estimations on regional fuel cell patenting (standard errors in parentheses)

| | (1) | (2) | (3) | (4) Stepwise | (5) Stepwise |
|---|---|---|---|---|---|
| FC-TR | | | | | |
| Conversion of chemical energy to electrical | | 1.695 (0.592)** | 1.888 (0.611)** | 2.008 (0.536)*** | 2.084 (0.554)*** |
| Catalysis and colloid chemistry | | −0.602 (0.371) | −0.756 (0.373)* | — | — |
| Non-metallic elements | | 0.192 (0.718) | 0.128 (0.717) | — | — |
| Separation | | 1.146 (0.430)** | 1.022 (0.439)** | — | — |
| Electrolytic processes | | −1.326 (2.478) | −1.723 (2.466) | — | — |
| Processes of compounding | | 0.705 (0.623) | 0.530 (0.629) | — | — |
| Cables, conductors, insulators | | 6.777 (1.216)*** | 5.826 (1.231)*** | 6.904 (1.215)*** | 5.721 (1.205)*** |
| Macromolecular compounds (double/triple bond) | | −0.237 (0.527) | −0.382 (0.528) | — | — |
| Macromolecular compounds (single bond) | | 2.495 (0.433)*** | 2.418 (0.438)*** | 2.417 (0.3334)*** | 2.156 (0.341)*** |
| Ceramics, materials | | 1.624 (0.569)** | 1.450 (0.575)** | 1.699 (0.541)** | 1.499 (0.545)** |
| Analysing materials | | 2.823 (0.196)*** | 2.984 (0.215)*** | 2.828 (0.183)*** | 2.922 (0.203)*** |
| FC-REL | | | 1.140 (0.215)*** | | 1.138 (0.212)*** |
| FC-UNREL | | | −0.001 (0.0007)* | | −0.001 (0.0007)* |
| LAG-FC | 0.0063 (0.001)*** | 0.004 (0.0004)*** | 0.004 (0.0004)*** | 0.004 (0.0004)*** | 0.004 (0.0004)*** |
| POPULATION (LOG) | −0.055 (0.109) | 0.099 (0.133) | 0.158 (0.143) | 0.055 (0.129) | 0.102 (0.139) |
| Log likelihood | −3293.683 | −3046.702 | −3029.834 | −3051.564 | −3034.179 |
| AIC | 6593.366 | 6121.403 | 6091.668 | 6119.127 | 6088.358 |
| BIC | 6610.504 | 6201.378 | 6183.067 | 6164.827 | 6145.482 |
| CONSTANT | 1.251 (1.589) | −1.798 (1.945) | −3.367 (2.057) | −1.122 (1.886) | −2.541 (2.006) |
| *n* (regions) | 172 | 172 | 172 | 172 | 172 |

***$p<0.001$, **$p<0.05$, *$p<0.1$.

some of these variables, this could be due to the generic character of the knowledge field; for example, catalysis, separation and non-metallic elements are technologies with a very broad range of applications, i.e. they are not narrowly associated with fuel cells. In other cases, it could be the case that some knowledge fields are more narrowly associated with a specific type of fuel cells, for example, 'processes of compounding' and 'macromolecular compounds (single bond)' are only important for fuel cell patenting related to PEMFC, and consequently, relationships with an aggregated measure of all types of fuel cells may thus not appear in the model. Finally, in the case of 'electrolytic processes', which is the inverse chemical process of what occurs in a fuel cell, descriptive statistics on the compositions of knowledge fields at different times indicate that the share represented by 'electrolysis' has decreased over time. This may imply that the two fields, electrolysis and fuel cells, have begun to diverge into two independent technological trajectories concurrent with increased specialisation.

Concerning the variety of technologically related knowledge fields, Models 3 and 5 report a positive and significant relationship between the FC-REL measure and fuel cell patenting. The results confirm that the larger number of knowledge fields represented in a region, i.e. the greater the variety of fuel cell–related knowledge fields, the more likely is the creation of fuel cell knowledge in the following 3 years. It also confirms that fuel cell knowledge does not emerge as a branch of one technology area but rather through the recombination of several technologies.

Interestingly, Models 3 and 5 reveal a negative and significant relationship between the stock of fuel cell-unrelated knowledge and fuel cell patenting. This underlines the importance of the overall thesis that regional knowledge needs to be related to the knowledge base of the emerging industry before it has a positive effect on knowledge production within the emerging industry. The AIC and BIC measures are smaller for Models 3 and 5 than those for Models 2 and 4, which support the decision of introducing the related variety measure and the stock of fuel cell-unrelated knowledge to improve model fit.

In summary, the analysis has confirmed the overall hypothesis of this article: the emerging fuel cell industry develops in regions with technologically related competences. However, it is important to avoid any deterministic reading of these results for several reasons. First and foremost because the knowledge base of fuel cells, or any technology, is dynamic and continuously evolving. This analysis was based on an aggregate of important and related knowledge fields over a 15-year period; however, the knowledge base is likely to change when different time spans are considered. Additionally, relevant knowledge fields also vary depending on the type of fuel cell being developed. Finally, the development of new industries clearly builds on factors other than the composition of a regional knowledge base, a matter that is revisited in the following section.

