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Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

Paper to be presented at the DIME-DRUID ACADEMY Winter Conference 2011

on

Comwell Rebild Bakker, Aalborg, Denmark, January 20 - 22, 2011

SPATIAL DYNAMICS OF TECHNOLOGICAL EVOLUTION: TECHNOLOGICAL RELATEDNESS AS DRIVER FOR RADICAL EMERGING TECHNOLOGIES

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Abstract:
Spatial Dynamics of Technological Evolution: Technological Relatedness as a Driver for Radical Emerging Technologies

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Despite the consent of the fundamental role technological change plays for economic growth, it seems that little attention has been paid to how new technologies come into being. In particular, an understanding of the spatial and dynamic processes driving the emergence of radical technology is lacking.
This paper seeks to fill out this research gap by bridging the school of evolutionary economics and the school of economic geography. Following Dosi (1988) two factors are in particular important for technological change in emerging technological paradigms: 1) accumulation of scientific and applied knowledge in firms, universities, research institutes etc., and 2) the existence of risk-taking actors who are willing and capable of implementing and exploiting radical technologies. This paper focuses on the former.
Where evolutionary economics have been occupied by accumulation of knowledge over time, economic geographers have been occupied by accumulation of knowledge in space. For long, it has been discussed whether Marshallian specialization or Jacobian diversification externalities favor regional innovativeness. In the case of radical innovation, studies have found empirical support for Jacobs externalities. However, a recent stream of literature (e.g. Frenken et al., 2007, Neffke et al., 2010) has shown that knowledge does not automatically spill over in diversified regions but requires related variety in the knowledge base of the region.
This paper tests empirically the overall hypothesis that the accumulation of knowledge at the regional level is an important driver for the emergence of radical technology. The paper focuses on the case of fuel cell (FC) technology, which is argued to be a radical technology, understood as a disruption and discontinuation of technological trajectories.
In more details, the paper tests two opposing hypotheses: 1) A diverse regional knowledge base leads to radical innovation, and 2) Related Variety in the regional knowledge base leads to radical innovation. And two specific hypotheses for the emergence of FC technology: 3) FC technological relatedness in the regional knowledge base leads to innovation within FC technology: where FC technological relatedness is defined as the knowledge fields that form the knowledge base of FC technology. And 4) in order to generate new FC knowledge, the higher the degree of FC technological relatedness, the more important it is that the specific knowledge field is present in the regional knowledge base: where the degree of FC technological relatedness is defined as the relative importance of each knowledge field for the FC technological knowledge base.
To measure knowledge production in general, and within FC and FC related knowledge fields, the paper uses patent applications as a proxy and defines knowledge

JEL - codes: O39, R11, -

Spatial Dynamics of Technological Evolution: Technological Relatedness as Driver for Radical Emerging Technologies

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Abstract:

The question of how new regional industrial paths emerge has recently received a renewed interest in the field of economic geography. In particular, the new evolutionary turn in economic geography, has suggested a new perspective on regional diversification into new industries. It sees diversification as a branching process where new variety is created through technological related knowledge spillover. This paper sets out to test the thesis that technological relatedness to existing regional activities are an important factor in understanding localization of new industry paths. The paper focuses on industrial development around a radical technology, namely the fuel cell (FC) technology. The paper develops a new indicator of technological relatedness between the knowledge base of the region and that of the FC technology, based on regionalized patent statistics. The empirical analysis confirms that technological relatedness is an important mechanism behind the spatial emergence of new industry. The paper also tests the more general hypotheses put forward by the localized knowledge spillover literature whether regional diversity or related variety is important for the development of industries and finds support for the related variety hypothesis

1. Introduction

How regions achieve economic prosperity is a central question to the literature of economic geography. It is broadly acknowledged that economic prosperity might be achieved by sustaining 'old' industries through a process of revitalization or by inducing new industries to emerge (Dalum et al., 1999). Both strategies are part of what we could call regional diversification, where regions based on regional competences and resources diversify into related industries. However, there is yet no clarity over these processes, hence, this paper sets out to test to what degree localization of new industries is a process of regional diversification.

The economic geography literature offers various interpretations of what causes early localization of new industries, ranging from a process that is almost structurally determined by the economic landscape to an outcome of random events (see Martin and Sunley, 2006). As Martin and Sunley (2006) argue, the recent literature on regional path dependency appears to emphasize events of almost accidental character as triggering factors for early industrial localization. However, leaving a large share of the processes of industrial localization to be explained by accidental events is somewhat unsatisfactory and can rightly be criticized for neglecting contextual and causal processes that result in the emergence of a new techno-economic path within regional borders (Martin and Sunley, 2006).

An alternative explanation is provided by the recent conceptualization around 'regional branching'. Here regional diversification is understood as a branching process, where new industries emerge out of the existing industrial structure in the region (Boschma and Frenken, 2009). Regional branching captures the process of the development of new industries at the regional level caused by enhanced knowledge transfers induced by technological relatedness to existing activities in the region. Where technological relatedness refers to the case where industries are related through partly overlapping knowledge bases. This causes firms to be more likely to learn from each other since the cognitive distance is short (Nooteboom 2000).

Boschma and Frenken (2009) argue that: "To the extent that new industries emerge from existing and related industries, the sectoral composition of a regional economy at one moment in time provides and constrains, but by no means determines diversification opportunities of regions in the future". The question remains to what extent new industries grow out of existing and related industries within the border of regions?

This paper seeks to answer this question by studying the spatial emergence of a new industry developed around a radical technology, namely the fuel cell technology. Fuel cells are an electro-chemical device that generates electricity based on a chemical reaction between oxygen and hydrogen. The FC technology is often being characterized as disruptive[1] because it has a huge potential to replace incumbent energy technologies. Disruptive technologies of this character are in the literature usually perceived as causing discontinuity in the existing techno-economic regime (Schot and Geels, 2007, Nelson and Winter, 1982). Moreover, knowledge production within disruptive technology is said to be discontinuous and revolutionary in some respects, but is arguably still cumulative (Zucker et al 2007). Since early 1990s FC technology development has gained a momentum in its technical achievements and is now seen as one of the promising alternatives to replace fossil fuel based energy technologies in the long term. This has happened as a result of an increasing interest in the technology by various types of actors; in the early years mainly universities and key upstream developers (dedicated firms) of FC stacks and FC systems, and in the later years also firms involved downstream in a diverse range of application opportunities (such as vehicles, back-up power units, auxiliary power units, combined heat and power plants etc.) Studies (Madsen and Andersen, 2010, and Tanner, forthcoming) show how FC knowledge production tends to be relatively concentrated in certain regions across Europe and the world. And the interesting questions arise, how can we explain why we see an embryonic concentration of the emerging FC industry in certain regions? And more specifically, is it possible to explain the spatial pattern of a radical technology by its technological relatedness to the knowledge base of the region?

