Technical University of Denmark

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Tanner, Anne Nygaard

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The mechanisms of regional branching: An investigation of the emerging fuel cell industry

Anne Nygaard Tanner
Technical University of Denmark
Management Engineering
anny@dtu.dk

Abstract

The growth of evolutionary thinking in economic geography has brought about the proposition that new industries are place dependent and tend to develop in regions where the pre-existing industry is technologically related to the knowledge base of the new industry, a phenomena that is termed ?regional branching?. What is still lacking, however, is a more thorough understanding of the mechanisms through which regional branching operates: firm diversification, spinoffs, labor mobility, and social networking. This paper analyzes which mechanisms dominate the current regional branching process of the emerging fuel cell (FC) industry and the degree to which the underlying logic of these mechanisms is technologically related. It is concluded that the actors currently dominating the emerging FC industry are either large incumbent multinational enterprises (MNEs) or smaller dedicated FC system developers. Large chemical MNEs diversify downstream building to a high degree on in-house competences that are technologically related to the knowledge base of the FC technology. Large MNEs that integrate FC systems into application diversify vertically upstream. However, they build less on technology competences that are related to the core scientific principle of the FC. Hence, the findings only partly corroborate the thesis of technological relatedness as an underlying logic for regional branching in the case of an emerging industry, suggesting the need to look further into how agency and supportive organizations such as universities and network organizations play a role in the creation of new knowledge-intensive industrial paths in regions.

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The mechanisms of regional branching: An investigation of the emerging fuel cell industry

1 Introduction

This paper examines the emergence of a new industry in its geographical context. Emerging industries attract great academic and policy interest because new industries are associated with innovation and entrepreneurial activity that may provide a platform for future economic growth (Feldman and Lendel, 2010). The evolutionary turn in economic geography (Grabher, 2009) has encouraged greater interest in the origin and early evolution of new industries. This has brought about the proposition that new industries are place dependent (Martin and Sunley, 2006) and tend to develop where the pre-existing industry is technologically related to the new industry (Boschma and Frenken, 2011b). During this process, which Boschma and Frenken have metaphorically labeled 'regional branching'[1], new regional industrial paths grow out of related pre-existing industry. This has been confirmed empirically for a region's long-term economic evolution (Neffke et al., 2011) and for the emergence of radical FC technology across European regions (Tanner, 2011). However, the emerging literature on 'regional branching' has a major shortcoming, which is the focus of this paper.

It has been put forward that we lack a thorough understanding of the mechanisms that catalyze regional branching (Neffke et al., 2011). Regional branching has been argued to operate through the mechanisms of firm diversification, firm spinoffs, labor mobility, and social networking, which function as knowledge channels from the pre-existing industry to the emerging industry. This paper aims at improving our understanding of the character of the direct mechanisms that operate the regional branching of radical emerging industries. The objective is to understand the nature of industrial dynamics in regional branching processes. Hence, the paper poses the following questions: i) which mechanisms dominate the current regional branching process in the case of the emerging FC industry, and ii) to what degree is the underlying logic of these mechanisms technologically related?

Keeping in mind that it is unlikely that there exists one model that would describe the early history of all modern industries (Martin and Sunley, 2006, Storper and Walker, 1989) or all processes of regional branching, this article focuses in depth on one contemporaneous emerging industry, namely, the fuel cell (FC) industry. The emerging FC industry is, with few exceptions, still in a pre-commercialization phase, and it remains uncertain if the technology will gain wide-scale market acceptance (Hellman and van den Hoed, 2007). Like many emerging technologies, the FC technology was characterized by hype in the beginning of the 2000s with announcements of large promises and near-term commercialization, and consequently, it received impressive policy interest (OECD, 2006). Although the hype was followed by downscaling of expectations and disappointment, it did not weaken the interest and engagement from industry and research communities around the world (Ruef and Markard, 2010) or policymakers, especially at the regional levels, where many local initiatives were generated (Madsen and Andersen, 2010).

A FC is an electrochemical device that generates electricity based on a chemical reaction between a fuel, usually hydrogen, and oxygen. Its wide scale potential was recognized due to progress in a number of

[1] In this paper, regional branching is used interchangeably with regional diversification.

related scientific fields, such as material science, chemistry, and nanotechnology. These and other knowledge fields have played a key role in the development of FC technology during the past decades and form the basis for the emerging technology's knowledge base. In other words, these fields are "the set of information inputs, knowledge, and capabilities that inventors draw on when looking for innovative solutions" (Dosi, 1988, p. 1126).

Technological change in the field of FC and hydrogen is highly systemic and complex. Thus, technological improvements (or impediments) in one component improve (or inhibit) the performance and cost of the whole system. The interdependency between components is similarly reflected in the highly complex FC knowledge base (Tanner, 2011, Dibiaggio and Nasiriyar, 2009). The systemic and immature character of the technology implies that innovation requires extensive cooperation and coordination along the value chain and supportive institutional structures (Hellman and van den Hoed, 2007, Musiolik and Markard, 2011).

The emerging FC industry is currently characterized by a mix of young dedicated FC firms and large incumbent multinational enterprises (MNEs) (Hellman and van den Hoed, 2007, Pilkington et al., 2009, Nygaard, 2008, Brown et al., 2007). Furthermore, a wide range of supporting actors, such as universities, public-private partnerships, and formal networks at the regional, national, and international levels, are involved in FC and hydrogen-related activities (Madsen and Andersen, 2010, Musiolik and Markard, 2011, Bourgeois and Mima, 2003, Mans et al., 2008).

Aside from a number of qualitative case studies of hydrogen and FC cluster initiatives (Mans et al., 2008, Holbrook et al., 2010, Hodson et al., 2008, Hodson, 2008), the emergence of the FC industry and its geographical context have not been analyzed systematically. Based on a mixture of patent studies and qualitative interviews, this paper builds upon the findings of Tanner (2011) and scrutinizes in more detail the industrial dynamics that characterize the process of the evolutionary term 'regional branching' in the emerging FC industry.