## 6. Conclusion

The objective of this article has been, first, to pursue the evolutionary thesis that regions also develop along technological trajectories in the case of radically new industrial paths. The article's primary contribution has been to empirically assess whether the creation of new regional industrial paths is driven by learning and knowledge spillover processes that are enhanced by technological relatedness to pre-existing regional economic activities; the findings support this series of mechanisms.

The second objective has been to expand our knowledge on the character of such location-specific resources. Previous studies have considered industry classifications, but the substantial advantage of the current study is that it provides more detailed evidence of the relationship between a region's knowledge base and its technological relatedness to an emerging technology. The empirical results can be summarised in the following two points: (i) the analysis indicates that there are specific technologically related knowledge fields that are significantly co-located with the generation of fuel cell development and (ii) it reveals that the higher the variety of fuel cell-related knowledge fields present in a given region, the more likely a region is to branch into fuel cell technological development. This indicates that fuel cell development takes place through the recombination of several technology fields, which may have been unrelated before the discovery of the scientific principle of fuel cells or until an unrelated technology field has developed new technical solutions with potential to solve issues related to fuel cells.

Third, the article has developed a new measure of technological relatedness using regionalised patent data, which seems to have certain advantages, in particular when studying new technology areas that are not recognised by industrial classification systems (e.g. SIC, NACE). In particular, the ability to measure the knowledge base of a region using patent classifications allows for the identification of cognitive relationships between existing technologies and emerging technologies, which previous methods have not been able to.

Consequently, the results shed new light on the discontinuity of radical technological change and its implications for new regional industrial paths. As noted in Section 2, the discontinuous nature of radical technology has caused economic geographers to argue that new industries develop independently of pre-existing industrial structures. The findings of this article suggest that even in the case of radical technology development, knowledge production is also cumulative and builds on pre-existing, localised scientific and technical knowledge resources, which implies that the emergence of radically new industrial paths is place dependent.

The findings raise a central question: what causes the evolutionary processes for the creation of new variety at the regional level? The results in this article suggest that this process is highly localised in space (at least within the borders of NUTS2 regions) but do not reveal the extent to which this process can be ascribed to firm diversification based on firm-specific scientific and technical knowledge, entrepreneurial spinoffs or locational advantages that generate positive externalities. Tanner (2014) demonstrates that for a group of regions highly engaged in fuel cell technological development firm diversification plays an important role for the regional diversification process. This contradicts previous research, which have demonstrated that spinoff processes play a larger role in regional diversification processes (Klepper and Simons, 2000; Boschma and Wenting, 2007). Future research should aim to provide further evidence on the mechanisms by which regions diversify. This would be extremely valuable for understanding the evolutionary development of new industries and their spatial manifestation.

Clearly, the development of new industries in regional economies is a complicated matter and cannot be ascribed to the regional composition of knowledge fields alone. We know from innovation system studies that the process of developing new industries not only requires the accumulation of scientific and technological competences but also the alteration of institutions and networks (Lundvall, 1992; Dalum et al., 1999). Other factors of an institutional, cultural, political or social character influence the development of new technological trajectories by creating favourable conditions for the technology, e.g. inducing knowledge diffusion among actors in the region and providing economic incentives to invest in R&D. This is also the case for the development of fuel cell industries (Madsen and Andersen, 2010). Therefore, it has not been the aim of this article to suggest a deterministic relationship between the knowledge base of a given region and the emergence of a new industry.

Nevertheless, these findings have clear policy implications. Most regional policy makers are interested in creating new growth paths that can spur entrepreneurial and innovative behaviour in their region. However, until recently, most regional policy instruments have focused on supporting clusters through building networks and establishing cluster management organisations. Often these cluster initiatives build on wishful thinking, poorly reflecting a region's actual strength (Feldman and Lendel, 2010; Tanner, 2012b). The findings of this article support the recent development at the European policy agenda for growth and jobs 2020: the introduction of the concept of 'smart specialisation' (Foray et al., 2011) in the European Cohesion Policy programmes (Boschma and Gianelle, 2014; Piirainen et al., 2014). Smart specialisation captures the idea that regions may want to pursue one of two goals when trying to promote new industries to locate in their region, either to host the core industry developers of a new technology, or to encourage pre-existing industry to adopt and apply the new technology into their product portfolio. Which strategy the region should follow depends on the regional current assets, such as knowledge bases, and the ways these are related to the emerging industry. Some regions may have strong technological competences related to the core of the emerging technology, as it has been shown in this article, and can consequently pursue the first strategy, whereas other regions may be endowed with downstream application-oriented industries that can apply the emerging technology in their products, thus following the second strategy (Tanner, 2014). Consequently, the findings of this article support the idea of 'smart specialisation', that regions should build regional innovation strategies on a deep understanding of the current productive structure of the region together with an understanding of potential technologically related emerging technologies.



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