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The Geography of Emerging Industry: Regional knowledge dynamics in the emerging fuel cell industry

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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The process of researching and writing this thesis has been an unforgettable adventure into the world of academia, regional development, and, not least, the fascinating world of hydrogen and fuel cell technology. My initial interest in conducting the research presented here was triggered by a natural scepticism regarding the eager engagement professed by many regions across Europe that were promoting an extremely complex high-tech industry. The widespread regional interest in promoting hydrogen and fuel cell technology made me wonder: are regional authorities, by the means of cluster policy, able to build up a new industry? More fundamentally, what are the mechanisms underlying the emergence of new industries in certain regions and not in others? The goal of this thesis is to answer the latter question by taking a step back from regional policy goals and means and to attempt to understand some of the more fundamental localised mechanisms that drive the emergence of new industries.

These questions initiated a three-year journey in which I have had the privilege to learn from a large community of scholars in innovation studies and economic geography. I am extremely grateful for all the inspirational ideas, comments, and feedback I have received from senior scholars and junior fellows. In particular, my participation in such PhD courses as DIMETIC, Globelics Academy, and the International PhD Course on Economic Geography at Utrecht University has provided invaluable input to the achievements presented in this PhD thesis.

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CHAPTER 1
THEORIES AND CONCEPTS

1.1. Introduction

Emerging technologies are intriguing to many people because they are associated with new products that forecast changes for society and for everyday life. This fascination is not only the case for modern technology, such as the mobile cellular phone, computers or the Internet. The Danish author and Nobel laureate Johannes V. Jensen surrendered unconditionally when standing face to face with a contemporary steam engine at the World's Fair in Paris in 1900. As he wrote in his 1901 novel 'The Gothic Renaissance', "*No living being can comprehend the force in the cylinders of a steam engine, no one can imagine the greatness in the movement of the smooth piston rod...*" (Jensen, 2000). Although new technologies have also been met with scepticism, it seems that emerging technologies always have fascinated people by their inherent potential to change the world.

Hydrogen and fuel cell technology, which are the empirical focus of this thesis, are no exception. This technology has inspired fascination and optimism about its potential to change the world's energy systems. Hydrogen and fuel cell technology are attractive because hydrogen has the potential to replace oil and coal as the central energy carrier. A conversion of the energy system to hydrogen energy thus has the potential to increase energy security in terms of supply and price stability and to reduce polluting emissions, profiting both the local and global environment. Provided that hydrogen is produced from renewable energy sources, the societal benefits are both attractive and necessary in a world and economy that are characterised by instable energy supply and enormous environmental costs.

The development of new technologies also generates the potential to create new industries or disrupt existing ones (Dosi, 1984, 1988b, Day et al., 2000). While emerging technologies often are defined as science-based innovations (Day et al., 2000) emerging industries may be defined as a group of firms that explore and exploit the economic potential of an emerging technology. New industry development is motivated by the desire to create value out of technological potential, and this development may attract both new and incumbent firms. If technological potentials are realised and a new industry starts taking shape, new technologies not only have the potential to bring about great changes for society and for everyday life but also for the geographical distribution of economic activity. As new industries are associated with entrepreneurial activity, creating jobs, and increasing exports, new industries benefit the regions[1] where they are localised. Conversely, new industries may also disrupt existing industries and potentially cause economic decline in other regions.

For these reasons, emerging industries attract a good deal of interest from both policy and academia. Particularly in a globalised economy with strong competition between countries and regions, the interest in emerging technology-based industries has increased, as emerging industries are perceived as platforms for future economic growth in the geographical territory where the new industry is localised.

Consequently, regional authorities across the world design regional innovation policies intended to attract high technology industries to locate or develop within their borders. Such policies often results in regional strategies to develop ICT clusters, Medicon Valleys, or Hydrogen Communities. For instance, there is widespread regional interest in promoting hydrogen and fuel cell technologies in Europe, as well as in many other places around the world. In Europe alone, 40-50 regions (see, e.g., www.hy-ramp.org) have designed strategies to harness the economic and environmental potential of hydrogen and fuel cell technology. These regions design various policies, such as the promotion of R&D networks, public-private partnerships, demonstration projects, and public purchase initiatives to induce technological development and create first-mover advantages for their region.

While there is a good deal of research on the dynamics of the emergence of new industries in general, there is notably little theory to support regional strategies to promote the emergence of new industries (Feldman and Lendel, 2010, Kenney and von Burg, 2001). This scarcity is the research gap that this dissertation aims to address.

[1] Here and in the following section, ‘regions’ refer to districts or territories at the sub-national level.

In the field of economic geography, research questions about how new industries emerge and the degree to which their emergence are anchored in regional economies are less commonly studied than concepts of localisation economies. Consequently, there is little knowledge regarding where new industries emerge and why new industries emerge where they do. Therefore there is a need to establish a more rigorous research agenda that will elucidate some of the more fundamental elements that contribute to the creation of new industries. This thesis contributes to research in that direction.

The study is guided partly by the innovation system approach (Nelson, 1993, Lundvall, 1992, Cooke, 2001) and partly by the recent exploration of evolutionary ideas in economic geography (Boschma and Martin, 2007, Boschma and Frenken, 2006, Grabher, 2009). The innovation system approach underlines the importance of creation, use, and diffusion of knowledge in the current economy (Foray, 2004, Lundvall et al., 2002), but this approach also emphasises that the interplay of actors, networks, and institutions matters in innovation and thus in the development of new industries.

The evolutionary approach to economic geography draws strongly on evolutionary economics (Nelson and Winter, 1982) and builds on the idea of path-dependent economic development (Arthur, 1994, David, 1985 etc. in, Martin and Sunley, 2010, Martin and Sunley, 2006). Although it may be argued that the influence of evolutionary economics in economic geography is new and untested (Maskell, 2001), this approach has generated a series of new questions about regional economic development and the geographical context of industrial dynamics. The evolutionary turn in economic geography has thus stimulated questions regarding the origin and evolution of spatial economic phenomenon, such as clusters (Braunerhjelm and Feldman, 2006, Menzel et al., 2010, Menzel and Fornahl, 2010, Martin and Sunley, 2011), and as in this thesis, the spatial emergence of new industries.

This thesis is article-based and consists of an introduction (this chapter), three papers[2] (presented in Chapters 2-4), and a conclusion (Chapter 5). The purpose of this chapter is to frame the overall theoretical problem and to describe why this study is important and novel.

This chapter proceeds as follows: first, it is important to define the concepts of emerging industry and emerging technology and the often-intertwined relationship between them. Second, I highlight some of the most common approaches to studies of emerging industries in the field of economic geography and discuss

[2] Each paper has been written with the purpose of being published in different journals and hence vary in their writing style and outline to comply with the journals' styles.

their weaknesses in explaining the spatial emergence of new industries. Third, I include a section on the different evolutionary approaches of spatial emergence of new industries that have emerged in economic geography over the past three decades. Finally, I present the research questions that this thesis aims to answer and outline the structure of the thesis.

1.2. Conceptual framing

1.2.1 Emerging technology

Industries and technologies are concepts that are closely related and yet differ substantially. Technology has been defined by Dosi (1984, p. 14) as "a set of pieces of knowledge, both directly 'practical' (...) and 'theoretical' (...), know-how, methods, procedures, experience of successes and failures and also, of course, physical devices and equipment."

This understanding of technology is therefore not limited to the physical device Arthur (2009, p. 28) calls "a mean to fulfil a human purpose" but also encompasses disembodied accumulated competences and expertise of the state-of-the-art of the technology. Engineers and scientists draw on this body of knowledge when solving the technical issues that lead to new innovations.

A crude distinction is often made between incremental and radical technological change (Garcia and Calantone, 2002). Incremental innovations[3] occur continuously and are cumulative within technological trajectories (Nelson and Winter, 1982, Freeman, 1994, Dosi and Orsenigo, 1988). Radical innovations, on the other hand, often lay the groundwork for totally new products or processes, generating paradigmatic changes (Dosi, 1982, Dosi et al., 1988). Radical innovations are of a discontinuous nature and may spur the emergence of new industries that have the potential to disrupt incumbent firms and industries.

Theories of evolutionary economics teach us that technological change is the core driver of economic development (Nelson and Winter, 1982, Schumpeter, 1934). The conditions under which technological change takes place vary depending on the nature of technological change; whether incremental or radical. It is generally acknowledged within the evolutionary paradigm that firms advance technologically through a process of search and selection driven by a search for new profit and new markets (Nelson and Winter, 1982, Dosi, 1988a). This process is also observed for firms building on emerging technological paradigms;

[3] In the following section, I mainly consider innovation as technological change, although innovation is a much broader concept that also includes organisational changes, new business models and services; however, all of these innovation types are strongly connected, and the emergence of radical technological changes often brings about all types of innovations, including product, processes, organisational, and service.

however, radical innovations distinguish itself from incremental innovation because search and selection processes occur in the context of a general "*weakness of market mechanisms*" (Dosi, 1982, p. 155). By this, Dosi emphasises a fundamental difference in drivers between incremental innovation, induced by market mechanisms, and radical innovations being relatively autonomous from short-run adjustments to the economic system (e.g., changes in costs, prices, market shares etc) (Dosi, 1982). Instead, the selection environment for radical technological change is determined by other factors, such as the notional opportunities provided by scientific progress, underlying economic factors, such as feasibility, marketability and profitability, and different types and sources of institutional influence (Dosi, 1984). Moreover, the emerging phase rely heavily on experimental learning processes, which results in accumulation of scientific and applied knowledge in firms, universities, and research institutes. This accumulation means that the presence of risk-taking actors, who are willing and able to implement and exploit an emerging technology, is crucial for the development of new industries (Dosi, 1982).

In reality, a complex set of variables develops interdependently under the influence of history and the nature of the given technology. For instance, circumstances that may trigger the emergence of one particular technology may not have a similar influence on other technologies. This concept can be illustrated by drawing a parallel between Dosi's study on the emergence of the semiconductor industry and the hydrogen and fuel cell technology in the 1950s and 1960s. Dosi (1984, p. 71) summarised the institutional influence on the semiconductor industry as follows: "...institutional intervention (mainly military and space agencies) performed in the USA a powerful focusing role which directed the accumulation of knowledge and expertise and helped the emergence of precise technological trajectories."

Hydrogen and fuel cell technology received similar interest from NASA's space programmes in the 1950s and 1960s, but this *intervention*[4] did not bring about a large commercial breakthrough for fuel cell technology. The opportunity conditions (Malerba and Orsenigo, 2000) for fuel cells were too low, and the scientific knowledge base may have been too immature to make fuel cells competitive with incumbent alternatives, e.g., the internal combustion engine, stationary power stations, or batteries. Institutional intervention is contextual, and its impact depends on the emerging technology and how it interacts with the other

[4] While the military did not pay much attention to fuel cell development in the West at this time, in Soviet Union the military engaged in developing fuel cell systems for submarines.

variables of scientific progress and the technology's feasibility, marketability and profitability.