To answer these questions the author analyzes the relationship between the knowledge base of the region and the knowledge base of the emerging FC technology. The knowledge base of FC technology is defined by patent applications and the International Patent Classification system and is correlated with regional knowledge bases at NUTS level 2. The analysis points towards a positive relationship between a strong regional knowledge base within FC knowledge and the rate of FC patenting, indicating that the regional knowledge base is an important factor in explaining why emerging industries appear where they do.

The paper is structured as follows. In section 2 the economic literature on early industrial localization patterns are briefly presented and discussed regarding differences in the underlying rationale. Section 3 presents the conceptualization of 'regional branching' in relation to the notion of technological relatedness and the mechanisms behind. Section 3 finishes with discussing the knowledge base of regions vs. that of technologies and the hypotheses this paper sets out to test are formulated. Section 4 presents the emerging industry of fuel cells that this paper focuses at, and provides descriptive statistics on its early development since the beginning of the 1990s. Section 5 introduces the method and data used to test the hypotheses of this paper and Section 6

[1] 'Radical technology' is another term often used in the literature to characterize disruptive technologies.

presents and discusses the results. Section 7 concludes that the spatial emergence of new industries is strongly influenced by the knowledge base of the region and suggests further research questions.

2. Early Industrial Localization

The last couple of decades have offered various interpretations of what causes early localization of new industries, ranging from a process that is almost structurally determined by the economic landscape to an outcome of random events (see Martin and Sunley, 2006). As referred in Martin and Sunley (2006) one interpretation sees new industrial development as caused by purely or mostly random events. These count Brian Arthur's (1994) model of 'path dependency' and Krugman's (1991, 2001) work on industrialization processes of the United States (see Martin and Sunley, 2006). Another perspective based on the 'windows of locational opportunity'-framework (WLO) sees localization of new industries as a combination of accidental events, human agency, and location specific conditions (Scott and Storper 1987, Storper and Walker 1989, Boschma 1996, Boschma and van der Knaap 1997, and Boschma and Lambooy 1999). The 'windows of locational opportunity' framework (WLO) emerged in the late 1980s out of an interest in explaining why old industrial regions since the 1960s and onwards experienced severe problems of deindustrialization and job loss (Scott and Storper 1987). This theoretical framework were mainly used to explain the relative spatial indeterminacy of new industries' localization patterns and fitted well to empirical observations of new innovative regions overtaking the position of old, declining industrial regions (Scott and Storper 1987).

The WLO-approach suggests that when a new industry emerges, it experiences a level of 'locational freedom' to locate in a large number of places that provide a set of generic resources. Accordingly, leading firms in emerging industries are to a larger extent dependent on its capability to create its own locational conditions than on specific initial conditions provided by the existing settings in the region, since the existing locational conditions hardly meet with the unique requirements of the emerging industry (Storper and Walker, 1989), Boschma 1996). The final choice of where to locate is according to the WLO-approach caused by potential triggers of more accidental character (Boschma 1996). In sum, the WLO-explanation of the localization of new industries, builds on a combination of agency, localized generic resources, and inexplicable chance and random events (Martin and Sunley, 2006).

However, the early WLO concept did not pay much attention to the possibility that new industries are linked to already existing industrial structures (whether it happens in declining or growing regions). Contrary to this spatial indeterminacy, Boschma's work in the 1990s modifies this understanding and suggests that new industries' spatial emergence is not an entirely accidental process (Boschma 1996). Boschma and Van der Knaap (1997) and Boschma and Lambooy (1999) question the inherent assumption in the early WLO-concept that new industries develop from scratch (Boschma 2007). They argue that new industries build on a set of generic, location specific resources that has the potential to trigger new industries to emerge.

In relation to the 'embryonic evolutionary turn' that has emerged in economic geography in recent years (Martin and Sunley, 2006, Boschma and Lambooy, 1999, Essletzbichler and Rigby, 2007) the idea that the regional industrial structure may explain emerging regional industrial paths has gained stronger emphasis. Boschma and Frenken (2009) employ the evolutionary metaphor 'regional branching' to illustrate that new industries grow out of the existing industrial structure within a region. Boschma and Frenken (2009) argue that regional branching either happens when a new industry grow out of an existing industry or when knowledge and competences from a combination of sectors are brought together to form the development of a new industry. I return to the causes behind regional branching in next section, but first I sketch out the main differences in the rationales behind the WLO-approach and the evolutionary 'regional branching'-approach.

By highlighting the locational freedom of new industries the WLO-framework stresses the role of human agency. According to the WLO-approach, the window of locational opportunity is open for leading firms of emerging industries and stresses their ability to create the necessary conditions that will help support the early development of a young industry at a certain location. Consequently, the WLO-approach gives relatively more power of explanation to human agency than to contextual constraining and enabling factors.

The theorizing around the concept of 'regional branching', on the other hand, places more emphasis on regional, industrial structures as enabling and constraining factors for the emergence of new variety. Accordingly, the economic landscape as it looks today influences the shaping of the economic landscape of tomorrow. Although, Boschma and Frenken (2009) note that regional diversification is by no means deterministically decided by the industrial structure of the region, the regional-branching literature gives less weight to human agency.

Clearly building new industries is a complicated matter, and cannot be ascribed to either agency or the industrial structure of a region. We know from the innovation system studies that the process of building new industries not only requires accumulation of scientific and technological competences but also altering of institutions and networks (Dalum et al., 1999). In this light, human agency is of great importance in order to build institutions and networks (e.g. to support new educational institutions in order to secure competent labor, or build up informal and formal networks), whereas the accumulation of scientific and technological knowledge is embedded in the industrial structure.

What I argue for, then, is to see processes of regional branching as driven by an actor-structure dualism. Where the industrial and institutional structure of a region constrain but at the same time enable actors (firms, entrepreneurs etc.) to act and they trough their actions alter the structures of the regional set-up. The regional knowledge base, thus, enables and constrains firms to innovate along certain technological trajectories. And it is through these actions that the actors are altering the composition of the regional sectors. Hence, structure and actors become a mutually dependent duality.

This matter is important to bear in mind. As Boschma and Frenken argue, the industrial structure of a region will never determine the development of a new industry, but might enable but also constrain actors to utilize a certain composition of available resources.

3. Regional Branching and Technological Relatedness

Regional branching builds on several ideas that have been developed in the field of economic geography over the last couple of decades. First and foremost, that knowledge tends to spill over in spatial proximity rather than globally, as shown by the literature on Localized Knowledge Spillover (LKS) (Jaffe, 1989, Jaffe et al., 1993, Feldman, 1999, Anselin et al., 1997, Audretsch and Feldman, 1996, Feldman, 1994, Maurseth and Verspagen, 2002).[2] Second, it has been argued that the positive externality of knowledge in a given field is more likely to spill over to third parties working in the same field. In other words, that localized knowledge sharing and transfers are enhanced by 'technological relatedness' between sectors (Boschma and Frenken, 2009, Neffke and Svensson Henning, 2008).