This paper is structured as follow. Section 2 outlines the theoretical understanding on which the paper builds. Section 3 describes the methodological approach of the paper. The analysis is conducted in Section 4 and is twofold. First, the analysis maps NUTS2 regions in Europe with the highest shares of FC patent applications. Second, the analysis examines the different types of regional branching mechanisms by focusing on the actor with the largest share of FC patents for each region. It is concluded in Section 5 that the actors currently dominating the emerging FC industry are large MNEs that diversify into the emerging industry in two ways. Upstream MNEs build to a large extent on in-house competences that are technologically related to the knowledge base of the FC technology, whereas more downstream firms that integrate the FC systems into applications build less on technology competences that are related to the core scientific principle of the FC. The downstream firms diversify vertically upstream.

2 Conceptualization: The emergence of industries

The objective of this paper is to investigate the emergence of new industries in their regional contexts. Analytically, the concept of emerging industry differs from concepts such as clusters, industrial districts, and innovative milieu, which attract most of the attention in economic geography (Asheim et al., 2011). Clusters are usually defined as geographic concentrations of firms that benefit from a common pool of skilled labor, specialized suppliers, and knowledge externalities (Porter, 1998) as well as firms that perform above average (Porter, 1996). There are several reasons why young industry development differs from the cluster concept, but the most notable reason for the difference is that the initial spatial industry evolution may only develop clustering features over time. Furthermore, it is not necessarily the regions hosting the most firms at an early stage that will host industrial clusters at a later stage (see e.g. Romanelli and Feldman, 2006). It is the author's belief that studies on the early emergence of new industries at a pre-cluster stage will increase the understanding of how new industries come into being, thus enriching the field of evolutionary economic geography and perhaps enlightening our understanding of the genesis of clusters, which has been receiving increasing attention recently (Braunerhjelm and Feldman, 2006, Fornahl et al., 2010, Menzel and Fornahl, 2010).

The concept of emerging industry consists of an analytical object and a temporal interval. The analytical object is the industry, which is usually defined as a group of firms producing closely substitutable products (Forbes and Kirsch, 2010). However, this definition is not without problems when traditional industry boundaries are met with radical technological change (Munir and Phillips, 2002). In such cases, the new activities related to developing the technology become the assembling point as the contour of a new industry emerges, though the delineation of the new industry may stay blurry for some time.

The concept of industry emergence is also defined by its temporal dimension, which refers to the early evolutionary stage of an industry life-cycle model (Forbes and Kirsch, 2010). The seminal work of Abernathy and Utterback (1978) labeled the early stage that an entrepreneurial firm goes through as the fluid phase. The fluid phase is characterized by *extraordinary high* levels of uncertainty in the direction of search, expectations of technology, identification of main players and the strategic orientation in approaching markets (Dosi, 1988, Utterback, 1996). The length of the emergent phase, where the company must survive with little or no sale in the market, is uncertain and highly unpredictable.

However, analytically, there are many challenges in studying the emergence of new industries as these by their very nature do not fit into existing classification schemes (see also Feldman and Lendel, 2010, Forbes and Kirsch, 2010). Emerging industries are, therefore, primarily studied in retrospect. However, it is increasingly important to be able to identify contemporary emerging industries and to take advantage of studying them in 'real time'.

2.1 Regional branching in the case of radical technological change

Despite the difficulties of studying emerging industries, a recent conceptualization in economic geography, which builds on evolutionary economics (Nelson and Winter, 1982), has proposed that new industries are place dependent (Martin and Sunley, 2006) and tend to develop where the pre-existing industry is technologically related to the new industry (Boschma and Frenken, 2011b). Technological relatedness is herein suggested as a pivotal concept in understanding the path-dependent, evolutionary development of the industrial structure of a region.

The notion of technological relatedness describes the cognitive proximate relationship between the knowledge bases of two or more industries, thereby increasing the possibility of inter-industrial learning (Nooteboom, 1999, Boschma, 2005). In recent years, increasing empirical evidence has been provided that confirms the path dependency of national (Hidalgo et al., 2007, Hausmann and Klinger, 2007) and regional economic development (Neffke et al., 2011). Neffke et al. (2011) reveal that firms that are technologically related to a region's industrial portfolio are more likely to enter that region, and firms that are technologically unrelated to a region's pre-existing industry are more likely to exit that region. This indicates a somewhat technological coherent development path for regional economic development. Furthermore, in the case of the emergence of radical technology development, the thesis of technological relatedness has been confirmed (Tanner, 2011). In Tanner (2011), it is confirmed that the more the regional knowledge base is technologically related to the knowledge base of the FC technology, the more likely the region is to branch into the emerging FC field.

2.2 Mechanisms operating regional branching

Because of the relatively young conceptualization of regional branching and technological relatedness, there remains a lack of thorough understanding of the mechanisms through which regional branching operates. Boschma and Frenken (2011a) tentatively note that firm diversification, spinoffs, labor mobility, and social networking are important mechanisms for the processes of regional branching. While these mechanisms are very different concepts and are related to regional branching in different ways, they all function as channels for knowledge transfer. Hence, other mechanisms could be added, such as collaborative R&D projects and university spinoffs. Where firm diversification and spinoffs represent the new industry, labor mobility, social networking, and R&D projects may function as knowledge diffusion mechanisms that trigger firm diversification or spinoffs at a later stage. Firm diversification and spinoffs into emerging industries become the actual indication and measure of regional branching, whereas labor mobility, formal collaborative work, and informal buzz (Bathelt et al., 2004) may secure a high level of knowledge diffusion in a region that may initiate regional branching. In the following, I concentrate on the nature of the direct diversification mechanisms: firm diversification and spinoffs.

2.2.1 Firm diversification

Firms may diversify in a number of directions. Kodama (1986) distinguishes between vertical and horizontal diversification processes. If a firm diversifies into fields that are either inputs or outputs for that firm, the diversification process is vertical. If, on the other hand, a firm does not diversify into a field that is in an input-output relationship with the firm, the diversification is said to be horizontal. The horizontal diversification is what is normally associated with Penrose's seminal work on the resource-based view of the firm, where 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 (Penrose, 1959). In the horizontal diversification process, the firm is said to have economies of scope because of commonalities in knowledge input to two technological fields (Breschi et al., 2003). The horizontal diversification process is consistent with the regional branching thesis that firms and, hence, regions diversify based on using technological related resources from the pre-existing industry.