The perspective is different for fuel cell technology today. Major scientific progress has been achieved in such knowledge fields as material science, chemistry, and nanotechnology, which form part of the current fuel cell knowledge base. This development has enabled a much wider breadth of notional possibilities to be provided by science within the emerging paradigm, enhancing the feasibility of the technology and thus of the opportunity conditions. Also, the institutional influence has changed, thereby resulting in a greater need for alternatives to incumbent energy technologies. This shift has increased the potential marketability and profitability of fuel cell technology. Developments, however, are still dependent on the presence of risk-taking actors who are willing and able to engage in the emerging fuel cell technology. This dependence takes me to the other core concept of this thesis, the 'emerging industry'.

1.2.2 Emerging industry

As has become evident in the previous section, technology and industry are strongly connected in the evolutionary economic understanding of technological change. According to Essletzbichler and Winther (1999), an emerging technology is defined by purposeful organisations that seek to exploit its economic potential. The early risk-taking actors who explore and exploit a new technological paradigm's possibilities are defined in this thesis as an emerging industry; however, a number of issues related to the definition of emerging industry are discussed in this section.

In industrial organisation economics, an industry is usually defined as a group of firms that produce closely substitutable products to a market (Porter, 1980, Forbes and Kirsch, 2010). This definition has been criticised for a number of shortcomings. First, the definition does not include the dynamically changing network of horizontally and vertically related firms that often share common competences (Bettis, 1998), and it disregards other potential competitors that may produce non-substitutable products (Sampler, 1998). In emerging industry, however, this definition's major shortcoming is that an analytical focus on products and firms are of little use in understanding innovation (Abernathy and Utterback, 1978), as the products do not exist yet, and firms are not the only actors involved in this early process.

Nevertheless, Porter's (1980) acknowledgement of the controversy related to defining industries in practice also applies to the emerging fuel cell industry.

Because there are several different types of fuel cells,[5] and each of these has specific characteristics that make it particularly suitable for a different end-product application, one could argue that these products cannot be categorised in a single industry. As, however, the different types of fuel cells are largely built on the same scientific principle (and hence on the same knowledge base), fuel cell technology is in this thesis perceived as a unifying technology group for all types of fuel cells. This categorisation is in line with Bettis's (1998, p. 359) alternative definition of an industry as "business units with similar capabilities". Consequently, the term 'emerging fuel cell industry' refers to a group of firms that base their businesses on fuel cell technology, regardless of the specific type of fuel cell.

Another definitional puzzle is related to the interface between traditional industry boundaries and emerging radical technological change. In such cases, the new activities related to developing the emerging technology become the point of exchange (Munir and Phillips, 2002), and the contour of a new industry emerges, consisting of newcomers and incumbents. Munir and Philips (2002) introduce the concept of an 'activity network' to comprehend this type of competitive environment; however, the meaning of the term 'activity network' is too generic and thus too imprecise. The concept of 'emerging industry' expresses both that the key actors are firms and that the competitive parameters are somewhat different from mature industries. The latter term is consequently preferred here.

In Abernathy and Utterback's (1978) seminal work, the emerging industry is characterised by a 'fluid pattern of product changes' with high levels of diversity and uncertainty. The fluid phase is characterised by *extraordinarily high* levels of uncertainty in the direction of search, expectations for the technology, identification of main players and the strategic orientation in approaching markets (Dosi, 1988b, Utterback, 1996). The length of the emergent phase, during which the company must survive with little or no sale in the market, is uncertain and is highly unpredictable (Rogers, 1995, Fagerberg, 2005).

A final issue that is key to understanding 'emerging industry' is that the term in itself implicitly indicates development towards a full-grown mature industry; however, this growth is far from given. An emerging industry may never grow into a mature industry. This uncertainty is the risk early actors take on when entering a new technology area. In the case of the emerging fuel cell industry, this risk is very real. In particular, fuel cell technology's dependence on hydrogen

[5] Fuel cells are categorized based on the type of electrolyte by which they function. For example, a solid oxide fuel cell (SOFC), the electrolyte is solid and made of ceramic. In a 'proton exchange membrane fuel cell' (PEMFC), also known as the polymer electrolyte membrane fuel cell, the electrolyte is made of polymers.

technology has raised questions about the feasibility of a 'hydrogen economy' and hence about the importance of fuel cell technology. The major concerns are related to the inefficient production of hydrogen from renewable energy sources and the difficulties of storing hydrogen under high pressure. Nevertheless, the emerging fuel cell industry still attracts immense interest from industry actors and research communities that are optimistic about the technology's potential.

1.3. Economic geography and studies of industry emergence

1.3.1 The temporal scope of industry emergence

As Abernathy and Utterback (1978) pointed out, emerging industries are difficult to study because they are challenging to identify and track until after their products appear on the market. This hindrance is associated with a lack of adequate data. For example, industrial classification schemes (e.g., SIC, NACE), which have been developed based on existing industry groupings, are problematic in studies of emerging industries.

It has recently been argued that scholars tend to stop asking questions about phenomena that are hard to study empirically, such as the emergence of industries (Forbes and Kirsch 2011). This aversion may also be why industry emergence has received so little attention in the field of economic geography; however, the reason may also be found in the temporal scope of most industry studies within economic geography. There seems to be a blind spot in the field of economic geography, as well as in many other disciplines (Forbes and Kirsch, 2010), regarding asking questions about the emergence of new industries.

Forbes and Kirsch (2010) illustrate how different types of studies may be categorised according to their temporal scope in relation to two time points: 'industry founding' and 'the end of the emergent stage' (see Figure 1.1). These authors' main point is that most studies of emerging industries fall within Interval A, which begins with the emergent period and extends through later periods. Forbes and Kirsch claim that fewer studies focus on the remaining intervals, such as Interval B, which focuses on the emergent period, Interval C, in which focus is on the emergent periods, as well as preceding periods, and Interval D, which extends through all three periods.

This bias can be illustrated by Gort and Klepper's (1982) use of the industry life cycle (ILC), in which they distinguish between two steps in product innovation that characterise emerging industry. The two steps are "the technical development of a new product and the introduction of the new product into the market" (Gort and Klepper, 1982, p. 630). Although the time prior to market introduction is often recognised in ILC-studies, this period is almost just as often neglected in the actual analysis, as in the study by Gort and Klepper (1982, p. 630): “Our analysis begins with the second step when the new product is introduced into the market.”

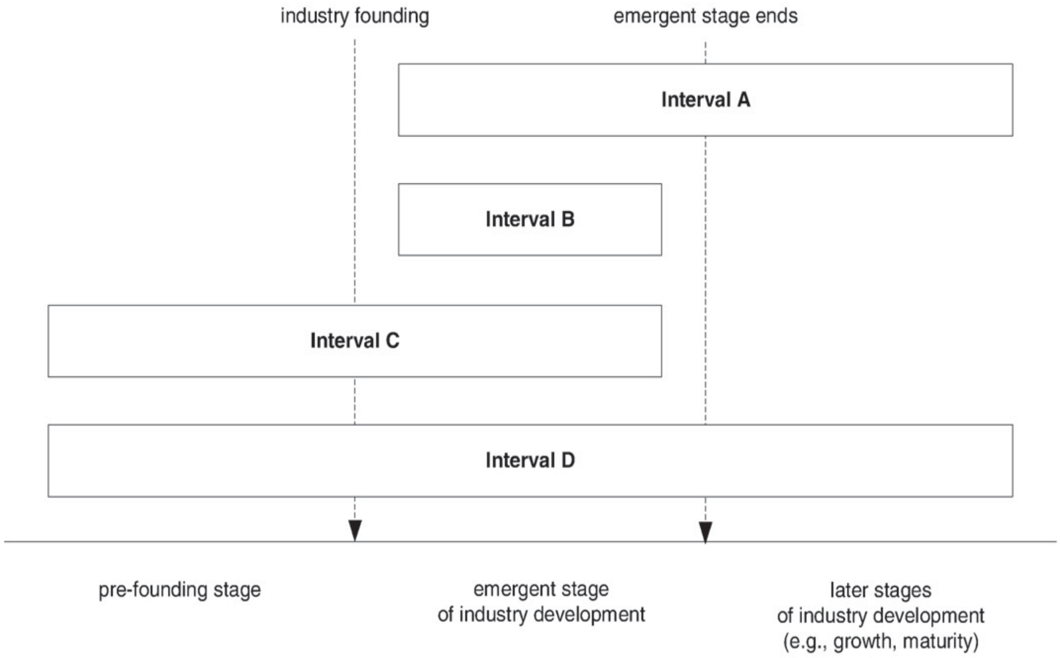

Figure 1.1: Alternative temporal intervals associated with theories of industry emergence, (Forbes and Kirsch, 2010)

Additionally, there has been a notable lack of attention in economic geography to periods that precede the conventional industry life cycle, or in terms of evolutionary economics: the period during which the emerging technological paradigm is developed ‘under a general weakness of market mechanisms’. In the following section, I discuss this tendency more thoroughly.

1.4. A lack of attention towards industry emergence

Most of the economic geography literature focuses on localised learning and agglomeration externalities framed by concepts such as industrial districts, clusters, innovative milieu, and regional innovation systems (Asheim et al., 2011). Core questions in industry emergence, such as ‘How do industries come into being?’ and ‘To what extent is industry emergence embedded in geographical territories?’ have received little attention in comparison. Only recently, with the *evolutionary turn* (Boschma and Martin, 2007, Boschma and Frenken, 2006, Grabher, 2009) in economic geography, scholars have began to pay attention to the origin and early evolution of industries (Boschma and Lambooy, 1999, Storper and Walker, 1989) and particularly to the emergence of clusters (Braunerhjelm and Feldman, 2006, Menzel et al., 2010, Martin and Sunley, 2011).

Clearly, several different emerging industries have received attention in economic geography (see, e.g., Feldman and Lendel, 2010, Feldman, 2003, Dahl et al., 2010, Zucker et al., 1998, Zucker et al., 2007), but they have mostly been studied through the lens of clusters (Braunerhjelm and Feldman, 2006, Menzel et al., 2010, Menzel and Fornahl, 2010) or the 'industry life cycle' (see, e.g., Audretsch and Feldman, 1996a, Neffke et al., 2011b). I will argue, however, that because of their inherent temporal focus on industry development after the founding stage, both approaches face difficulties in grasping the essentials of how new industries come into being.