There are in general two ways we can perceive the concept of technological relatedness. Activities can be related because they are 'similar' in character or because they 'complement' each other (Richardson, 1972) Similarity occurs when knowledge bases of two activities tend to overlap, for instance, when two products

[2] Often have other measures of proximity been included in studies of LKS. As Boschma (2005) argue, geographical proximity do not tell the whole story, but proximities such as cognitive, organizationally, institutionally and socially may complement, or substitute, the effect of geographical proximity. For example have most of the studies mentioned above included some kind of measure for cognitive proximity as a complementary explanation, by focusing on measures of technological relatedness in the knowledge spillover process. Fewer studies have included direct measures of other kind of proximities, mostly because proximities of social or institutional kinds are very difficult to measure quantitatively. But no matter what complementary explanation has been included, the past 20 years' studies on localized knowledge spillover have found support of the hypothesis that knowledge spills over and that the spillover process is influenced by geographical and other proximities (Audretsch and Feldman, 2004).

build on the same knowledge base. In the case of FC technology, firms with strong competences within the chemical industry, for instance catalysis, might find that their skills and competences can be used in developing and enhancing the process of converting chemical energy into electricity (which is the key process of the FC). Similarity could then be caused by a form of technical interdependency (Boschma and Frenken, 2009), where a new technology open up for a whole new set of innovations.

On the other hand complementarity occurs when two or more activities represent different phases of a process of production and hence explain the division of labour (Richardson, 1972). Boschma and Frenken (2009) argue that there is several ways complementarity result in technological relatedness between industries. They can be technologically related through a) user-producer relations, or through b) production-system interdependency (for example FC innovation requires innovation in the vehicle engine).

Complementarities can then be said to make firms technologically related up- and downstream (vertically) whereas similarity makes firms technologically related horizontally. For example, within the FC industry, firms applying FC systems within various applications can be seen to be technologically related because they build on similar knowledge bases; however, they do not depend on each other in a complementary sense. However, within each application opportunity firms are complementary vertically in the value chain, for instance between PEM FC developers and vehicle manufacturers.

There are several mechanisms that lead to the process of regional branching. Common characteristics of these mechanisms are that they function as localized channels for knowledge transfers from existing industries and universities to the emerging industry. Neffke et al (2009) point out four mechanisms that play this role and at the same time tend to be regionally bounded (albeit not exclusively). These count firm diversification, spinoffs, labor mobility, and social networking. To this list we can add collaborative R&D projects and universities startups, which seems to play an important role for the FC technology development. These mechanisms will briefly be discussed in the following.

Firms tend to diversify into industries that allow them to take advantage of skills and competences they have developed by being active in related industries (Richardson, 1972,Penrose, 1959). As Porter (1990) argues: "Diversification through internal development is almost always through related diversification, because creating a new entry from scratch almost demands that a company possess a base of relevant skills". Hence, knowledge and assets are transferred from the existing firm to the new entity and increases its potential competitiveness. At the same time by building on existing and related competences the firm may achieve to reduce uncertainties and switching costs associated with diversifying its economic activities into new fields (Nelson and Winter, 1982). Additionally, firm diversification tends to happen in geographic proximity to the mother company. Accordingly, firm diversification is an important source for regional diversification.

Spinoffs and startups are another source of regional branching. This happens when new firms in an emerging industry are created by entrepreneurs who have build up experience and knowledge in a related industry, or in the case of startups, at a university. Entrepreneurial spinoffs and startups tend to locate in proximity to their parent company or university and hence is argued to be a main reason for spatial concentration of economic activity (Dahl and Sorenson, 2007). For example, Zucker et al. (1998) find for the biomedical innovation system, that localized industrial benefits is caused by embedded tacit knowledge in star scientists who decide to start up own businesses in geographical proximity to their faculty laboratory.

Labor mobility is widely accepted to be one of the key mechanisms behind localized knowledge spillover, but has not yet been studied in relation to technological relatedness between firms, and hence, its impact on regional branching (see Neffke et al 2009). Same thing apply to the mechanisms of social networks and collaborative R&D projects. They can arguably be considered as sources of regional branching, because of their function as knowledge diffusing mechanisms, but they have not yet been explored in the light of the argument of technological relatedness.

The understanding of technological relatedness as promoter of diversification is not an entirely new idea. It draws on the fundamental evolutionary economic thinking of the knowledge based theory of the firm (Richardson, 1972,Penrose, 1959). Also a number of case studies have shown how new industries draw on competences from old industries because they are somewhat technologically related. For example, Klepper and Simons (2000) have shown that successful television producers were experienced radio producers prior to entering the television industry. The study described in this paper applies this argument to the unit of regions and supply data that can be interpreted as further evidence of the validity of regional branching as a process induced by technological relatedness to the existing regional industrial structure.

Several studies have shown that technological relatedness is an important factor in localized knowledge spillover and induce regional economic growth (e.g. Frenken et al 2007, Bishop and Gripaios 2009). One study is in particular interesting for the purpose of this paper. Neffke et al. (2009) show how Swedish regions develop along a somewhat coherent path resulting in lower entry-barriers for firms related to the region's production structure and higher exit-rates for firms unrelated to the region's productive capacity. Their study provides valuable insight in the industrial history of regions' development path in the case of established industries. However, it has not yet been explored, if the emergence of a single radical industry can be explained by its technological relatedness to the knowledge base of the region, which is the main claim of this paper.

Hypotheses building: the relationship between the regional knowledge base and the knowledge base of the FC technology

A regional knowledge base is constituted by all the knowledge resources located in the region. Knowledge may in principle both take the form of knowledge about manufacturing, markets and end-users and knowledge about technological and scientific domain. For the purpose of this paper, focus is on the latter since the early evolution of young industries relies heavily on technological and scientific knowledge in order to solve problems of technical character.

Regional knowledge bases may be characterized in many ways. Depending on which knowledge producing organizations are located in the region, i.e. the industry structure of the region and other knowledge producing organizations such as universities and research institutes. Each region has their own unique knowledge base depending on the composition of knowledge fields that have been accumulated in the past. This gives regions diverse opportunities for developing along new technological paths. And hence, the opportunity for industries to develop in a given region is larger for regions that have regional knowledge bases technologically related to the knowledge base of the new industry. This leads the author to formulate the main hypothesis of this paper:

Hypothesis 1: The frequency of FC patenting in a given region and at a given time is correlated with the degree of technological relatedness to the knowledge base of the region

Another discussion the classical LKS studies have given raise to (Jaffe, 1989, Jaffe et al., 1993, Audretsch and Feldman, 1996, Feldman, 1994) is a discussion on whether Marshallian specialization or Jacobian diversification externalities favor regional growth through higher regional innovativeness.