However, in a vertical diversification process, a firm may diversify into technologies that are not related to the knowledge base of the firm. This process may occur if a firm moves into product fields that are inputs to the firm, and the firm then diversifies *upstream*. Or a firm may diversify its production further downstream if it begins to apply its outputs in products. Vertical diversification may occur because of changes in the firm's competitive environment or because an integration strategy is the best way to facilitate incentive alignment and control innovative activity (Teece, 1986). Changes in a firm's environment may be caused by increased competition. For example, when a large part of the European textile production was overtaken by newly industrialized countries, some textile firms in Europe moved upstream into areas such as improving and manipulating materials by applying, for example, nanotechnology (Fianti et al., 2006). Changes in a firm's environment can also occur because of changes in consumer preferences, toughened regulations, or uncertainty in supply (Arrow, 1975). Vertical diversification may also occur because the particular *stage of production* does not exist (Langlois, 1992). Langlois refers to the costs incurred as a result of the changes as 'dynamic transaction costs', which correspond to *"costs of not having the capabilities when you need them*" (Langlois, 1992, p. 113).

Consequently, firms do not diversify vertically because of economies of scope but because of changes in the external conditions of the firm. Vertical diversification processes thus contradict the regional branching thesis in that a firm's pre-existing knowledge base is not technologically related to the knowledge base of the new industry. The lack of related knowledge resources leaves firms that diversify vertically to build up new sets of skills and competences that are related to the new industry. In this case, the regional knowledge base, as manifested in a competent labor force or university and research institutes with technology-specific related resources, may encourage and assist firm diversification.

2.2.2 Spinoffs

Spinoffs are another source of regional branching. A spinoff is created when employees leave their workplace to establish a new firm based on skills they have acquired in the parent organization. I distinguish here between firm and university spinoffs as the former is clearly connected to the pre-existing industry and the latter is related to the knowledge exploring of the regional knowledge base. The semiconductor industry is the most notable example of an industry with a high rate of firm spinoffs at a very early stage of the industry life cycle (Klepper, 2001). Because firm spinoffs have been shown to resemble their parent company in the spinoff's initial products and markets (Klepper, 2001, Klepper and Sleeper, 2005), they are likely to be the primary mechanism for regional branching under certain specific conditions in the case of radical, emerging industry. Such conditions could include high levels of research and development in incumbent firms, which result in new ideas that the parent company has decided not to pursue. In the case of large firms, because they may decide to cut back on their portfolio activities, whole divisions may be spun off as they become redundant in the firm's strategy.

The biotechnology industry is, on the other hand, an example of an industry with a high rate of university spinoffs. For example, Zucker et al. (1998) find that the biotechnology industry is driven by embedded tacit knowledge in star scientists who decide to start their own businesses in geographical proximity to their faculty laboratory. Entrepreneurial spinoffs, whether from firms or universities, have been shown to locate in proximity to their parent organization (see Stam, 2010 for review) and, hence, fit well as a mechanism for regional branching.

2.2.3 Conceptualization, final comments

New industries are challenging to study, which is all the more reason to try to understand them. The evolutionary proposition that emerging industries are place dependent in the sense that they build on localized technological resources is consistent with the *explanans* of the evolutionary economic paradigm – industrial dynamics. Because the core mechanisms, firm diversification and spinoffs, are geographically biased toward the location of the knowledge and competences they build upon, they seem well qualified to explain and capture the process of regional branching.

Although the recent conceptualization of regional branching stresses the importance of related knowledge resources and competences in a given region for economic development, it does not suggest a deterministic relationship between a given region's knowledge base and a new industry. The claim is that the propensity for a region to branch into new industries is greater when the regional portfolio of knowledge, skills, and competences are technologically related to the new industry. Hence, the conceptualization of regional branching processes may explain some of the very fundamentals of new industry emergence in regions, but there are other aspects of emerging industry development that are either crucial for the regional branching process or may have a more supportive character. One crucial element is the strategic, deliberate actions of the entrepreneurs (or intrapreneurs) that constitute the new industry (Martin and Sunley, 2006, Garud and Karnøe, 2001). It is obvious that these actions are not strictly bounded by the pre-existing knowledge resources of a firm or region but they naturally must deviate from the established knowledge bases to create a new path (Garud and Karnøe, 2001).

Moreover, supportive actors such as universities, governments, and interest organizations that make up the regional innovation system (Cooke, 2004) are similarly important for the further development of emerging industries. In particular, in knowledge-intensive industries, universities and research institutes are of great importance because, together with the pre-existing industry, they constitute the regional knowledge base.

3 Method

This study focuses on a selection of European regions that make up the majority of FC knowledge production approximated by patent applications. The analytical strategy is as follows. First, European NUTS2 regions with the largest shares of FC patenting between 1993 and 2007 are identified. Second, the largest FC patenting players for each region are identified, and third, the largest players' development paths into the emerging FC field are examined. This provides us with a profile of regions and actors that may not be representative of the emerging industry, but it provides qualitative insight into the main regional branching mechanisms for a variety of regions.

The analysis is conducted and built on three different types of data, including patent applications filed under the Patent Cooperation Treaty as designated by the European Patent Office, secondary qualitative data, and interviews.

The main quantitative data source is the OECD REGPAT database, December 2010. This dataset is unique as it is a comprehensive attempt to ascribe a large detailed patent dataset to regional statistical units. The analysis of the location pattern is based on the address of the inventor as this is presumed to be a better proxy for where knowledge production actually occurs rather than using the address of the applicant. Likewise, I use 'priority year' to date time of invention. The International Patent Classification (IPC) system is used to identify patent applications with FC content. The IPC-code 'H01M008' refers to the classification of "fuel cells, and manufacture thereof". This method defines FC patent activity rather narrowly, which is consistent with the purpose of this study, that is, to identify actors with core development activities.

Once the FC patent applications were identified, the sample was linked to the applicants with the OECD Harmonized Applicants Names (HAN) database. The OECD HAN database is an attempt to clean and consolidate the many versions of the same applicant name (see Magerman et al., 2006 for method). Although the OECD's standardized harmonization method contributes significantly to cleaning the data, it was still necessary to clean and consolidate applicant names manually.