First, cluster studies clearly fall within Interval A in Figure 1.1, as the earliest firms to enter an emerging industry area would not qualify as clusters: geographical concentrations of firms from related industries that benefit from a common pool of skilled labour, specialised suppliers, and knowledge externalities (Porter, 1990). Clusters are spatial economic phenomenona that are much more narrowly defined than industry and *appear* at a later time than the industry itself. Hence, industry emergence falls outside the analytical scope of cluster studies. Clusters may still be an essential component in the economic evolution of industries, but it is necessary to go beyond the concept of clusters in order to appreciate industry emergence in its geographical context.

The ILC perspective is another approach that has been employed in economic geography-studies of emerging industries, which also belongs to Interval A in Figure 1.1. The use of ILC in economic geography has, similar to its application in other fields (Forbes and Kirsch, 2010), a tendency to focus on the part of early industry development that begins with commercialisation. Also, the pre-commercial phase, which tends to be both lengthy and costly, is often not included in such studies (e.g., Neffke et al., 2011b, Audretsch and Feldman, 1996b).

From the ILC approach in economic geography, we learn often-stylised facts about what distinguishes the fluid phase of industry evolution from later and more mature stages. For example, the propensity of innovative activity to geographically cluster is higher at the early stage of the ILC (Audretsch and Feldman, 1996a), and young industries benefit more from Jacobs' externalities (Neffke et al., 2011b, Henderson et al., 1995). Such insights may be useful in understanding the conditions underlying emerging industries, but there are yet other underexposed aspects of industry emergence belonging to what Forbes and Kirsch (2010) have termed the pre-founding stage of an industry. These aspects call for studies with a temporal scope that extends backwards to include some period of time prior to what we generally perceive as the boundaries of an emerging industry.

It is the objective of this thesis to study the origin and early evolution of the emerging fuel cell industry (Interval C in Figure 1.1). Consequently, the temporal and spatial scope of this thesis comprises what we could call a pre-cluster stage, i.e., the location where an industry first appears but does not necessarily develop into dominant places characterised by localised increasing returns effects. This growth may occur eventually, but a nascent industry may also wither away or relocate to more fertile ground. In both cases, there is a theoretical interest in understanding the early processes of industry emergence or industry failure. The next section presents and discusses the integration of evolutionary economics into the field of economic geography and its implications for understanding industries' emergence.

1.5. An evolutionary understanding of spatial industry emergence

The evolutionary economic paradigm offers an explanatory perspective that includes the emergent phase of industry development. This integration of evolutionary economics into economic geography has stimulated questions about the spatial emergence of economic phenomena (Boschma and Lambooy, 1999, Storper and Walker, 1989), as well as about other related matters, such as the role of the firm in economic geography (Maskell, 2001), regional resilience (Hassink, 2010), and cluster life cycles (e.g. Menzel and Fornahl, 2010, Ter Wal and Boschma, 2011). This section presents two models that build on an evolutionary understanding of the spatial emergence of new industries: first, the geographical application of path dependence, as introduced by Arthur (1994), and second, the model of windows of locational opportunities (Boschma and Lambooy, 1999, Storper and Walker, 1989). The major assumptions of the models are discussed in relation to other perspectives on path dependence in the emerging field of evolutionary economic geography (Martin and Sunley, 2006, Martin, 2010). Finally, the gap in the literature, which this thesis aims at addressing, is outlined. This section is not meant to be a complete account of evolutionary understandings of industry emergence in economic geography, nor is it an account for the complete sources of literature the subsequent chapters build on. Rather, this section presents the general discussion in the literature to which this thesis aims to contribute.

1.5.1 Path dependence

A concept that has played a central role for the evolutionary turn in economic geography is path dependence (Arthur, 1994, David, 1985), which is key to understanding technological and industrial development in evolutionary economics. According to Martin and Sunley (2006, p. 399) "a path dependent process or system is one whose outcome evolves as a consequence of the process’s or system’s own history.” Path dependence is born of the view that the opportunities of today are formed by decisions made in the past and that the technology or system exhibits strong features of irreversibility. This concept also recognises that even small events or decisions made in the past can have a decisive impact on how a system or a technology develops and may consequently affect the range of later opportunities (Arthur, 1994). Hence, path dependence is closely related to the concept of lock-in, which describes a situation in which a development process is locked, or constrained, to a given technological paradigm because of decisions made in the past.

Arthur (1994) has applied the concept of path dependence on regional economic development by simulating three types of locational processes. Arthur’s first model builds on the deterministic assumptions of traditional economic geography in which the geographical distribution of resources is the only factor determining an industry’s location. In this model, a firm’s choice of location does not affect other firms’ choices of location.

The second model is framed as a ‘pure chance’ model in which the only mechanism driving regional formation of an industry is spinoffs. It is assumed that new firms stay in their parent location and that every firm, including the new spinoffs, has a certain probability of spinning off a new firm. The result is highly unpredictable and shows a high degree of path dependence with industry location; every time the three-region simulation model is run, the location pattern changes. Arthur concludes that *history* is the determining factor for industry location. In this model, “history” is the initial conditions in the region that originates the spin off firms, which is the number of initial firms.

Arthur’s third model builds on the assumption of ‘location under agglomeration economies’. This term means that the more firms that end up in one location ‘by chance’, the higher the probability that the next firm will be found in the same region. This phenomenon results in a concentration of firms in one region that outperforms other locations. The choice of favoured location for later firms depends on the initial location pattern of the early firms, which, according to Arthur’s model, is determined equally by chance and by the attractiveness of the region that the first firms enter. Hence, the fundamental principle in Arthur’s two latter models is that ‘small events’ at different points in history decide the regional formation of industry. Thus, the location of new industries becomes unpredictable (Arthur, 1994).

Arthur’s ascription of so much explanatory power to random, small events in a highly simplistic simulation of economic development has drawn criticism (see, e.g., Martin, 2010, Boschma, 2007). This criticism can be summarised in three points (Boschma, 2007). First, Arthur's models completely neglect evolutionary industrial dynamics; for example, he does not account for the fact that firms are heterogeneous in terms of size, resources, and strategic goals at different points in time. Second, the models do not take into account possible negative lock-in in the regional economy, which may manifest itself in higher costs, inadequate knowledge resources, and institutional inertia that may hinder future regional economic development (Hassink, 2010). Third, the models do not incorporate an understanding of geographical, contextual factors that may influence the spatial emergence of new industries (Martin and Sunley, 2006, Boschma, 2007). In other words, Arthur's models provide a *one-way* account for how new industries shape regional path-dependent development, but they fail to integrate feedback mechanisms from pre-existing regional economic structures.

1.5.2 Window of locational opportunity

Another branch of the literature that to some extent assumes that new industries form space, and not the other way around, is the window of locational opportunity (WLO) (Storper and Walker, 1989, Scott and Storper, 1987). The WLO model is an attempt to understand why new industries locate in new places and cause 'old industrial regions' to decline. Storper and Walker argue (1989) that because the input requirements of a new industry in terms of labour skills, materials, machines, parts and equipment is rarely met by pre-existing locational conditions, firms have *locational freedom* - the opportunity to choose their own locations. The period during which firms experience locational freedom is termed the 'window of locational opportunity'.

Once a firm has established itself in a given region, it is tied to its location by fixed investments, established relationships to other actors and training of its employees (Storper and Walker, 1989). Hence, the WLO model claims that the initial location of a firm, whether it is caused by a short-term strategic choice or an accidental event, structures the spatial landscape. The more firms that choose a specific location and the more these firms create their own unique locational conditions by interacting with their local surroundings, the narrower the window for new locations becomes.

The WLO approach has been extended and refined by Boschma and Lambooy (Boschma and Lambooy, 1999) Boschma and van der Knaap (1997) and again by Boschma (2007). In these modifications, evolutionary concepts, such as chance, selection environment, and increasing returns (agglomeration economies), become more pronounced. The selection environment is excluded because of the disparity between the requirements of the radical new technology and the production structure of regions; chance, on the other hand, plays a significant role, albeit not as much as in Arthur's model, and increasing returns play a role after the industry has emerged and the window starts to close.

The principal expansions on the WLO model place a greater emphasis on possible generic parameters, such as general knowledge, skills, suppliers of services, and urbanisation economies, which may influence the location of new industries. Boschma and Lambooy (1999) distinguish between generic and specific factors. Specific factors (i.e., specialised inputs) are not considered important because of the wide gap between the requirements of an emerging industry and the resources of a region at a given time. Furthermore, generic resources are typically present in a large number of regions and consequently cannot decide the emergence of new industries.

As a consequence of poor explanatory power of regional resources, both the early and later version of the WLO model assign greater explanatory power to human agency (Boschma and Lambooy, 1999, Storper and Walker, 1989), arguing that the firm creates its own locational conditions and that this process depends on the creative ability of the firm to turn generic resources into specific assets (Boschma and Lambooy, 1999). This ability also includes encouraging the development of specialised educational and other supportive institutions (Storper and Walker, 1989). The more successful human agents are in creating specific knowledge assets from generic resources, the more attractive the region becomes to later entries. Hence, as the window narrows, the early evolution of the industry becomes more and more driven by localisation economies (increasing returns).

1.5.3 Alternative evolutionary perspectives on spatial emergence of industry

The WLO model is appealing because it accounts for the idea that regional economic development is neither deterministic nor static. Relatively less developed regions may generate new industries that cause the region to leapfrog old industrial centres; however, the fundamental assumptions of this model concerning relative spatial independence and the role of chance events have been criticised.

The two assumptions regarding locational freedom and chance are highly related, as is seen with the introduction of generic resources as a possible explanatory factor for the localisation of emerging industries. In contrast to Arthur's model, generic resources constrain the role of chance because firms do not develop entirely independently of local resources. As Boschma frames it,

> ”...the WLO model enables us to determine empirically the extent to which chance influences the spatial outcome: the more potential locations can be identified empirically, the lower the degree of predictability, and

> the more open the windows of locational opportunity are" (Boschma, 2007, p. 45).

Accordingly, chance events become important when the generic resources are plentiful and located in multiple regions. Conversely, when relevant generic resources are scarce (only present in few locations), the role of chance in the locational process of emerging industries is much smaller.