Some scholars have argued that Marshallian externalities understood as sectoral specialization of a region's economy is positively related to economic growth, because knowledge spills over more easily when firms from same industry are co-located. However, Marshallian externalities are often associated with incremental innovations and are therefore less relevant for the purpose of this paper.

Others have emphasized that regions with diversified sectoral structures increase the value of knowledge spillover because firms learn from other firms active in other industries and hence are able to come up with radically new ideas within their own sector (Jacobs, 1969, Glaeser et al., 1992, Feldman and Audretsch, 1999). This is often labeled Jacobs externalities after Jane Jacobs' work on American cities in 1960s (Jacobs, 1969). But as opposed to Marshallian externalities, Jacobs argue that the most important sources of knowledge spillover are external to the industry within which the firm operates. Therefore, Jacobs externalities, are associated with a diverse regional knowledge base, and have often been associated with radical innovation. Since FC technology development is considered to be a radical innovation following hypotheses is formulated:

Hypothesis 2A: The frequency of FC patenting in a given region and at a given time is correlated with a diverse regional knowledge base

In a more recent stream of literature (Frenken et al., 2007, Neffke, 2009, Boschma et al., 2009, Boschma and Iammarino, 2009) focus has been on the underlying mechanisms and prerequisites for knowledge spillover. It is not only spatial proximity that induces knowledge spillover but there need to be a certain level of cognitive proximity. This has resulted in the argument that a region, do not only need to have a diversified regional knowledge base, but there has to be relatedness in the portfolio of knowledge fields, before learning between actors take place. This is labeled related variety[3] (RV), and leads to following hypothesis:

Hypothesis 2B: The frequency of FC patenting in a given region at a given time is correlated with a regional knowledge base that is characterized by Related Variety

4. The case of fuel cell technology

These hypotheses is tested by a study of the FC technology. FC technologies are seen as one of many alternatives to replace incumbent fossil-fuel based energy technologies. Its positive environmental effects are among other things that the exhaust from a FC is pure water.

FCs are also an interesting case for many theoretical reasons. First, its knowledge base is highly complex and serves therefore as a good illustration on a modern, emerging technology. Second, the technology has the characteristics of being a general purpose technology (Helpman, 1998) with a wide range of application opportunities across several sectors (e.g. vehicles, combined heat and power systems, back-up units, auxiliary power units, mobile phones and laptops). A third characteristic is that FC technology, for some applications, is

[3] RV can be understood as a modification of Jacobs externalities. In the 1990's literature it was common to associate Jacobs externalities with diversity, the requirement of technological relatedness has been added in the more recent literature. However, for the purpose of this study it is valuable to distinguish between Jacobs externalities in its "pure" form and the modification of RV.

infrastructure dependent. Meaning that the validation of technology needs infrastructure support, for instance hydrogen fuelling stations, distribution systems etc. This dependency on infrastructure development might have consequences for the learning processes and its geographical embeddedness. The infrastructure dependency point to a fourth characteristic, that technological innovation in FC is systemic. This implies that innovation hardly takes place by a single company but instead requires corporation and coordination along the whole value chain. And finally, a last characteristic is the demand side. The demand side is characterized by a strong policy drive expressed in visions such as 'the hydrogen economy'. This has on the positive side implied a lot of financial support to R&D projects and to demonstrate and test the technology in real life surroundings. On the negative side it creates immense uncertainty because a too strong dependency on political goodwill makes the innovation system vulnerable to changes on the political agenda.[4]

5. Method, data and the model

For the purpose of this research the main interest is to measure the knowledge base of the region and the technology, respectively. To do this we want to measure knowledge within different knowledge fields at the regional level. The intangible nature of knowledge makes it clearly difficult to measure in any precise way. Furthermore, knowledge takes many types and forms. This paper focuses on the scientific and technical knowledge domain and not on knowledge domains needed for market introduction, e.g. users, markets and demand (Malerba & Orsenigo 2000).

A possible way to measure knowledge production within scientific and technical domains of knowledge is to use patents. In general, it is reasonable to assume patentable knowledge is of scientific and technical character, therefore patent applications are considered to be a good proxy for the domain of knowledge this study has in focus. However, patentable knowledge indicates novelty, which means a lot of knowledge production with scientific and technical content but without the novelty aspect is not measured by patent applications. Nevertheless, for the purpose of this study patent applications are still considered to be the most appropriate measure. Mostly because it indicates that there are firms or universities located in those regions that does produce knowledge within the technology area this article focus on.

[4] The hydrogen and fuel cell technology area experienced this in the beginning of 2009 when the recently inaugurated United States Secretary of Energy, Steven Chu lowered the budget to R&D in hydrogen and fuel cells in the US.

Data

The OECD, REGPAT database, June 2010 is the main data source used. The OECD, REGPAT database, June 2010 collects regionalized patent applications filed under the Patent Co-operation Treaty (PCT) at international phase designated to the European Patent Office.[5] A general reason for choosing PCT applications is that they are considered to contain least country based bias, because they represent international patent applications. The advantage of applying for PCT patents is the possibility to seek protection for an invention simultaneously in multiple countries. This sets applicants across the world equal before the PCT filing system and indicates more precisely the intention of patenting at an international level.

For the specific case of FC patenting, the PCT dataset is preferable for two reasons. As we know from previous studies[6] patenting is a highly used strategy for firms to protect their knowledge in the FC field. Because of the technology area's immaturity and its immense uncertainty about what the future brings, firms who have invested heavily in this new technology are extremely concerned about protecting their knowledge.[7] As they often do not have products (applied knowledge) or internal know-how and skills in manufacturing, the technological knowledge is their main asset.

Second, due to the fact that firms within the fuel cell industry see themselves as global players[8] it is appropriate to assume that they make use of the PCT system when applying for patents, because this give them the possibility to seek patent protection for an invention in each of a large number of countries at the same time (Arechavala-Vargas and Holbrook, 2009).

The OECD REGPAT has regionalized the addresses of both applicant and inventor into two hierarchical levels: Territorial Level 2 (TL2) and Territorial level 3 (TL3)[9]. In this study the sample of analysis refers to 235 NUTS2

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[5] Another dataset contained in the REGPAT database is patents granted by EPO, but this dataset is not used, because PCT applications are considered to cover more patents.
[6] The author's own interviews with fuel cell stack and systems developer and from Arechavala-Vargas et al (2009)
[7] This concern is not only about the technological knowledge, but also information on suppliers and collaboration partners, which most firms do not want to reveal.
[8] The author's own interviews with fuel cell stack and systems developer) and from Arechavala-Vargas et al (2009)
[9] TL2 is the most aggregated level, and consists of 335 regions and corresponds for most EU countries to the NUTS classifications. For Belgium, Greece and the Netherlands the NUTS2 level corresponds to TL3, for UK NUTS1 corresponds to TL2, For Denmark, TL2 corresponds to TL3/NUTS3 regions.

regions across Europe[10]. All patent data used is based on the inventor's address, since this is considered to be closest to the place of invention, and priority year, since this is considered to be closest to time of invention.