Patents are a much debated data source in innovation studies primarily because patents are not equivalent to innovation, and not all knowledge is patented. Another specific drawback for this study is that it biases large companies over small firms because larger firms are better geared to patent new knowledge, which is a costly endeavor. However, when studying an immature technology field where innovations (such as new products or processes) mainly exist as prototypes, a way to measure progress and activity is to measure the level of knowledge production. Consequently, for the purpose of this study, patent data yield valuable insights into the shaping of an emerging industry that no other quantitative dataset can provide.

Another data source is of a more qualitative character. This source includes various types of documents such as strategy papers, annual accounts, homepages, newsletters, press releases, and consultancy reports. These sources provide general background data on the sample firms, an account of different types of events that have influenced the development of the FC industry, and an impression of the state of affairs at different point in times.

Finally, a number of interviews have been conducted with experts who are familiar with the FC technology and/or industry and with companies from each node in the FC value chain, that is, upstream, downstream and core FC system developers. Additionally, a few interviews were conducted with representatives from regional hydrogen and FC organizations. The interviews were based on a semi-structured guide that addressed the firms' history, state-of-the-art of the firms' technology activities, and the linkages between existing industry structure and the new industry.

4 Analysis

The analysis is introduced with a brief description of the emerging FC industry and the main barriers that currently inhibit a full commercialization. The analysis then identifies the largest FC regions in Europe measured by their FC patent production and provides a general presentation of the regions with high shares of FC knowledge. Finally, the analysis examines, in greater detail, the different types of regional branching mechanisms that characterize the emerging FC industry.

4.1 The framing of FC industry emergence

FC technology and the emerging industry that evolves around it belong to a wider platform of innovations that is referred to as 'green innovations' (Cook, 2010). The green potential of hydrogen FCs makes it a promising alternative to incumbent energy technologies and has attracted the interest of various types of enterprises over the past few decades as well as significant interest in policy and research. The interest is founded on the potential to solve the challenges that dominate the energy agenda, such as self-sufficient energy supplies and local and global environmental improvements.

The characteristic feature of FC technology is that it can replace batteries and internal combustion engines, and hence, it is applicable within 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 as auxiliary power units. Although FC technology outperforms the incumbent energy technologies on a number of non-traditional performance measures, such as no-noise, no-exhausts, and no moving parts, the technology needs further enhancements to improve costs, *traditional* performance measures and overall reliability. Hence, the application of FC systems into products continues to face a number of challenges. The technology faces severe lock-in from incumbent energy technologies that can be compared to other large paradigm shifts, such as the steam engine and electric power. The gestation period for such new paradigms can be very long because of inertia within the incumbent systems (Perez, 1983, in Freeman, 1996), and this may explain why this type of green innovation faces such severe difficulties in reaching markets.

4.2 The diversity of regions branching into the emerging FC industry

Analogous to other studies on the spatial distribution of high-tech patenting (Feldman and Lendel, 2010), FC patenting is concentrated in a small group of regions (see Table 1). Out of a total number of 271 NUTS2 regions, 189 regions have a share in the 2165 FC patents applied for between 1993 and 2007. During the same period 60% of the total FC patent applications are applied for by 6.6%, or 17, of the 271 NUT2 regions. This confirms a clear pattern of concentration of FC knowledge generation in a low number of regions.

Table 1: Distribution of FC patent applications across European NUTS2 regions; calculations based on OECD REGPAT, December 2010

Number of NUTS2 regions	Total FC patent count	Percentage of total patent count	Mean	Median	St. Deviation
1993-2007					
189	2165	100	11.5	3.2	25.7
42	1732	80	41.2	20.7	42.8
17	1296	60	76.3	68.3	49.8
1993-1997					
189	209	100	1.1	0.0	3.6
42	174	83	4.2	1.1	6.6
17	150	72	8.9	8.7	8.5
2003-2007					
189	1035	100	5.5	1.5	11.5
42	792	77	18.9	12.6	18.8
17	547	53	32.2	28.0	23.4

However, the development during this period reveals a diminishing spatial concentration. The share of FC patent applications recorded by the 17 most active patenting regions decreases from 72% in the first period (1993-1997) to 53% in the second period (2003-2007). As this is still considered the fluid phase, the period reflects increasing entry, mirroring a decreasing concentration.

Figure 1 illustrates the geographical distribution of the 17 regions that account for 60 % of FC patenting activity. The map shows a clear concentration of more than half of the 17 regions in southern Germany, including Stuttgart, Karlsruhe, Freiburg, Tubingen, Upper Bavaria, Upper Franconia, Middle Franconia, Bavarian Swabia, Darmstadt, and Rhineland Palatinate. Additionally, Mecklenburg-Western Pomerania in northern Germany and Cologne in West Germany are among the largest FC patenting regions. Four other countries have NUTS2 regions that are among the most FC knowledge-producing regions in Europe. These include Lombardy in Italy, North Holland in the Netherlands, Ile de France and Rhône-Alpes in France, and the NUTS2 region of ‘Berkshire, Buckinghamshire and Oxfordshire’ in southeast England. It is important to underline that the 17 largest FC patenting regions are not interpreted as clusters in a Porterian sense because, as argued in Section 2, the cluster concept is not analytically applicable at the very early stage of industry emergence.