Nevertheless, the WLO model has been criticised for the relatively large share of the explanatory power it ascribes to accidental events and for its inadequate emphasis on contextual and causal factors (Martin and Sunley, 2006). Martin and Sunley (2006) and Martin (2010) propose a different interpretation of path dependence that allows for stronger interdependence between paths in regional economic development:

> "The emergence of a new local industry may not be due to 'chance' or 'historical accident,' but may be stimulated or enabled—at least in part—by the preexisting resources, competences, skills, and experiences that have been inherited from previous local paths and patterns of economic development." (Martin, 2010 p. 20)

The path-dependent process in Martin's (2010) interpretation thus becomes a path-enabling process in which new paths are made possible through entrepreneurial activities that build on localised resources. According to Martin and Sunley (2006), new industry development shape the economic landscape, but the place where a new industry emerges strongly influences the path-dependent development of an industry. Martin and Sunley argue that because many mechanisms underlying path dependence have an inherent local dimension, the process of industry emergence is place-dependent. Consequently, Martin and Sunley (2006) and Martin (2010) advocate for a model wherein localised knowledge resources play a greater role than in the WLO model, reducing the role of chance as a driver of industry emergence.

In sum, the conceptualisation of the spatial emergence of new industries has caused a dispute in the emerging field of evolutionary economic geography. On the one hand, the WLO model argues that firms in newly emerging industries experience relative locational freedom and can choose their location among a number of regions with generic resources. On the other hand, a reinterpretation of path dependence perceives a stronger interdependency between regional industrial paths. This interdependency is also seen in the emergence of industries.

The latter perception of path dependence has been applied to studies of regional economic development with incremental evolution of regional industrial structures (Neffke et al., 2011a). Neffke et al. (2011a) demonstrate that regions diversify in a relatively coherent path over time, confirming that the paths are interdependent. This path-dependent development is induced by spillover of localised knowledge, which is enhanced by cognitive proximity (technological relatedness) between industrial paths in a given region (Boschma and Frenken, 2011a). Accordingly, regions with high degree of 'related variety' (Jacobs, 1969) in their economic activities support a higher degree of knowledge spillover, which, in turn, enables economic growth (Frenken et al., 2007). Related variety is thus one measure of the cognitive proximate relationship between industrial paths in a given region; however, in the case of radically new industrial paths, it remains to be determined whether the emergence of the new industry depends on pre-existing paths or if the new industry experiences locational freedom from pre-existing economic structure.

Framed differently, the dispute in the emerging field of evolutionary economic geography hinges on the degree to which cumulative knowledge influences the creation of new technological paradigms (Dosi, 1988b) and to what extent this process is localised or occurs relatively independent of the spatial industrial structure. The more explanatory power is ascribed to regional knowledge dynamics and human agency, the less importance need to be assigned to chance.

1.6. Research objectives

Based on the above theoretical and conceptual considerations, the overall purpose of this thesis is to examine the extent to which industry emergence is embedded in geographical territories.

The objective is to increase our understanding of the spatial relationship between pre-existing knowledge resources and the creation of new economic variety. In other words, the role regional knowledge dynamics play in the emergence of new industry. Hence, this thesis focuses on the geographical context of industry emergence that builds on radical technological changes.

This research has been approached in several different ways, which I will account for on the following pages. The thesis is article-based, and the different papers relate to the overall objective in different ways. The two first papers (Chapters 2 and 3) focus on the accumulation of knowledge in specific locations in Europe and examine possible drivers of this accumulation. The final paper (Chapter 4) examines the risk-taking actors who are willing and able to implement and exploit the radical fuel cell technology. All of the papers explore where fuel cell development takes place and how we can understand the drivers of this early localisation of a young industry.

Chapter 2 is an exploratory investigation of the relationship between broad, generalised measures of regional economic activity and hydrogen and fuel cell demonstration activities. The findings of this study are somewhat preliminary in nature and served as a stepping-stone to the research in Chapter 3 and Chapter 4. Chapter 3 and Chapter 4 follow a more explanatory approach, applying evolutionary economic geography to the problem. Chapter 3 is a systematic investigation of the relationship between regional knowledge bases and the knowledge base of the emerging fuel cell industry. Chapter 4 examines the industrial dynamics underlying different types of regional diversification processes.

Chapter 2 also deviates from Chapter 3 and 4 in other dimensions, including its empirical focus and data sources. In Chapter 2, both hydrogen and fuel cell data is included, whereas the latter two chapters only focus on fuel cell technology. This distinction is further explained below.

1.6.1 Data sources

All of these papers evince an interest in studying the emerging (hydrogen and) fuel cell industry and identify the regions that are highly engaged in this emerging technology field. As has been noted earlier in this chapter, emerging industries are difficult to identify and track because these are not covered by any industrial classification schemes. Likewise, these industries create few commercial products[6]; most products are considered to be prototypes. Consequently, this thesis builds on two other data sets that measure knowledge production within the emerging technology.

The first paper builds on data collected in the European Integrated Projects Roads2HyCom.[7] These are data on a) hydrogen and fuel cell demonstration projects, b) hydrogen fuelling stations, and c) 'Registration of Interest' for communities to undertake large-scale hydrogen and fuel cell projects and innovative applications. Hydrogen and fuel cell demonstration activities together with hydrogen fuelling stations are indications of 'learning by doing' and represent the first practical learning examples involving the technology outside of laboratories. The Registration of Interest indicates a high level of political support or interest groups that favour the new technology. Based on these data, we

[6] The fuel cell products in the market include backup power solutions for telecom and leisure markets. Nevertheless, no company made a profit by the end of 2010 (Wesoff, 2011) from fuel cell products, which indicates that sales are low, while R&D expenses and other costs are still notably high.

[7] According the homepage of Roads2HyCom, "The Roads2HyCom project is a partnership of 29 stakeholder organisations supported by the European Commission Framework Six programme. The project has studied technical and socio-economic issues associated with the use of Fuel Cells and Hydrogen in a sustainable energy economy by combining expert studies in technology status, energy supply and socio-economics with an active programme of engagement with key stakeholders, especially early adopters of the technologies." www.roads2hy.com

calculated a total score for each European region's activity in hydrogen and fuel cell technology. The nature of the data made it unfeasible to distinguish between hydrogen and fuel cell technology activities. Although the Roads2HyCom data do not provide a complete picture of hydrogen and fuel cell knowledge production in Europe, these data seemed to be the best available at the time and provided a broad idea of where hydrogen and fuel cell experimental learning is located.

The Roads2HyCom data, however, are not necessarily a good measure of where the preceding knowledge production has taken place, as the demonstration and fuelling station sites are often located far from where the technology has been developed. For example, many remote islands have hosted such demonstration activities, including Utsira in Norway, the Outer Hebrides in Scotland and Kythnos, Greece (see also Madsen et al., 2006). Such projects may bring several local and international industrial partners and public actors, such as national and regional authorities, universities, and research institutes, together in one project, making it hard to disentangle sources and receivers of knowledge not alone their location. Furthermore, these data were only available as a static variable last updated in 2007. Regardless of these shortcomings, the Roads2HyCom dataset provides unique insight into where experimental, practical learning activities take place.

The data source that forms the basis for the analysis in the two remaining papers is the more recent OECD REGPAT database. The OECD REGPAT is a comprehensive attempt to locate patent data to the regional levels of NUTS3 (for Europe) and Territorial Level 3 (for all OECD countries). The patent data allows defining fuel cell knowledge production rather narrowly (as is described thoroughly in the method sections of Chapters 3 and 4) and is considered a better indication of where economically valuable knowledge production takes place than the more practical learning indicators used in Chapter 2. Another advantage of the patent data is that these data make it possible to conduct longitudinal analysis of the development of fuel cell knowledge production.

The two data sources are compared in Figure 1.2. While the patent data are mostly represented in western parts of central Europe, northern Europe and in the United Kingdom, the hydrogen and fuel cell demonstration activities are much more dispersed across Europe.

Figure 1.2 confirms that many of the outskirt regions score high on practical demonstration activities, even when the technologies have been developed in other places. Hence, the localisation of patent activity, as measured by where the inventors live, is a more precise measure for where economically valued knowledge production takes place.

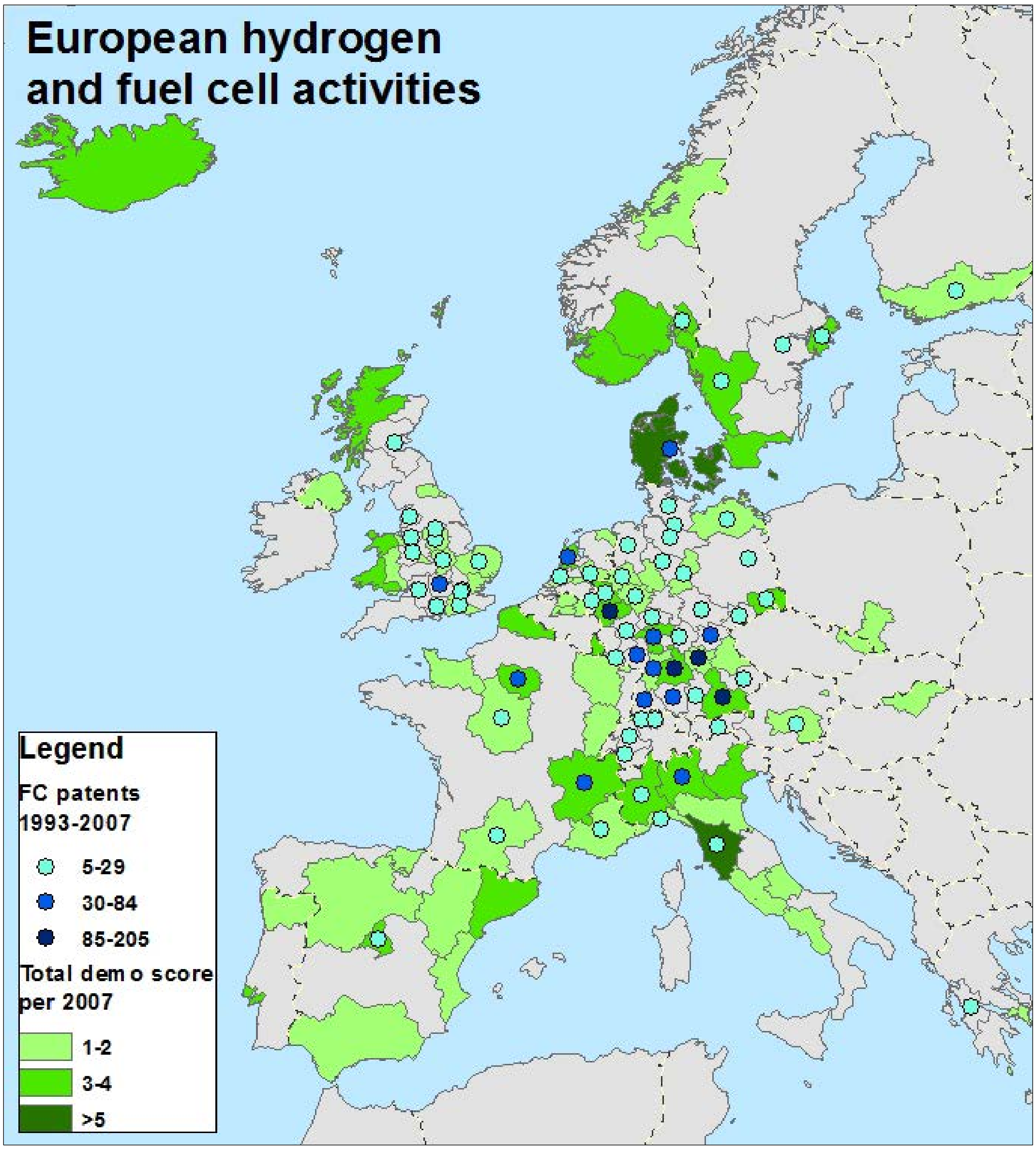

Figure 1.2: Comparison of hydrogen and fuel cell demo-activities with fuel cell patent activity
Source: Roads2hycom-data for demo-score and OECD REGPAT, December 2010 for patents

Patent statistics

The majority of the findings in this thesis build on patent statistics, which has often been criticised for being a weak proxy for innovation. Patents can be problematic measures of economic activities in relation to innovation, but patent data certainly also have several advantages in relation to the purpose of this study; measuring knowledge production.