The dependent variable

The dependent variable (FCpt) is defined as all patent applications with IPC-code[11] equal to H01M008, "Fuel cells and manufactures thereof". This 7 digit classification of fuel cell technology makes it possible to delimitate all fuel cell knowledge patented in the years 1992-2007 rather precisely. The patents are ascribed at the regional level using a non-fractional count. Note that, when more than one inventor participates to the patent, the patent is equally shared between them. Because I am interested in measuring knowledge activity and because knowledge is a non-divisible asset I use non-fractional counts. As a consequence the total knowledge production is larger than the sum of the actual patent applications.

The analysis focuses on the period 1992-2007, which is where the main patenting activity in FC takes place. Total for this period the dataset contains 8.572 FC patent applications defined by the IPC code H01M008. Figure 2 shows the development of FC patent applications for the whole dataset (world[12]), Europe, US, and Japan. The world count shows the actual count of patent applications, for the remaining it is the non-fractional count indicating the level of knowledge production in FC and not the actual patent activity. For Europe the total knowledge production counts 2.429.

[10] Due to lack of some of regional data (controls) regions for following countries are included: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hyngary, Iceland, Ireland, Italy, Luxembourg the Netherlands Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, and the United Kingdom. Furthermore, 2 Italian autonomous regions and French Guadalupe has been dropped.

[11] The International Patent Classification taxonomy (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 specialization is reached. The classification consists of 5 hierarchical levels: Sections (A – H), Classes (3 digits), Subclasses (4 didgits), Main groups (7 digits) and Subgroups (9-digits).

[12] Note that the OECD REGPAT database covers 42 countries, whereas 30 are OECD members: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hyngary, Iceland, Ireland, Italy, Japan, South Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Sweden, Switzerland, Turkey, the United Kingdom, and the United States.

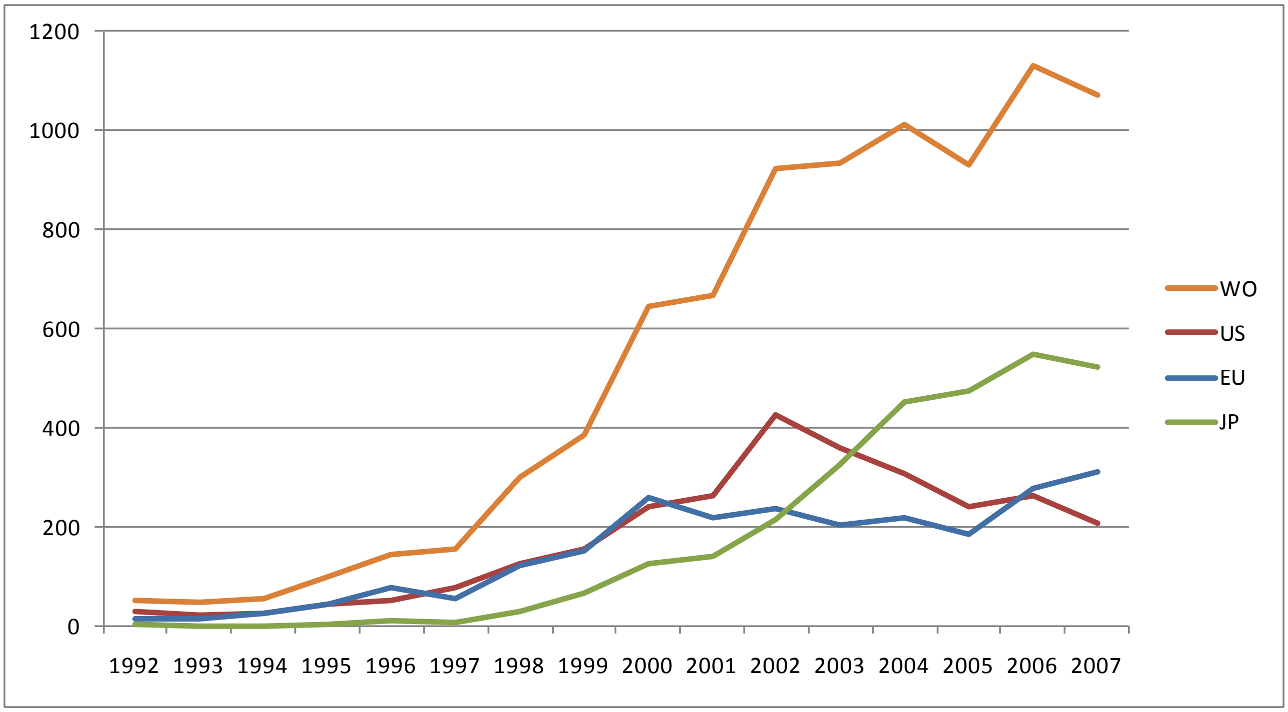

FIGURE 1: DEVELOPMENT OF FC PATENT APPLICATION FILED UNDER PCT FOR THE WORLD (WO), UNITED STATES (US), EUROPE (EU) AND JAPAN (JP) FOR 1992-2007 (BASED ON INVENTOR'S ADDRESS AND PRIORITY YEAR)

Explanatory variables

To test our hypotheses following three measures are calculated as independent variables:

- Specific Technological Relatedness
- Diversity
- Related Variety

Specific Technological Relatedness

The specific technological relatedness measures (TR) are indicators of knowledge fields that together form the technological knowledge base of FC. TR is identified using the IPC-codes that are co-classified with the total sample of FC patents at subgroup level[13]. The measure is calculated at the level of subclasses (4 digits). 312 out

[13] As all patents and patent applications are classified with IPC codes at the subgroup level (9 digits) some co-classifications fall within the same subclass (4 digits). If this is the case the subclass is only counted once. The subclass represents broad knowledge fields and we are interested in knowing the share of FC patents that are co-classified with these broad

of 628 IPC subclasses are co-classified with the total sample of FC patents. Only IPC-subclasses with a share >1 pct. has been included in the TR measure. This gives a total number of 8 subclasses with a total share of approximately 70 %. Hence, the final TR measure contains 8 knowledge fields which are related to the knowledge base of FC, as seen in Table 1.