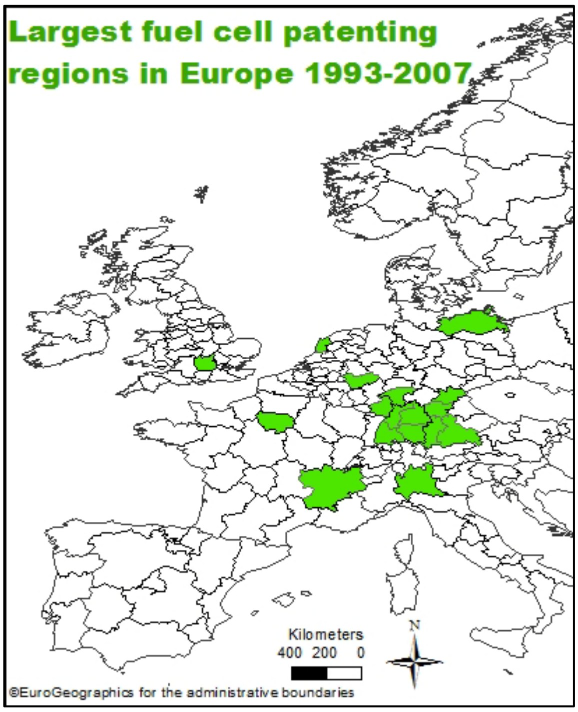

Figure 1: Largest FC patenting regions in Europe, 1993-2007, Source: OECD REGPAT, Dec 2010.

The geographical distribution confirms, to a certain degree, the general impression of the geographical distribution of high-tech industries and employment across Europe, supporting the findings by Madsen and Andersen (2010). In 2006, high-tech sectors accounted for 4.4% of the total employment in Europe (Meri, 2008). In comparison, most of the 17 largest FC patenting regions already had employment shares in high-tech sectors that were much higher than 4.4 % in 2000 (see Table 2). Bavarian Swabia and Upper Franconia in Bavaria have shares near the European average, while Mecklenburg-Western Pomerania, at 3.2%, is the only region with a share below the European average.

Although the total level of FC knowledge production is important, a comparison of the largest FC regions based on a relative measure can indicate how productive the regions are in FC knowledge generation. Table 2 shows the ratio of FC patents per 10,000 high tech employees. The relative measure of FC patenting per 10,000 high tech employee ranges from approximately 1.6 in Ile de France to 28.4 in Middle Franconia, Bavaria. The low number in Ile de France reflects a very high level of high-tech employment (415,000 in 2000), equivalent to 8.4% of the total employment, and it reveals that FC knowledge generation accounts for a minimal share of its high-tech patents. Considering the most patent-productive regions, column 5 in Table 2 highlights the six German regions of Upper and Middle Franconia in Bavaria, Stuttgart and Tubingen in the neighboring federal state of Baden-Wuerttemberg, Cologne in North Rhine-Westphalia and Mecklenburg-Western Pomerania in northeast Germany. Most of these regions also have high total counts of FC patents, except for Upper Franconia with 35.8 and Mecklenburg-Western Pomerania with 33.6 FC patents. The latter two produce, respectively, 16.6 and 13.6 FC patents per 10,000 high-tech employees.

Table 2: Regions with total FC patent applications and European high-tech employment, 1993-2007.

NUTS2-regions	NUTS1-regions	Total # of FC patent applications[i]	High tech share of total employment[ii]	FC patents per 10,000 high tech employees[iii]
Stuttgart	Baden-Wuerttemberg	205,0	7,3%	15,4
Karlsruhe	Baden-Wuerttemberg	38,8	8,0%	4,1
Freiburg	Baden-Wuerttemberg	42,4	7,2%	6,2
Tübingen	Baden-Wuerttemberg	85,1	4,8%	21,3
Upper Bavaria	Bavaria	124,3	7,5%	8,3
Upper Franconia	Bavaria	35,8	4,3%	16,6
Middle Franconia	Bavaria	129,4	5,8%	28,4
Bavarian Schwabia	Bavaria	31,2	4,2%	9,1
Darmstadt	Hesse	84,3	7,3%	6,7
Mecklenburg-Western Pomerania	Mecklenburg-Western Pomerania	33,6	3,2%	13,6
Cologne	North Rhine-Westphalia	152,7	5,0%	16,9
Rhineland Palatinate	Rhineland Palatinate	42,6	5,1%	9,4
Ile de France	Île de France	68,3	8,4%	1,6
Rhône-Alpes	Rhône-Alpes	74,3	5,7%	5,8
Lombardy	Lombardia	41,9	5,0%	2,2
North-Holland	Netherland	38,2	5,7%	5,3
Berkshire, Buckinghamshire and Oxfordshire	Southeast England	68,9	12,5%	5,0

Source: Calculations based on OECD REGPAT, December 2010, i) regional count based on inventors' addresses. ii) source: Eurostat, year 2000. iii) Normalized by annual 2000 high-tech employment.

In particular, it is interesting that Mecklenburg-Western Pomerania is among the most productive places in FC knowledge production as regions in the northeastern part of Germany have been characterized as relatively inefficient regional innovation systems (Fritsch and Slavtchev, 2006). In fact, Fritsch and Slavtchev's assessment of the efficiency of German regional innovation systems places Stuttgart and the Bavarian regions at the very top, while Mecklenburg-Western Pomerania is at the very bottom of the ranking. The fact that our sample of the largest FC patenting regions comprises regions from each end of the spectrum confirms the window of locational opportunity thesis that new industries have the possibility to localize in regions independent from current economic centers (Storper and Walker, 1989) and that, consequently, they may potentially disrupt the current economic landscape. I now address the mechanisms that have caused this development.

Table 3: Largest NUTS2 regions with # of FC patenting entities, university share, and largest patentee, 1993-2007

NUTS2-regions	NUTS1-regions	# of FC patenting entities	Mean per patenting entity	University pct of total patent appl.	Largest Patenting entity Pct.	Entity name
Stuttgart	Baden-Wuerttemberg	47	4.6	14%	25%	DAIMLER
Karlsruhe	Baden-Wuerttemberg	31	1.5	25%	23%	CARL FREUDENBERG
Freiburg	Baden-Wuerttemberg	17	2.5	44%	41%	FRAUNHOFER-GESELLSCHAFT
Tübingen	Baden-Wuerttemberg	39	2.1	8%	39%	DAIMLER
Upper Bavaria	Bavaria	47	2.4	6%	14%	SFC ENERGY
Upper Franconia	Bavaria	8	5.5	2%	89%	SIEMENS
Middle Franconia	Bavaria	19	6.7	4%	83%	SIEMENS
Bavarian Schwabia	Bavaria	24	1.6	9%	24%	DAIMLER
Darmstadt	Hesse	38	2.2	7%	15%	BASF
Mecklenburg-Western Pomerania	Mecklenburg-Western Pomerania	11	2.7	3%	56%	NEW ENERDAY
Cologne	North Rhine-Westphalia	33	4.6	67%	64%	FORSCHUNGSZENTRUM JULICH
Rhineland Palatinate	Rhineland Palatinate	20	2.2	6%	66%	BASF
Ile de France	Île de France	29	2.8	26%	37%	RENAULT SAS
Rhône-Alpes	Rhône-Alpes	32	2.7	58%	44%	COMMISSARIAT A L ENERGIE ATOMIQU
Lombardy	Lombardia	18	2.5	1%	39%	NUVERA FCS
North-Holland	Netherland	16	2.5	63%	59%	ENERGY RESEARCH CENTER OF THE NL
Berkshire, Buckinghamshire and Oxfordshire	Southeast England	27	2.5	5%	55%	JOHNSON MATTHEY