The most obvious fault is that patent applications only reveal knowledge that is patentable. According to Dosi's definition of a technology's knowledge base it is “the set of information inputs, knowledge, and capabilities that inventors draw on when looking for innovative solutions” (Dosi, 1988, p. 1126). Consequently, relevant knowledge is much broader than what is mirrored in patent data and includes tacit knowledge such as experiences of successes and failures, and knowledge about procedures and methods. Conversely, in the lack of a more appropriate and accurate data source, patent data are argued to be a relatively good indication of the level of knowledge production.

Furthermore, if we accept that patents are a relatively good proxy for knowledge production, the question remains if all patentable knowledge is patented. In the case of fuel cells it is argued in Chapter 3 that patents are a very common mean for companies and universities in protecting their assets, and thus, perceived to be a good proxy for fuel cell knowledge production.

Griliches (1998) argues that there are two further problems with using patent statistics for economic analysis. The first is of a technical character and is related to the allocation of patent data to economically relevant industry or product groups; however, this allocation has not proved as problematic for the emerging fuel industry as it often is when one allocates patents to more mature industries. Fuel cell patents have been categorised using the International Patent Classification system, which in 1974 introduced the IPC-code ‘H01M008’ for ‘fuel cells and manufacture thereof’ at the main group level (7 digits). The narrow definition excludes other types of electrochemical cells, e.g., batteries.

The second problem Griliches (1998) refers to is that patents differ qualitatively in terms of their technical and economic significance. This point of critique also applies to the studies carried out in this thesis, as I do not distinguish patent applications based on suggested quality measures like citations or attempt in any other way to measure their impact; however, the purpose of the research carried out here is not to identify the most influential pieces of knowledge but rather to detect where and to what degree different locations have been involved in knowledge production within the emerging fuel cell paradigm. Consequently, the rate of patent applications is a satisfactory proxy, despite the faults in these data.

1.7. Outline of the thesis

The remainder of the thesis consists of four chapters. The first three chapters present inquiries into the spatial nature and embeddedness of hydrogen and fuel cell technology and industry development. These chapters are based on papers that belong to different stages in academic publishing: the first paper was published in Energy Policy and is co-authored with Per Dannemand Andersen; the second is a single-authored working paper published in the working paper series Papers in Evolutionary Economic Geography (PEEG) at Utrecht University, and the third is also a single-authored working paper awaiting publication. The final chapter unites and discusses the findings of the three papers, as well as the questions for further research that arose from this work.

Chapter 2

The first paper builds on the broader theoretical framework of innovation systems and explores the relationship between regional (Cooke, 2001) and technological innovation systems (Hekkert et al., 2007). The paper asks whether geographical and cluster aspects matter in the establishment of a European hydrogen energy technology innovation system. The analysis investigates the relationship between regions with high levels of hydrogen and fuel cell demonstration activities (in terms of demonstration sites, hydrogen fuelling stations, and registration of interests to become hydrogen community test site in Europe) and three elements that are considered to play a role in inducing a high level of demonstration activities:

- Pre-existing hydrogen infrastructure and hydrogen production sites
- Generally innovative regions (according to the Regional Innovation Scoreboard)
- Existing industrial clusters in Europe (according to the European Cluster Observatory)

The paper concludes that hydrogen and fuel cell activities are not equally dispersed across Europe; instead, they are clustered in a number of regions. We find a positive relationship between regions that are generally perceived as high-functioning innovation systems and a high level of hydrogen and fuel cell activities. Finally, the paper confirms a positive relationship between certain types of industrial clusters and hydrogen and fuel cell activities. Most noticeably, this result seems to confirm that highly innovative regions engage in hydrogen and fuel cell activities, as it is mainly high-tech innovative clusters that are co-located with high levels of demonstration activities. In clusters that are found to be related to the hydrogen fuel cell technology, the relationship is particularly strong for chemical products, power generation, production technology, oil and gas, and automotive and aerospace technology. In contrast, the study determined no relationship to specific pre-existing knowledge assets within hydrogen production and infrastructure facilities. Consequently, the paper calls for more studies of the interdependency between the pre-existing industry in a region and the potential for developing hydrogen and fuel cell clusters. The paper recommends regional innovation policy makers to consider interplay with the local industry when developing regional hydrogen and fuel cell initiatives.

Chapter 3

The first paper's initial findings on the relationship between hydrogen and fuel cell activities and pre-existing industrial clusters gave rise to a more systematic analysis of this relationship in Chapter 3. Chapter 3 limits the empirical focus to fuel cell technology development (measured by fuel cell patent applications), its geographical localisation, and its relationship to the regional knowledge base. The paper is an investigation of the proposition in evolutionary economic geography that new economic variety is place-dependent. The paper argues that because of the localised nature of knowledge spillover (Audretsch and Feldman, 1996b, Feldman, 1999, Jaffe et al., 1993, Anselin et al., 1997), regions with knowledge bases technologically related to the emerging knowledge base of fuel cell technology are more likely to branch into fuel cell technology development. The unit of analysis is the European NUTS 2 region, and the argument is examined through an econometric test. To this end, I use a negative binomial regression model with fixed effects on a dynamic panel dataset covering the years 1992-2007. The analysis points toward specific technologically related knowledge fields that are significantly co-located with fuel cell development; perhaps more interestingly, the analysis suggests that the higher the degree of technological relatedness present in a given region, the higher the probability that a region will branch into the emerging field of fuel cells. These findings corroborate the evolutionary thesis that new technology development is place-dependent, including the case of radical technological change.

Chapter 4

Chapter 3 does not shed light on the mechanisms underlying the regional emergence of a new technology path. These mechanisms are the focus of Chapter 4. In evolutionary economic geography, it is proposed that regional diversification occurs through firm diversification, spinoffs, labour mobility, and social networking, all of which function as channels for knowledge spillover. This paper aims to investigate which of the mechanisms dominate regional diversification into fuel cell technology. The analysis is carried out on 17 NUTS2 regions, which constitute 60% of all European fuel cell patenting activity from 1993-2007. For each region, I identify the major patenting organisation and analyse their path into the emerging fuel cell industry. The findings give qualitative insights into different types of firms and their interest and activities in an emerging industry characterised by high levels of uncertainty.

Chapter 5

The research in this thesis supports elements of the emerging evolutionary research agenda in economic geography. In Chapter 5, I discuss these results and their limitations. Moreover, these findings have initiated the quest for more research in this direction, research that will provide answers to evolutionary questions in economic geography and specifically in the spatial emergence of the fuel cell industry. These issues are outlined in the final chapter.

CHAPTER 2
INNOVATIVE REGIONS AND INDUSTRIAL CLUSTERS

by

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ABSTRACT

Regional governments in Europe seem to be playing an increasing role in hydrogen and fuel cell (H2FC) development. A number of regions are supporting demonstration projects and building networks among regional stakeholders to strengthen their engagement in H2FC technology. In this article we will analyse regions that are highly engaged in H2FC activity, based on three indicators: existing hydrogen infrastructure and production sites, general innovativeness, and the presence of industrial clusters with relevance for H2FC. Our finding is that regions with high activity in H2FC development are also innovative regions in general. Moreover, the article highlights some industrial clusters that create favourable conditions for regions to take part in H2FC development. Existing hydrogen infrastructure, however, seems to play only a minor role in a region's engagement. The article concludes that, while further research is needed before qualified policy implications can be drawn, an overall well-functioning regional innovation system is important in the formative phase of an H2FC innovation system.

2.1. Introduction

Innovation in energy technology is high on the political agenda in Europe, not only for reasons of energy and climate policy, but also to help increase the EU's overall competitiveness (the "Lisbon Agenda") through initiatives such as the Competitiveness and Innovation Framework Programme (CIP). In this connection, competitiveness refers not only to minimising firms' expenditures on energy, but also (and perhaps in particular) to industry's ability to innovate and remain competitive in the new and sustainable energy technologies.

The regional level seems to have an increasing importance in providing good political and socio-economic conditions for innovation. Asheim and Gertler (2005) have emphasised that a regional level in the governance of economic processes – between the national level and the level of clusters and firms – is important in supporting the institutional settings that can promote innovation. In a study of the impact of the global economy on innovation policy Lundvall and Borrás (1999) found that "*The region is increasingly the level at which innovation is produced through regional networks of innovators, local clusters and the cross-fertilising effects of research institutions*". This trend seems to be confirmed by studies and actions in the H2FC area in Europe, where the regional level has been recognised as a significant driver on the pathway to a hydrogen economy. An example of this is the work done in recent years to get the local and regional authorities represented in the Fuel Cell and Hydrogen Joint Technology Initiative and the Hydrogen and Fuel Cell Platform, which has culminated in the creation of the Regions and Municipalities Partnership on Hydrogen and Fuel Cells (HyRaMP) in April 2008.