TABLE 1: EIGHT MEASURES OF TECHNOLOGICAL RELATEDNESS AND THEIR SHARES OF CO-CLASSIFICATION WITH ALL FC PATENT APPLICATIONS 1992-2007, SOURCE OECD PATSTAT, AND WIPO

IPC	IPC name	Knowledge Field (TR)	Description[14]	Share[15]
B01D, B01J, C01B, C08G, C08J, C08L[16]	*Catalysis, Colloid, chemistry, separation, non-metallic elements, organic macromolecular compounds*	**Physical and chemical processes**	**Physical and chemical processes cover the main processes that take place at the core of the FC.**	**28.8 %**
H01M	*Processes or means , e.g. batteries for the direct conversion of chemical energy into electrical energy*	**Direct conversion of chemical energy into electrical energy**	**This is obviously one of the core knowledge fields in FC development, since converting chemical energy into electrical energy is the key function of FCs**	**23.1 %**
H01B	*Cables, conductors, insulators, selection of materials for their conductive, insulating or dielectric properties*	**Cables, conductors, insulators.**	**The fact that FCs generate electricity makes electrical conductors, conductive materials, cables, insulators etc. very central to the development of FCs**	**4.3 %**
C25B	*Electrolytic and electrophoretic processes for the production of non-metals, apparatus therefor*	**Electrolytic processes**	**Electrolytic processese is the inversed reaction of what takes place in the FC. In electrolysis, electricity generates gaseous, e.g. hydrogen.**	**3.4 %**
B60L	*Electric equipment or propulsion of electrically-propelled vehicles, electrodynamic brake systems for vehicles, in general*	**Electrical Vehicles**	**The knowledge field of electrical vehicles are strongly related to FC applications in the transport sector. Since FCs generate electricity applied knowledge in vehicles will lie within this knowledge field.**	**2.0 %**

knowledge fields. However, counting the co-classified subclasses multiple times does not change which related knowledge fields are included. It changes the order of the knowledge fields, but not substantially.

[14] Based on interviews with scientists from RISØ DTU, division of Fuel Cells and Solid State Chemistry.

[15] The share indicates how strong relatedness there is between the knowledge field and the knowledge base of FC, it can be seen as a measure of the degree of technological relatedness as will be tested in hypothesis four.

[16] This knowledge field is the sum of 6 subclasses, since the correlation between them were >0.70 and would cause collinearity in the regression.

C04B	*Lime, Magnesia, slag, cements, compositions thereof, e.g. mortars, concrete or like building material, artificial stone, ceramics.*	**Ceramics, materials**	**Ceramics are used mainly in solid oxide fuel cells that have a ceramic (solid oxide) electrolyte**	**1.7 %**
G01N	*Investigating or analyzing materials by determining their chemical or physical properties*	**Analyzing materials**	**The chemical and physical processes taking place in the heart of the FC involves testing and measuring, as well as analyzing the effects of various materials. In particular important in the stage of development**	**1.4 %**
H02J	*Circuit arrangements or systems for supplying or distributing electric power, systems for storing electric energy*	**Circuit arrangements, energy storage**	**This area is more peripheral to the key functions of FC. Circuit arrangements and systems for energy storing is considered to be supportive arrangements**	**1.3 %**

The distribution of TR for all years (1992-2007) can be seen in Figure 3 in the first column, and the development in three year periods is shown in the remaining five columns. The TR measure is relatively stable from 1992-2007. However, we can note that the share of electrolytic processes decreases over time while ‘electrical vehicles’ and ‘circuit arrangements and storage’ increases.

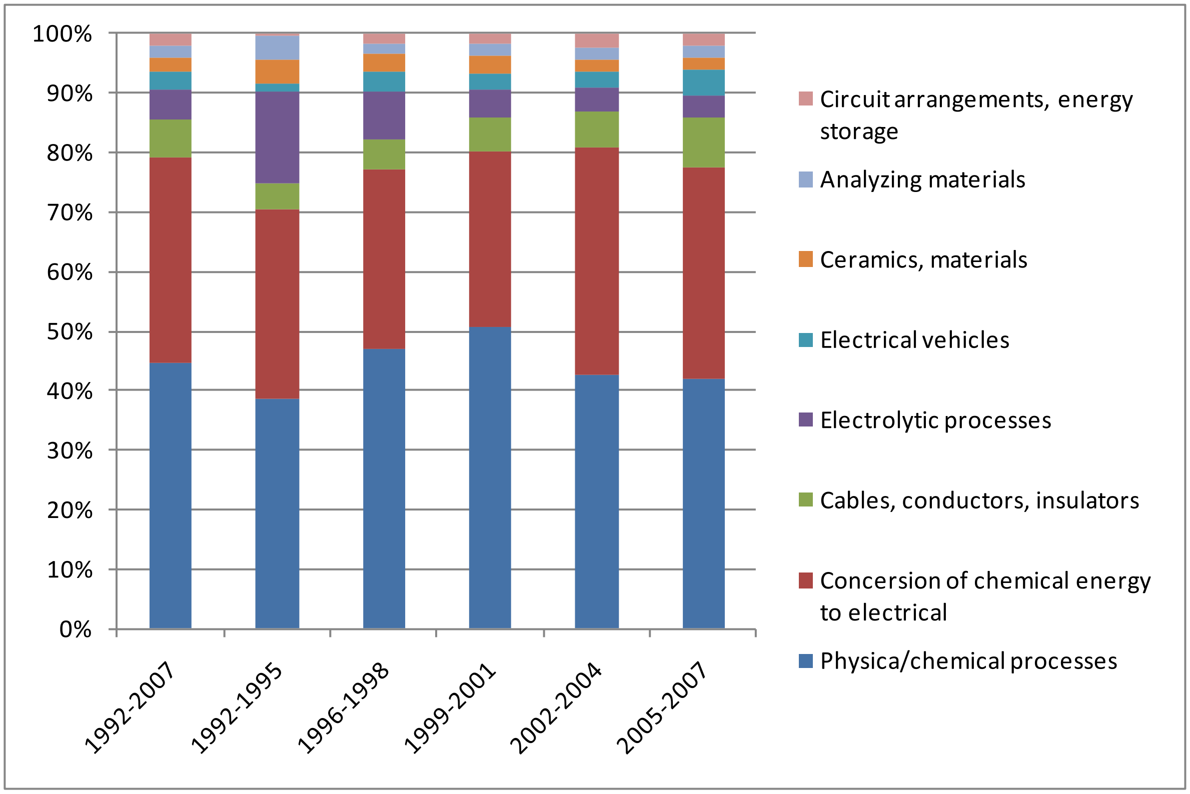

FIGURE 2: DISTRIBUTION OF THE EIGHT TECHNOLOGICAL RELATEDNESS MEASURES IN DIFFERENT PERIODS,

To use the TR measures as independent variables, all FC patent applications were extracted from the dataset and the cumulated stock of the 8 TR measures was calculated for each of the sample regions for each year. Following Zucker et al (2007) the size of all stocks are computed by cumulating counts for all previous years, and discounting by 20 % annually to reflect depreciation of knowledge.