4.3 Regional diversification mechanisms

Table 3 displays the number of total FC patent applications, patenting entities, mean per patenting entity, and the share of university patents and the largest patenting entity for each of the largest FC patenting regions over a fifteen-year period. The largest FC patenting regions are characterized by housing either a large anchoring MNE, a smaller dedicated FC system developer, or a university or research institute. According to the narrow definition of FC knowledge, the actors all have development activities within the core of FC technology. However, the different actors are related to the FC value chain in different ways (see Table 4 for a description of the FC value chain).

4.3.1 Upstream FC component developers

Upstream in the FC value chain are material developers and suppliers of catalysts, electrodes, polymers, membranes and gas diffusion layers (Nygaard, 2008). These are often generic products and processes that fit into a wide range of products of which FCs constitute a minor part. Next, node (2) in the value chain encompasses components and sub-systems such as sensors, membrane electron assembly (MEA), stacks, bipolar plates, fans, hydrogen and other fuel storage systems. These products are usually generic for the various types of FCs and may work for many types of applications.

Upstream →	**(2)** →	**(3)** →	**Downstream**
Catalysts Electrodes Membranes Polymers Gas diffusion layers	Membrane electrode assembly Bi-polar plates Heat exchanger Liquid pumps Stacks Sensors Fuel storage tanks etc.	PEMFC SOFC DMFC etc.[i]	Transport Central energy production Distributed energy production Portable equipment Back-up power
Materials	**Components and subsystems**	**FC System developers**	**System integrators**

Table 4: The FC value chain based on Nygaard (2008) i) The abbreviations refer to the types of FCs such as proton exchange membrane FC (PEMFC), solid oxide FCs (SOFC) and direct methanol FCs (DMFC).

From our sample, the Freudenberg Group, BASF, and Johnson Matthey comply with the upper part of the value chain. The Freudenberg Group is located in Karlsruhe in Baden-Wuerttemberg, which is close to the automotive industrial agglomeration in Stuttgart. Its large knowledge base and network in the automotive industry encouraged the firm to start research in FC technology, although it did not have any clear competences in that field. The group found that its skills in nonwovens from its textile assets could be used in the development of gas diffusion layers and that its core competences in seal technology could be leveraged to produce seals for FCs (Fianti, 2009). The Freudenberg Group has thus diversified horizontally based on clear economies of scope.

The large chemical companies of Johnson Matthey and BASF have also diversified vertically downstream. Both BASF, located in the border area of Rhineland Palatinate, Baden-Wuerttemberg and Hessen, and Johnson Matthey, located in southeast England, build on their core skills in catalysts and chemical processes, which they apply to the FC field by developing complete MEAs for proton exchange membrane FCs (PEMFC). Johnson Matthey's FC development activities date back to the 1950s, when they focused on alkaline FCs for the NASA space program and phosphoric acid FCs for large stationary power stations. Since 2000, however, Johnson Matthey's FC activities have been organized in the subsidiary Johnson Matthey FCs

Ltd. in partnership with Anglo Platinum, which owns 17.5%, and the company is now focused on MEAs for PEMFC.[2]

BASF has also had experiences in another type of FC, namely, the direct methanol FC (DMFC). However, in 2007, BASF changed their technological focus in favor of high-temperature MEAs. BASF's activities today are based on competences and skills that were developed and enhanced in the chemical company of Hoechst and spun off as the independent company, Pemeas Fuel Cell Technologies in 2004. In late 2006, BASF acquired Pemeas, which laid the key building block for BASF's current FC-related activities. BASF builds on its core competences in polymers, membranes, and catalysts in the development and production of MEAs. According to the head of BASF's Global Fuel Cell Coordination and Research Centre, Carsten Henschel, BASF has taken an unusual step for chemical companies and moved downstream into developing and producing components, stating *"We are upstream (in the FC value chain, ed.), but if you look at the experiences of chemical companies, this is actually very downstream; usually chemical companies produce monomers or polymers as liquid or powder. In this case, we still have to do more than 30 different production steps to get to the MEA, so it is something like producing a circuit board, something that is very unusual for us"* (Henschel, 27/10-2011).

This underlines that technological competences must be developed consistent with the buildup of new organizational routines in the chemical industry and knowledge of the end-product. By moving downstream, the chemical companies must increase their knowledge about the variety of components and their interaction with the end-product.

All three examples highlight the ways these large companies have diversified based on economies of scope where competences in their respective knowledge bases are leveraged into the FC technology field. However, both BASF and Johnson Matthey have moved a step downstream and developed the core component of the FC, where the electrochemical reaction occurs.

4.3.2 Dedicated FC system developers

Further downstream in the FC value chain are the FC system developers where sub-systems and components are integrated into a FC system. This segment is represented by three smaller companies in our sample, namely, SFC Energy AG, New Enerday, and Nuvera Fuel Cells Europe. These are dedicated FC system developers that differ from one another with respect to the type of FC they develop and their market approach, which often has a niche character.