The Internet provides numerous examples of regions (remote islands, cities, local authorities, federal states, etc.) that have declared themselves hydrogen communities. In many cases, regional authorities have developed fully fledged strategy plans and allocated significant public financing to the achievement of the goals of such strategies. Two examples, representing small and large communities respectively, are:

- The Western Isles Hydrogen Community Plans: Creating a Pathway to the Hydrogen Economy (in the Outer Hebrides, a part of the UK)
- Fuel Cell and Hydrogen Network in North Rhine-Westphalia (a federal state in Germany)

The European project Roads2Hycom analysed 96 potential hydrogen communities, based on a call for Registration of Interest (Shaw and Mazzucchelli 2007). Their analysis shows that government or regional/local authorities are involved in nearly 80% of the registered projects. This makes regional authorities the most important actor in the field, ahead of SMEs and large corporations. The engagement of regional authorities is typically guided by energy and environmental policy concerns, but also by industrial or politico-economic policy concerns – especially in stimulating new industrial clusters based on this new technology. Since regional authorities are actively involved in stimulating H2FC technology and related industrial clusters, a range of questions arise, which form the basis of the research for this article:

- Do geographical and cluster aspects matter in the establishment of a European hydrogen energy technology innovation system?
- Are there any geographical relationships between regions with a high level of H2FC activities and:
    - Existing hydrogen infrastructure and hydrogen production sites?
    - Generally innovative regions in Europe?
    - Existing industrial clusters in Europe?

In the next section, we introduce a general discussion on innovation systems and clusters, and how these concepts relate to the promotion of H2FC technology. Section 3 discusses problems of data availability. Section 4 looks at the regions in Europe that are highly engaged in H2FC development, and in Sections 5, 6, and 7 we analyse whether or not there is a correlation between H2FC infrastructure, innovativeness and industrial clusters at a regional level. Section 8 discusses the results of our analysis and the implications for energy and regional policy.

2.2. Innovation systems and industrial clusters

The process of innovation is often complex and uncertain, and technological innovation is not solely a matter of technology, manufacturers and markets. Policy makers, analysts and innovators also have to address the wider framework or environment in which companies operate and from which new innovations and technologies emerge. This may be particularly true for the innovation system of H2FC technology. The successful development of a hydrogen-based energy system requires strong engagement from the public sector to help provide and resolve infrastructure issues to support its deployment.

The concept of *innovation systems* takes this broad view of the process of innovation. An innovation system can be defined as the "*elements and relationships which interact in the production, diffusion and use of new and economically useful knowledge*" (Lundvall, 1992). These elements are the various actors that constitute the system: manufacturers, suppliers, consultancy companies, public authorities, policy makers, universities, research institutions, trade associations, consumers, etc. Relationships take shape as informal or formal networks, such as project activities or buyer-supplier relationships. These relationships link the actors in interactive learning processes. For instance, the relationship between actors involved in a demonstration project is built on the exchange of knowledge and know-how. The interaction is influenced by the institutional set-up in which it takes place. This institutional set-up is comprised of laws and rules, shaped by policies that regulate the interaction between the actors. It also includes norms and codes of practice, which typically are affected by cultural differences.

When analysing regional policy measures for promoting hydrogen communities, two theoretical branches of innovation system studies are available. Firstly, the analytical focus can be placed on the technology or the emerging industrial sector, and innovation theorists then talk about technology-specific innovation systems – TIS (Jacobsson & Bergek 2004, Hekkert et.al. 2006, Carlson & Stankiewicz 1991) or sectoral innovation systems – SIS (Breschi & Malerba 1997, Malerba 2002). Secondly, the analytical focus can be placed on the geographical entity of the community, and innovation theorists then talk about regional innovation systems – RIS (Cooke, 2001; Asheim & Gertler, 2004; Asheim & Gertler, 2005). These two theoretical approaches are parallel to two distinct, but often related policy fields: Research and Development policy and Regional Development policy, respectively. The technology specific approach is more concerned with directing R&D initiatives on an overall level. Its focus is on analysing barriers to and opportunities for technological development.

The regional innovation system approach is, to a greater extent, interested in directing regional innovation policy. This approach takes a more holistic view of a region's production structure. In the regional approach the administrative borders of a region define what to include in the analysis, depending on what industries are located in the region. The focus is partly on strengthening the regional innovation system's ability to innovate, and partly on improving its ability to benefit from external links. The two approaches, TIS and RIS, can therefore be seen as relevant to two different policy levels; the national (or supra-national) level and the regional level, respectively.

2.2.1 Regional innovation systems and clusters

Focus in analyses of regional innovation systems (RIS) is on the "*institutional infrastructure supporting innovation within the production structure of a region*" (Asheim & Gertler, 2005). RIS emphasises the importance of a regional level of governance of economic processes, between the national level and the level of clusters and firms.

The RIS approach focuses particularly on localised learning and intra- and interregional knowledge flows. As in the other branches of innovation system studies, learning is viewed as a socially interactive process, built on trust (Lundvall 1992, Cooke 2002). But, in the RIS, geographical proximity is often seen as a vital facilitator of innovation processes because of the tacit character of knowledge. In RIS studies, geographical proximity is thought of as one of several factors positively influencing innovation processes. Other factors are 1) specialised suppliers with a specific technology or knowledge-base, 2) regional culture such as norms, values, routines and expectations (Asheim and Gertler 2005), and 3) a certain degree of social cohesion to avoid polarisation in a region (Lundvall and Borrás 1999).

The approach of RIS is tightly connected with the concept of industrial clusters, but the two concepts should not be conflated. Clusters should be seen as more sector-specific than RIS (Asheim and Coenen 2004). The latter can in principle stretch across several sectors, because it includes the entire production structure within a region. In consequence, regional innovation systems may consist of several clusters with relevance for H2FC development.

Porter (2000) defines a cluster as a "*Geographic concentration of interconnected companies, specialized suppliers, service providers, firms in related industries, and associated institutions (for example universities, standard agencies, and trade associations) in particular fields that compete but also co-operate*".

Two matters are important to notice in Porter's definition of a cluster. The first is the notion of geographical concentration. Physical proximity is seen as extremely important for the innovation process because it eases the sharing of tacit knowledge. Another important matter in the definition of a cluster is how companies are interconnected. In a cluster, companies, suppliers and service providers compete and cooperate both horizontally and vertically in the value chain. In fact, interaction between companies and their physical proximity are two sides of the same coin. They are mutually related, and that is what creates spillover in the form of a specialised workforce, specialised regional suppliers, information, and training facilities, which are considered to increase the productivity with which companies can compete, both nationally and globally.

Nevertheless, some studies have found that, for some high-tech sectors, physical proximity is of less importance (Mans et al. 2008). In some high-tech sectors, external relationships with companies located worldwide can be of just as great importance – or even greater – than relationships with companies located in their own region. In the case of H2FC technology, this factor should not be neglected. On the contrary, when regions formulate their policy strategies, they should probably pay special attention to how these ties can be strengthened.

From a regional policy perspective, the most commonly used policy instrument in promoting clusters has been to support network activities (Sölvell et al.2003). In the area of H2FC this has often been in the form of Public Private Partnerships (PPPs). Other policy objectives have been to promote innovation through research, development and demonstration (RD&D) funding, creating a special brand for the region, attracting new firms and talent to the region, providing assistance to businesses, diffusing technology in the cluster, studying and analysing the cluster and its needs, etc.

H2FC industrial clusters, in Porter's version, do not yet exist, and it seems uncertain whether it is an appropriate strategy to start creating H2FC clusters from scratch. Instead, the most reasonable way for regions to promote the creation of H2FC clusters seems to be to support other relevant and existing clusters in the direction of a stronger uptake of H2FC technology. In this way a region will be able to build their H2FC engagement upon competences and strengths already present in the region.

However, to create the right conditions to fulfil the vision of a hydrogen economy, the cluster approach seems to be too partial to stand alone. Its focus on segregated single clusters seems to be inadequate to address the system character of a future hydrogen-based energy system. Furthermore, policy directed towards a single cluster is at risk of favouring certain technology options ("picking the winner"). So regional innovation policy needs to create framework conditions for H2FC innovation that are broader based than the single cluster focus. For this purpose, a broader analytical perspective, such as the regional innovation system approach, might be more appropriate. The RIS approach provides greater insight into strengths and competences at the regional level. As an analytical tool, it can reveal the functions of the system that need support to improve the overall innovation environment in the region.

2.3. Data for innovation studies

Following the interest in innovation studies and policy analyses in recent decades, solid statistical data has been accumulated by various authorities. However, for this study one analytical challenge has been that it deals with both geographical units and distinct technologies. H2FC is a new area of industrial technology, and the data available describing and analysing its characteristics is rather limited; neither comprehensive time series have been established nor does the technology data necessarily match with regional data.

2.3.1 Geographical units

The main analytical focus in this study is on the geographical distribution of H2FC activities in EU-27, Iceland, Norway, Liechtenstein and Switzerland. Data has been mapped at NUTS level 2 by means of a geographical information system tool (GIS).

NUTS (Nomenclature d'Unités Territoriales Statistiques) was created by Eurostat as a hierarchical classification of geographical units for use in statistical production across the European Union. NUTS level 1 corresponds to a territory with a population of 3-7 million inhabitants. NUTS level 1 thus often reflects fairly high administrative levels such as the German Länder. The analyses made in this study are carried out at NUTS level 2 (NUTS II), defined by Eurostat as 'basic regions' and comprised of 268 regions in Europe. Basic regions are used by Member States for the application of their regional policies. Although this was the intention with the subdivision of NUTS II, some countries are too small in terms of population to comply with Eurostat's definition of regional geographical entities; for instance both Denmark and Luxembourg are characterised as NUTS II regions, even though they represent nations with national policy authorities. The more detailed level of NUTS III is comprised of 1213 administrative regions in Europe.

2.3.2 Sources of data

Regional innovation system and industrial cluster analyses usually draw on the vast amount of geographically oriented statistical material provided by national statistical offices and Eurostat. In Europe, comprehensive statistical data is typically available as two entries: geographical entries at the NUTS levels, and industry-level entries based on the NACE (Nomenclature statistique des Activités économiques dans la Communauté Européenne) codes. NACE is a European industry standard classification system, consisting of a 6-digit code, and data is provided by national statistical offices, based on questionnaires filled in by individual firms (for example NACE code DJ.28.22 is "Manufacture of central heating radiators and boilers"). The challenge is that codes are available for neither hydrogen nor fuel cells, and the dispersed field of energy technology is spread over many different NACE codes. A recent analysis of self-declared hydrogen clusters in the Netherlands (Mans et al. 2008) is based on a database on 166 hydrogen-related projects carried out in the Netherlands between 2000 and 2005 involving 250 Dutch actors. The database contains geographical information on each of the actors, allowing analysis of the geographical concentration of actors at the level of the so-called COROP areas. The Netherlands is divided into

40 COROP areas which correspond to Eurostat's NUTS III level. Such detailed databases are not yet available for a Europe-wide study like the present one.