Diversity and Related Variety

The measures for diversity and related variety are calculated as entropy measures using the knowledge profile of each region (see Frenken et al., 2007, and Boschma and Iammarino, 2009).[17] The entropy measure for diversity is calculated for IPC-classes (3 digits) for each region for each year in the period 1992-2007. If we let all IPC classes fall exclusively under a single digit IPC Section K_g, where g=1, …, G. |

$$DIVERSITY = \sum_{g=1}^{G} P_g \, log_2 \left(\frac{1}{P_g} \right)$$

[17] As noted by Frenken et al (2007) the decomposable nature implies that variety can me beasured at several digit levels and enter a regression without causing collinearity.

where

$$P_g = \sum_{i \in S_g} p_i$$

where p_i stands for the share of IPC class *i.* The more diversified the regional knowledge base is, the higher is the DIVERSITY measure.

RV is measured as the weighted sum of the entropy measure at the sub-class level (4 digits) within each IPC class (3 digits). It is expected that the higher the degree of related variety is, the higher will the rate of FC knowledge production be. When all IPC subclasses fall exclusively within the IPC classes K_n, where n=1,…, N, RV is calculates as:

$$RV = \sum_{n=1}^{N} P_g H_g$$

where

$$H_g = \sum_{i \in S_g} \frac{p_i}{P_g} log_2 \left(\frac{1}{p_i / P_g} \right)$$

As argued above, the diversity measure is considered to be an indicator of Jacobs externalities because it measures the extent regions' knowledge bases are diversified within different sections of the IPC system. And RV is considered to be an indicator of the relatedness between knowledge fields in the regional knowledge base, because it measures the variety of subclasses within each IPC-classes (3 digits).

As controls are included: total R&D expenditures (size of total knowledge production), the population (size of the region), and the lagged dependent variable. See list of variables in Table 2.

TABLE 2: LIST OF VARIABLES FOR SAMPLE REGIONS (SEE NOTE ELSEWHERE)

List of variables	**European NUTS2 regions**				
	N	Mean	S.D.	Min	Max
Fuel cells (FCpt)	3633	5.55	22.77	0	302
Diversity	3633	2.24	0.58	0	2.94
Related Variety	3633	1.11	0.53	0	2.36

Specific TR					
Physical/chemical processes	3633	266.38	722.06	0	10,788
Conversion of chemical energy to electrical	3633	10.32	26.79	0	341
Cables, conductors, insulators	3633	10.31	24.24	0	254
Electrolytic processes	3633	3.69	10.02	0	117
Electrical vehicles	3633	3.59	14.19	0	176
Ceramics, materials	3633	21.93	49.59	0	587
Analyzing materials	3633	121.43	268.55	0	3328
Circuit arrangements, energy storage Controls	3633	7.36	22.15	0	340
R&D exp.	3633	774.85	1,216.857	0	17,026.9
Population	3633	1,854,668	1,515,435	0	1.15e+07

The model

The dependent variable is a count variable and suggest the use of a count model. The variance of the dependent variable is about 20 times larger than the mean which suggest not using a Poisson model but the negative binomial model. The distribution (see Figure 4) also confirms using the negative binomial.

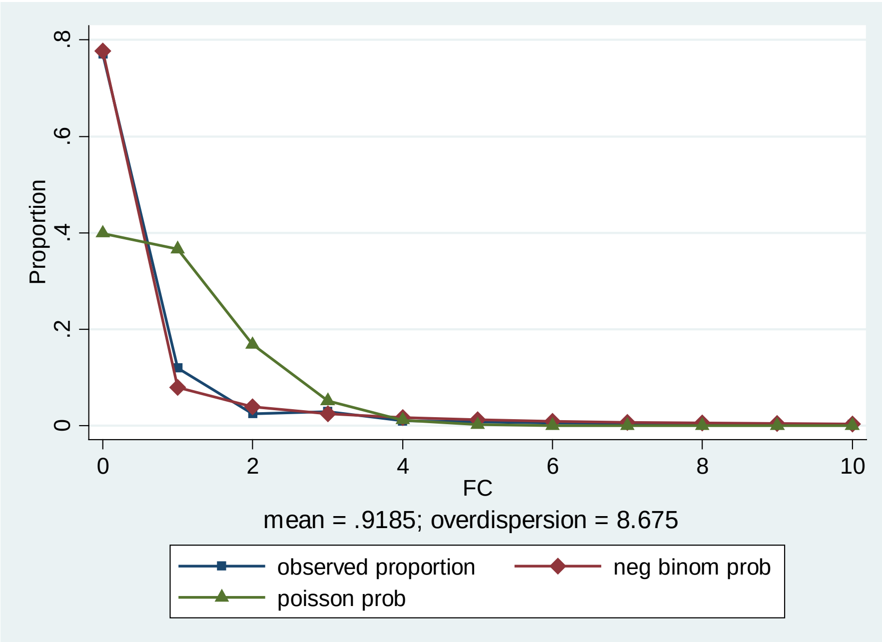

FIGURE 3: DISTRIBUTION OF OBSERVED PROPORTION AND ITS FITNESS TO POISSON AND NEGATIVE BINOMIAL, RESPECTIVELY.

It was tested whether fixed effects or random effects should be used. Fixed effects were chosen since a Hausman test preferred this over the random.[18]

6. Results

This section starts from running the model with the controls; R&D expenditure and population (size of the region) see Table 3. As model (1) show both variables are significant but where R&D expenses are positive related to FC knowledge production, population (or the size of the region) is negative related with FC knowledge production. Model (2)-(4)[19] test the hypotheses.

[18] However, both models were run and estimations did not deviate substantially.
[19] Since the model tests whether the regional knowledge base has an impact on the production of FC knowledge, the independent measures are all lagged by two years. It is a reasonable time lag to expect for knowledge to spill over and generate new patentable knowledge within FC.

TABLE 3: TECHNOLOGICAL RELATED KNOWLEDGE STOCK EFFECTS ON FC PATENTING, NEGATIVE BINOMIAL REGRESSION WITH FIXED EFFECTS FOR EUROPEAN REGIONS (NUTS2), 1992-2006

	(1)	(2)	(3)	(4)
CONSTANT	18.595(1.427)***	19.611(1.648)***	9.452(6.943)	12.682(5.547)**
DIVERSITY		0.629(0.129)***		0.122(0.097)
RELATED VARIETY		1.650(0.102)***		0.442(0.080)***
LAG.2 DV			0.273(0.019)***	0.301(0.023)***
Specific TR				
CHEMICAL OR PHYSICAL PROCESSES			0.658(0.041)***	0.678(0.049)***
CONVERSION OF CHEMICAL ENERGY INTO ELECTRICAL ENERGY			0.085(0.020)***	0.075(0.025)**
CABLES; CONDUCTORS; INSULATORS;			-0.004(0.022)	-0.010(0.028)
ELECTROLYTIC PROCCESES			-0.014(0.016)	-0.033(0.021)
ELECTRICAL VEHICLES			-0.047(0.014)***	-0.072(0.018)***
CERAMICS; MATERIAL			0.172(0.030)***	0.195(0.039)***
ANALYSING MATERIALS			0.220(0.040)***	0.115(0.048)**
CIRCUIT ARRANGEMENT; STORING			0.039(0.017)**	0.046(0.023)**
R&D (LOG)	1.307(0.077)***	0.862(0.089)***	0.304(0.101)**	0.004(0.099)
POPULATION (LOG)	-1.876(0.123)***	-1.996(.137)***	-1.029(0.428)	-0.985(0.393)**
N(Regions)[20]	155	155	155	155