The three dedicated FC system developers have followed different paths into the FC field. New Enerday, with approximately 10 employees, is a firm spinoff based in Mecklenburg Western-Pomerania. This small firm has the majority of the IP rights in Mecklenburg Western-Pomerania, which has a relatively limited patent activity and few patenting entities, perhaps as a consequence of being a less efficient innovation system. Founded in 2010, New Enerday is based on FC activities performed in Webasto's previous subsidiary, Enerday. Webasto is a world leading supplier to the automotive industry of convertible roofs and heating, cooling and ventilation systems. In 2000, Webasto initiated a number of research projects in FC technology systems that were built upon its related core competences in heating and auxiliary electrical arrangements. However, in 2010, Webasto sold off the FC development activities, and New Enerday was

[2] http://www.jmfuelcells.com/index.html (accessed 17/10-2011)

founded by its current director, Matthias Boltze, who acquired Enerday's intellectual property rights from Webasto (Boltze, 18/10-2011).

Another example is SFC Energy AG, located in Bavaria, which is a university spinoff from the Technical University of München (TUM). SFC Energy was founded in 2000 based on Dr. Manfred Stefener's promotion of electrode structures for direct methanol FCs. SFC Energy produces FC systems (DMFC) to leisure markets, off-grid and defense organizations. Since 2003, SFC has shipped more than 20,000 FC systems to a range of niche market segments, and it has grown to approximately 100 employees.[3]

Nuvera Fuel Cells Europe was originally the Italian electrochemistry Group De Nora's FC subsidiary. De Nora FCs was acquired by the American company Epyx Corporation in 2000, which then formed the current Nuvera Fuel Cells, which, in addition to its headquarters in the US, still has a location in Milan.

The dedicated FC system developers focus on assembling the system and, hence, rely heavily on suppliers of FC stacks and other components and system integrators that integrate the system into products. They are a varied group of firms that depict the instability of an emerging industry where spinoffs, acquisitions, and alliances continue to change the industrial outline.

4.3.3 FC system integrators

Closest to the markets are the end-users that incorporate the FC system into a complete product. Examples include automobiles, combined heat and power systems, laptops, and hearing aids. In the largest FC patenting regions, Siemens, Daimler, and Renault SAS stand out as this type of end-user. While Siemens has mainly been focused on developing SOFC systems for application in stationary power units, the carmakers (Daimler and Renault) have been involved in developing FC drive systems for the propulsion of vehicles. All three, however, can be said to diversify vertically upstream into the field of FC technology.

The automotive manufacturers' interest in FC technology was initiated by the Canadian Ballard Power System's breakthrough at the end of the 1980s, which reduced the cost of a FC system to power a car from approximately US$ 50,000 to potentially a couple of hundred dollars per car (Steinemann, 1999). Daimler had, at this time, been involved in battery technology development, but they assessed that FC technology provided greater potential because of the higher energy density level obtainable with high-pressured hydrogen as fuel. However, moving into the field of FC technology has not been uncomplicated for Daimler, as their core competences are technologically centered on the internal combustion engine (ICE) and skills associated with the mechanically moving part in this type of engine. Therefore, Daimler did not have a high level of in-house capabilities that was technologically related to the core scientific principle of the FC. According to Dr. Jörg Wind, Daimler AG, Daimler first had to establish a basic understanding of the FC technology: "*First, we had to build up some capacity to understand the technology to be able to decide if it was something which could be done alone or if we would need a partner, and the choice was to collaborate with Ballard Power System. Because electrochemical technology and, in particular, FC technology was, 20 to 30 years ago, not a part of the competences of any car manufacturers*" (Wind, 17/10-2011). Daimler chose a collaborative strategy for its FC endeavors (Steinemann, 1999) and has thus formed many alliances and joint ventures over the past two decades. Today, Daimler's activities are organized in two subsidiaries that carry out R&D and produce FC stacks and systems, respectively. The FC stack developer and producer is the

[3] www.sfc.com including financial reports, press releases, etc. Accessed September 2011.

Automotive Fuel Cell Cooperation (AFCC), a joint venture with Ford, which owns 30%, and Ballard, which owns 19.1%, located in Vancouver, Canada, and the FC system integrator and developer NuCellSys, which is located in Nabern, near Daimler's headquarters in Stuttgart.

Upstream	2	3	Downstream
Freudenberg Group			
Johnson Matthey →	Johnson Matthey FCs Ltd.		
→	BASF Global FC and Research Centre		
BASF			
		New Enerday	
		SFC Energy	
		Nuvera FCs ◄- - -	- - -► **Renault**
	AFCC ◄——	NuCellsys ◄——	**Daimler**

Table 5: Firm diversification along the FC value chain. Arrows indicate direction, dashed line=strategic alliance, Italic= spinoffs

Table 5 illustrates the diversification paths the different firms have followed. The Freudenberg Group has diversified horizontally into the FC field, but it has not diversified along the FC value chain. BASF and Johnson Matthey have, on the other hand, moved downstream in the FC value chain and are currently developing MEAs for PEMFC. Renault builds on a strategic alliance with Nuvera Fuel Cells in delivering FC systems, while Daimler has diversified vertically upstream and, by maintaining control of the two subsidiaries, is in control of most of the FC value chain.

A measure of firm's FC-related competences

For four MNEs[4], it has been possible to calculate a specialization index[5] for a five-year period (1988-1992) prior to the time when the development in FC technology exploded (see Table 6). The last row shows the percentage of the total FC knowledge base that is embraced by the particular knowledge field.[6]

The table indicates that the large MNEs build on different FC-related competences and that this corresponds with their position in the FC value chain. As described above, BASF and Johnson Matthey are engaged upstream in the FC value chain; they build on their in-house capabilities within chemical and physical processes that are at the core of the FC technology. This is illustrated by the fact that BASF and Johnson Matthey are specialized in the knowledge fields that make up 29 % (see Table 6) of the FC knowledge, thereby indicating a high degree of technological relatedness to the FC knowledge base.

[4] It is not possible to calculate the specialization index for the other large MNEs or for the smaller FC system developers as their patent portfolio filed under the PCT during the years 1988-1992 was too small.

[5] The specialization index (S) is a measure that indicates a firm's technological specialization for a number of FC-related knowledge fields (see Tanner, 2011 for the methods in defining fuel cell related knowledge fields). S is calculated as $S_{jki} = (Pjk_i/Pj_T)/(Pwk_j/Pw_T)$ where Pjk_i = number of patents granted in knowledge field *i* (k_i) to firm *j* and Pjk_T = total number of patents applied for by firm *j*, and Pwk_i = number of world patents applied for in knowledge field *i* and Pw_T = total number of world patents.