Technology specific innovation system analysis usually draws on slightly different types of statistical data from geographically oriented analysis. Bergek, Hekkert and Jacobsson (2007) have proposed a number of indicators and types of data to map the functions of technological innovation systems (TIS). Examples of indicators of the development and diffusion of knowledge are patents, bibliometrics (publications, citations), and governmental expenditures on R&D. Examples of indicators of market formation are the size of the market (e.g. for fuel cells) and support schemes (e.g. public investment subsidies). In the context of the European Environmental Technologies Action Plan (EU ETAP), a variety of investigations have been carried out on the concept of "eco-innovation" and its indicators (Andersen, 2006). Much of such statistical information is available for energy technologies such as H2FCs. Consultancies, such as Fuel Cell Today (www.fuelcelltoday.com), provide market-based intelligence on the fuel cell industry. Fuel Cell Quarterly, published by FuelCell.org provides similar market surveys on both fuel cells and hydrogen technology. Patent statistics can be obtained using databases like Derwent, and bibliometrics (publications and citations) can be obtained from Web of Science – familiar to most scholars. The International Energy Agency (IEA) provides statistics on governmental expenditure on energy-related R&D; but it has only included statistics on hydrogen and fuel cells since 2004, and data is still lacking from a number of countries. Seymour, Borges & Fernandes (2007) discussed and applied indicators such as patents, publications and citations in an analysis of European countries' public research in H2FC technology. Similarly, Lee, Mogi and Kim (2008) used the same kind of indicators to analyse scenarios for Korea's industrial potential based on this technology.

For our purposes, the problem is that this statistical data is only available at national, and not at regional levels. We are, therefore, left with having to make analyses based on what is available, and in the following sections we will analyse data available from the Roads2Hycom project (see the description and use of data below). In addition to this data, we have included data from two major studies of the spatial economy of Europe –the Regional Innovation Scoreboard and the European Cluster Observatory (www.clusterobservatory.eu).

2.4. Hydrogen and fuel cells activity in Europe

H2FC technology is an emerging technology field, and the markets for this technology are still in their formative phase; so it is not yet possible to analyse existing industrial clusters based on this technology. However, certain tendencies can be observed from analysis of the information that is available at present. Various parts of the Roads2Hycom project have provided the following data at NUTS II level:

- H2FC demonstration projects
- Hydrogen fuelling stations
- Registration of Interest (RoI) for communities undertaking large-scale H2FC projects and innovative applications

Comparison of this data indicates which European regions (at NUTS II level) are involved in H2FC activity. Although the data may not give a complete picture of all H2FC activity in Europe, it seems to be the best available at present and can provide us with a broad idea of where hydrogen activity is located.

We classified the data (for each indicator) into four intervals based on natural breaks in the data, i.e. the biggest gaps in the dataset were used to classify the data into groups (Nelson, R. 1999). We used this classification method to ensure that similar observations were grouped together in the same interval. So that we could sum the three indicators into one total score for H2FC activities, we then ranked the intervals with a score from 1-4. For example, for the dataset on demonstration sites, we first classified the data into five groups: 0, 1, 2-3, 4-5 and 5<. Next, we ranked the intervals with the values from 0 to 4. The total score for each region was calculated by summarising the score for the three indicators: demonstration sites, fuelling stations, and registration of interests. All NUTS II regions with a total score higher than three (15 regions) have been included in the further studies. Moreover, we included one NUTS I region (Wales, NUTS-code: UKL) because the data on the Regional Innovation Scoreboard (that we use to compare the regions with later) only exists for UK regions at this level. An adding up of activities from NUTS II to NUTS level I for the UK regions ranked Wales among the most active regions in H2FC.

2.4.1 Hydrogen and fuel cell demonstration projects

Based on existing and regularly maintained databases, the European project Roads2Hycom has identified and analysed over 130 hydrogen demonstration projects in the European Union and the associated countries, Norway and Iceland (Steinberger-Wilckens and Trümper, 2007a). The demonstration projects were mostly related to transport, stationary usage, and combinations hereof. The study included and distinguished between four types of demonstration projects: in planning, in operation, completed and interrupted. Only two of the projects comprised portable use of H2FC technology.

The NUTS II regions were ranked in accordance with data for demonstration projects using the following score: 0: no demonstration projects, 1: one demonstration project, 2: two or three demonstration projects, 3: four or five demonstration projects, 4: more than five demonstration projects.

There were demonstration projects in fifteen countries. Most were located in Germany (24%), but France, Denmark and Italy each hosted more than ten percent of the total. Steinberger-Wilckens and Trümper (2007) concluded that an early clustering of demonstration projects seems to be appearing in the German Rhein-Ruhr/Rhein-Main area and in the cross-border region of Denmark and southern Sweden.

2.4.2 Hydrogen fuelling stations

Hydrogen fuelling stations are a prerequisite for developing the use of hydrogen in the transport sector. Based on a study by German consulting firm Ludwig-Bölkow-Systemtechnik, the Roads2Hycom project has analysed both existing and planned hydrogen fuelling stations for vehicles (cars and buses) in Europe. The analysis included stations in operation, stations no longer in use, and planned stations (Perrin, Steinberger-Wilckens, Trümper, 2007).

At the time of the study (late 2007), there were 35 hydrogen fuelling stations in operation in Europe. Most of these were located in Germany. Furthermore, a large number of fuelling stations were planned, especially in Scandinavia. In total, seventy-two operational or planned hydrogen fuelling stations were analysed with geographical data at NUTS III level. Data for the analysis of this study was aggregated at NUTS II level and ranked by following the natural breaks (see above) of the data set: 0: no H2 fuelling stations, 1: one H2 fuelling station, 2: two or three H2 fuelling stations, 3: four or five fuelling stations, 4: more than five H2 fuelling stations.

We did not distinguish between planned and operational hydrogen fuelling stations in our mapping exercise in this study. We believe that an aggregated count of fuelling stations ‘in planning’ and ‘in operation’ is adequate to indicate the level of activity. Although there is a risk that the planned fuelling stations will never be realised, at the present stage they indicate a region’s intentions and can, therefore, very well illustrate the activity level.

2.4.3 Registration of Interest (RoI) for communities undertaking hydrogen and fuel cell projects

In 2006, the European project Road2Hycom launched a call for “Registration of Interest” for potential hydrogen communities in Europe (in this case: EU27, EEA and acceding and candidate countries). In an overall database, 96 potential

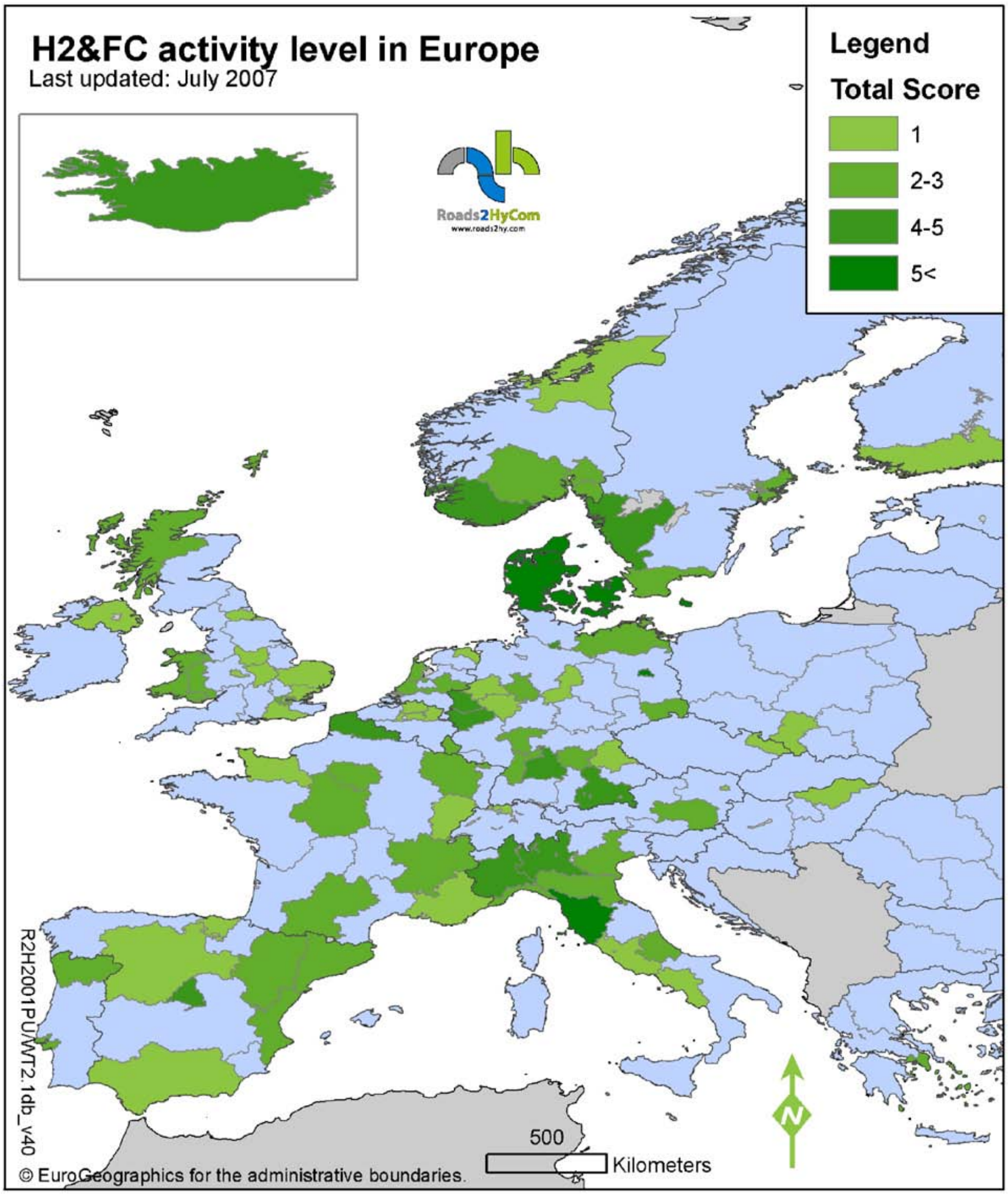

Figure 2.1: Map showing combined H2FC activity at NUTS II level

hydrogen communities were listed. Not surprisingly, the largest numbers of potential hydrogen communities were registered in Germany, with almost a quarter of the total. Also Italy and the UK each had more than 10% of the total number of communities. Collectively, the five Scandinavian countries accounted for 17% of all projects (Shaw and Mazzucchelli, 2007a). From the overall database, a sample of 36 projects is included in this analysis. They are the communities which have responded to the Call for RoI for potential hydrogen communities. The call was launched in May 2006 and is regularly updated as new information becomes available.

Due to the low number of registrations, the highest count in any region is three. The ranking of the regions is therefore as follows (with a maximum score of three): 0: no RoI, 1: one RoI, 2: two RoI and 3: three RoI.