Based on the results (3) for the specific related variety measure (TR), hypothesis 1 is partly confirmed. From this we can conclude that it is important the regional knowledge base is complementary to the knowledge base of the technology, but that some knowledge fields are more important than others. In total, five out of eight technology areas have a positive impact on the regional FC knowledge stock. The technology fields: 'chemical or physical processes', 'conversion of chemical energy into electrical energy', 'materials e.g. ceramics', 'analyzing and determining materials physical and chemical properties', and 'circuit arrangements and systems for storing electric energy' all have a positive significant association with the FC knowledge stock.

[20] 80 groups dropped because of all zero outcomes

Two knowledge fields seem not to play a role, ‘cables and conductors’ and ‘electrolytic processes’ are both not significantly related to FC knowledge production. Recall from Figure 3, that ‘electrolytic processes’ have decreased its share in IPC co-classifications since 1992. Since electrolysis is the reversed process of what takes place in the fuel cell, this might indicate that the two fields have started growing into two independent technological paradigms concurrently with an increased specialization. ‘Cables and conductors’ on the other hand seem not to be significantly related even its share of co-classifications grow over time (see Figure 3). A reason could be that the technology class ‘cable and conductors’ have a more generic character and hence is related to many fields besides FC. Another (more theoretical) explanation could be that this knowledge field is not required to be present in the region, but can be accessed over longer distance.

Finally, one knowledge field, ‘electrical vehicles’, is negatively related to the production of FC knowledge. This might be explained by two reasons: first, the recent development in strategies for FC vehicles (FCV), and second, the practice of designating IPC codes. The recent development in national strategies[21] for applying FC in the transport sector, stress that effort should be concentrated in combining the advantages of the electrical vehicle (EV) with those of the hydrogen FCV. Honda’s fuel cell electric vehicle “FCX Clarity” is an example of a fuel cell electric vehicle (FCEV) with both a lithium-ion battery and a fuel cell running on hydrogen. The fuel cell generates electricity to drive the electric drive motor and the battery supplements the FC’s output and stores energy from a regenerative braking system. The result is a longer driving distance than you can achieve from either FCV or EV alone. Most development within EVs is taking place independently of FC development because most EVs rely solely on batteries as the energy converter technology. FC knowledge might consequently be perceived as a sub-system that is applied in the EV, but the contrary does not apply. EV knowledge is not necessarily associated with FCs. As for the practice of designating IPC-codes FC knowledge might be applicable in electric cars, such as the FCEV, and hence the IPC code for EV (B60L) is designated to the patent, but this is not the case the other way around.

In the light of the rivalry we see between EV and FCEV as two alternative technologies to replace the internal combusting engine, the negative relationship between EV and FC knowledge production is interesting. It indicates that regions involved in pure electrical vehicles are not engaged in FC knowledge production.

Evaluating the 8 knowledge fields together, the claim that the degree of technological relatedness to the knowledge base of the technology should have an importance in inducing FC knowledge generation, has

[21] For example, the Danish Strategy: “Hydrogen and Fuel Cell for transport in Denmark”, www.hydrogennet.dk

limited evidence. For the two most related knowledge fields it is confirmed, they are also the two fields with strongest correlations. But the following three knowledge fields do not confirm the hypothesis. Here two fields are not related and one is negative and significant. Subsequently, the last three measures of technological relatedness, with the least shares of the co-classifications, show again a positive significant relationship to FC knowledge production. This picture indicates that the relationship between the knowledge base of the technology and knowledge base of the region is rather complex. It also indicates that the right combination of related knowledge fields might be more important.

Hypothesis 2A on the positive relationship between diversified regional knowledge bases and the emergence of radical technology cannot be confirmed, in the case of FC technology. At first, model (2) indicates a positive relationship, but when the TR measures are included in model (4) it is no longer significant.

The results, on the contrary, support hypothesis 2B that RV in regional knowledge bases leads to FC innovation. RV is according to the model, positively related to the production of the emerging technology field, FC. Even when we include the specific TR measures RV is positive and significant (correlations between the general measure of RV and the eight TR measures are all <0.5).

7. Conclusion

The objective of this paper has been to analyze the relationship between regional knowledge bases and the emergence of an industry in the case of the radical FC technology. The main contribution has been to test empirically if regional branching is driven by knowledge spillover processes enhanced by technological relatedness to existing regional economic activities. The findings indicate that new industries do emerge where they are technologically related to the knowledge base of the region.

In more detail, the objective has been to test the linkage between the regional knowledge base and the emergence of a radical technology, since this causal relationship previously has been assumed in empirical studies (see e.g. Glaeser et al., 1992, Frenken et al., 2007). The analysis tested three measures characterizing the regional knowledge base: its specific technological relatedness to the emerging industry, diversity, related variety. Moreover the results support the assumption that RV in a regional knowledge base is a prerequisite for radical innovation, at least in the case of FC technology. Diversity, as Jacobs argue is not adequate to explain the emergence of FC technology. Instead, these results confirm that cognitive proximity (RV) is an important element in the process of knowledge spillover at the regional level.

The study's findings improve our understanding of regions' possibilities to branch along nascent technological trajectories and thus are valuable for enhancing regional innovation policy. In the specific case of FC technology the results give insight to policy-makers in regions who have launched strategies on becoming hydrogen FC communities in the future. According to these findings such strategies will benefit from supporting regional FC activities that are technologically related to the knowledge base of the region.

The results are significant for the emerging FC technology, but one can ask: What can we tell about the emergence of other radical technologies? Theoretically the argument of related variety has been strengthened by this study, because it shows the conceptual value of RV in the case of a specific radical technology. This gives us additional reason to assume that it also will be the case for other technologies. However, future studies should attempt to verify this.

Other issues, future studies should focus on are the mechanisms that drive the process of regional branching. It is of great interest to uncover which of the mechanisms outlined earlier is the main driver for regions diversification into the FC industry. For example to what extent do new industries build on industrial vs. scientific knowledge production? Furthermore, it is of interest to explore where in the FC value chain localized knowledge plays a larger role. The knowledge fields covered in this study seems to be more relevant upstream, than downstream (application specific) in the value chain, but further studies are needed to confirm this issue.

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