[6] The knowledge base is defined by the co-occurrence of IPC-codes for all FC patents between 1993 and 2007. The percentage is thus an expression of the share of all FC patent applications that are co-classified with the particular knowledge field.

	FC knowledge base								
	Total FC-related knowledge base	Chemical and physical processes	Conversion of chemical energy into electrical energy	Cables, conductors, insulators	Electrolytic processes	Electrical vehicles	Ceramics, materials	Analyzing materials	Circuit arrangements, energy storage
Daimler	-	-	-	1.87	-	12.69	-	-	5.15
Siemens	-	-	-	1.32	-	6.29	-	-	4.98
BASF	1.45	2.42	-	-	2.13	-	-	-	-
Johnson Matthey	2.17	2.41	-	-	-	-	-	-	-
Shares of FC knowledge base 1993-2007	66%	29%	3.1%	4.3%	3.4%	2%	1.7%	1.4%	1.3%

Table 6: Specialization index for selected MNEs in a five-year period (1988-1992) before FC development took off. Source: OECD REGPAT December 2010. For definition and identification of FC knowledge base, see Tanner (2011)

Daimler had, on the other hand, strong technological advantages in electrical related knowledge fields, such as 'cables, conductors, insulators', 'circuit arrangements and energy storage', and 'electrical vehicles'. Dr. Jörg Wind confirms that Daimler had certain capabilities in electrical drive trains from its prior experiences with battery technologies but very little knowledge about electrochemistry and FCs in particular. Consequently, as Table 6 shows, Daimler had to enhance in-house competences (absorptive capacity) to be able to understand the technology.

The system integrators' vertical diversification is not caused by economy of scope but by a combination of changes in the external environment and the technology's immaturity. External changes in the firm's environment have mainly been induced by the current climate debate and the increase in stated objectives to reduce CO2 emissions. Such objectives foresee the need for great changes in the incumbent energy system and, consequently, in the markets, which large players like Daimler and Siemens cannot disregard. The most notable example is Daimler, where an increasing concern about the environmental consequences of ICE cars and, concurrently, an outlook for increasing environmental regulations has raised the need for substituting the ICE in the long run (Van den Hoed, 2007).

Another reason for the vertical diversification is the immaturity of the technology that has caused system integrators to invest heavily in technology development by diversifying upstream. This is consistent with Langlois' (1992) claim that vertical diversification may occur because the stage of production does not exist; that is, there is a lack of the 'right capabilities' to adjust to external changes. Together with the need to control and align incentives along the value chain (Teece, 1986), system-integrators have had to expand the boundaries of the firm upstream in the value chain regardless of the lack of a high degree of technological relatedness (economies of scope).

5 Conclusion

This paper set out to investigate the mechanisms through which regional branching into the emerging FC industry operate. The analysis was performed on a profile of regions (17 NUTS2 regions) representing 60 %

of all FC patents in Europe during the period 1993 to 2007. The largest patenting entities in the 17 regions correspond to a segment of the industry that may not be representative of the total population of firms in the emerging FC industry but a segment, nonetheless, that provides qualitative insight into the various types of actors that have initiated regional branching processes in the FC industry. In addition, our sample turned out to have firms well distributed along the FC value chain, which provides unique insight into the heterogeneity of the actors currently constituting the FC industry.

The results depict an industry that is dominated by large MNEs that diversify vertically along the FC value chain and by smaller dedicated firms that concentrate on developing and assembling FC systems. The dedicated FC system developers, with the exception of SFC Energy, had in fact been part of a firm diversification process before they were spun off or acquired. Hence, based on the sample of firms, firm diversification seems to be the dominating mechanism through which regional branching operates in the emerging FC industry. Although it is necessary to make certain reservations regarding the sample that may be biased toward large companies due to their greater propensity to patent, it seems to be a characteristic feature of the FC industry that it needs large players who are able to place large investments over long periods of time.

Secondly, the paper raised the question to what degree the underlying logic of regional branching builds on technological relatedness. The FC technology builds on a new knowledge base that draws strongly on electrochemical disciplines. According to Dosi's (1988) definition of a knowledge base, all of the firms in our sample build, to a certain degree, on pre-existing technological related resources with either an emphasis on the *electro* or the *chemical* part of electrochemistry. Whereas upstream MNEs have been stronger technologically related to the FC knowledge base, downstream MNEs have had fewer competences that were technologically related to the core principle of the FC. This partly confirms the technological relatedness thesis in the case of emerging industry, but it also stresses that regional branching relies on purposeful deliberate actions to deviate from the path (Garud and Karnøe, 2001).

Moreover, it has also become clear that building new technology-specific competences in the case of radical technology development requires knowledge that is new to the firm and, in fact, new to the world due to the radical nature of technology. It is still unclear to what extent this search occurs within regional borders in favor of the regional diversification process. There are some indications that the emerging FC industry experiences an early globalization (Arechavala-Vargas et al., 2009), which is not unusual for knowledge-intensive emerging industries (see e.g. Gertler and Levitte, 2005). It has been proposed (Murtha et al., 2001) that early globalization occurs because the knowledge requirements are so complex that they will unlikely be present within a single country or region. Hence, both small dedicated FC firms and large MNEs need to be internationally oriented, and they need to build channels of communication to knowledge sources located outside the region (Bathelt et al., 2004). Moreover, MNEs, as their name indicates, have an innate capability to act in multiple locations across national and regional borders. As a large number of MNEs have entered the FC industry, their inherited routine-based behavior of acting globally through a net of subsidiaries is passed on to the knowledge-producing activities within FC development.

Hence, there is a need to investigate the degree of *local vs. global* learning processes and how such processes may influence the regional branching of knowledge-intensive emerging industries. Such a study should include the indirect mechanisms of regional branching such as labor mobility, collaborative R&D work, social and professional networking, and university and research institutes. It would be of great interest to see more research on how these mechanisms affect regional branching processes and the extent to which these channels of knowledge diffusion are localized.

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