2.4.4 European regions with a high level of hydrogen and fuel cell activities

Figure 2.1 shows the total H2FC score of the NUTS II regions in Europe. Furthermore, the detailed results for the 16 NUTS II regions with the highest H2FC score are shown in Table 2.1.

In many cases, the clustering of activities in neighbouring regions matches the location of partnerships or co-operative H2FC initiatives. The high score in the Scandinavian regions matches the location of the 'Scandinavian Hydrogen Highway Partnership' (SHHP), which focuses its collaboration on south/south-eastern Norway, the Swedish west coast and Denmark (www.scandinavianhydrogen.org). SHHP is a collaboration between three national bodies: HyNor (Norway), Hydrogen Link (Denmark) and Hydrogen Sweden.

The score in the regions of the federal state of North-Rhine-Westphalia in Western Germany reflects the many activities carried out by the 'Fuel Cell and Hydrogen Network NRW'. One should note that the NUTS II level is well below the political entity of North-Rhine-Westphalia: looking at NRW requires an adding up of these activities.

In northeast Spain, there is the Aragon hydrogen initiative, started by the Spanish Ministry of Industry in 2002. The high score in Northern Italy reflects the many and varied Italian projects that have been carried out during the last decade. For example, in Lombardy: the Zero Regio project in Mantova, the Bicocca Project in Milan, and the Arese project in Arese. In Tuscany: the HBUS project in Florence and the Arezzo project. And in Piedmont: the Hydrogen system laboratory in Turin.

The German cities of Hamburg and Berlin also score among the highest ranked regions along with northeastern England, Iceland, and Nord-Pas-de-Calais in France.

NUTS II region		Demonstration Sites		Fuelling stations		Registration of Interest		H2FC-SCORE
Code	Name	Count	Point	Count	Point	Count	Point	Total points
DE11	Stuttgart	3	2	5	3	0	0	5
DE21	Oberbayern	1	1	5	3	1	1	5
DE30	Berlin	5	3	3	2	1	1	6
DE60	Hamburg	4	3	1	1	1	1	5
DEA1	Düsseldorf	3	2	1	1	2	2	5
DEA2	Cologne	3	2	1	1	1	1	4
DK00	Denmark	17	4	9	4	3	3	11
ES30	Comunidad de Madrid	4	3	1	1	0	0	4
FR30	Nord - Pas-de-Calais	4	3	1	1	1	1	5
IS	Iceland	5	3	1	1	1	1	5
ITC1	Piemont	3	2	1	1	2	2	5
ITC4	Lombardy	2	2	3	2	1	1	5
ITE1	Toscana	1	1	4	3	2	2	6
NO04	Agder and Rogaland	2	2	3	2	1	1	5
SE0A	Western Sweden	3	2	0	0	2	2	4
UKL	Wales	4	4	0	0	1	1	5

Table 2.1: Distribution of H2FC activities on type in the 16 most active H2FC regions in Europe
Listed according to NUTS II code

2.5. High-level H2FC regions and existing infrastructure and production capacities

In this section, we will examine whether the 16 high activity H2FC regions are located in regions with existing infrastructure, such as hydrogen pipelines and hydrogen production sites.

2.5.1 Existing hydrogen production capacity

Hydrogen is used as an industrial gas in many process industries throughout Europe. The total industrial hydrogen consumption in Europe is estimated to be about 61bn cubic metres (in 2003). The majority of this hydrogen was consumed by two industries: in oil refineries (ca. 50%) and in the production of ammonia (ca. 32%). ´The total production of hydrogen in the European Union amounts to 80 bn m^3 (Steinberger-Wilckens, Trümper, 2007b) – which means that some overcapacity exists.

The number of hydrogen production sites in each NUTS II region was counted. The ranking of the regions is based on the following score: 1: one or two production sites, 2: three to five production sites, 3: six to eight production sites, 4: nine to fourteen production sites. It was not possible to look at the specific production processes of these facilities within the scope of this study.

The most important clusters of hydrogen production are in the Benelux-countries, the Rhine-Main area, the Midlands in the UK, southern France, and in northern Italy; but regions on the rim of the European Union such as Ireland, Finland Lithuania, North East Spain and Romania also produce hydrogen. Moreover, it is interesting to note that the new member states have many H2 production sites in total.

2.5.2 Existing hydrogen pipeline infrastructure

The Roads2Hycom project identified 15 large hydrogen pipeline networks in different parts of Europe, with a total length of nearly 1600 km (Perrin, Steinberger-Wilckens, Trümper, 2007). These pipeline networks are operated by firms such as Air Liquide, Linde Gas and Air Products. Pipelines are located in western Belgium, southern and western Netherlands, the German regions North-Rhein Westfalen, Sachsen and Sachsen-Anhalt and in the three regions of eastern France (incl. South-East France). The length of the pipelines is measured in km and mapped at NUTS II level. A ranking of the areas is based on the following score: 1: 2-25 km, 2: 26-61 km, 3: 62-163 km, and 4: 164-284 km. Figure 2.2 shows the geographical distribution of hydrogen production sites and hydrogen pipelines respectively.

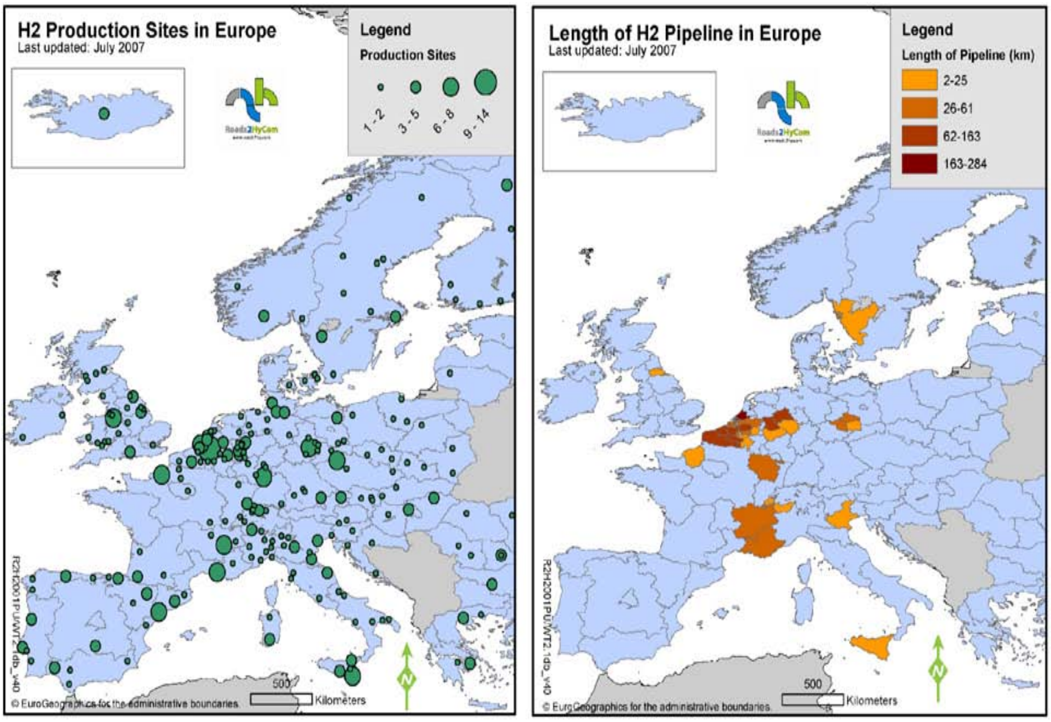

Figure 2.2: Left: Total H2 Production Sites in Europe, Right: H2 Pipelines in Europe

2.5.3 Relationship between high-level H2FC regions and existing hydrogen infrastructure

A total score for existing infrastructure and production capacity was calculated by summarising the score for production sites, and the length of H2 pipelines respectively. We then grouped the NUTS II regions based on their score on existing infrastructure into 3 groups: High score: 4-8 points, Medium score: 2-3 points and Low score: 1 point or less. The distribution of the 16 high activity H2FC regions between the three groups can be seen in Table 2.2. Only 4 of the high activity H2FC regions score high on existing infrastructure and production capacity (Düsseldorf (DEA1) and Cologne (DEA2) in Nordrhein-Westphalia, Nord – Pas-de-Calais (FR30) and Lombardy (ITC4) in Northern Italy). Half of the high activity regions score 2-3 points (Medium) on existing infrastructure, and four regions score 1 point or less (Low).

Table 2.2: Relationship between 16 high-activity H2FC regions and existing infrastructure

Total existing infrastructure and production capacity score	Count of high activity H2FC regions
High score on existing infrastructure (>3 points)	4 (25%)
Medium score on existing infrastructure (2-3 points)	8 (50%)
Low score on existing infrastructure (0-1 points)	4 (25%)

This means that we cannot conclude that existing H2 production capacity and H2 pipelines play a dominant role when regions decide to engage in H2FC activity. However, the analysis highlights four regions that have a high activity level and a high H2 capacity: Düsseldorf and Cologne in Nordrhein-Westphalia, Nord – Pas-de-Calais in France, and Lombardy in Northern Italy. Given that existing H2 infrastructure (production capacities and pipelines) is rewarding for H2FC development, these four regions seem to have comparative advantages for carrying out large-scale lighthouse projects.

2.6. Correlation between regions' level of H2FC activities and their score in the EU's Regional Innovation Scoreboard

The Regional Innovation Scoreboard 2006 was conducted by the Maastricht Economic and social Research and training centre on Innovation and Technology (MERIT). It measured seven innovation indicators: human resources in science and technology, participation in life-long learning, public and private R&D, patent applications, and employment in medium-high and high-tech manufacturing. It indicates the general innovation climate, based on quantitative data in a region. The scores of the scoreboard data lie within an interval of 0 to 1, whereby the region with the highest ranking score has 0.90 (Stockholm, Sweden).

For the purposes of this study, the Regional Innovation Score can be split into three categories; the bottom third, the middle third and the highest third. Of the 16 highest placed H2FC regions, 10 (or 62.5%) are also among the top third most innovative regions. (See Table 2.3).

This clearly indicates that H2FC activity takes place in regions that are generally innovative. This, in turn confirms the general thesis in cluster theory that greater spillover will occur where knowledge concentration is high beforehand (so-called endogenous growth theory). Given that these regions also perform better (which has not been analysed here), the results suggest that innovative regions have been faster in their attempts to promote H2FC activity. It also suggests that innovative regions find it easier to jump onto new technological paths, or are at least keener to take a chance on new and uncertain technology.

The high activity H2FC regions in the medium third are the Italian regions – Toscana, Piedmont and Lombardy, the UK-region Wales, and the German region Düsseldorf. The only high activity H2FC region in the bottom third is Nord – Pas-de-Calais, a major centre for heavy industry in the 19th century (coal mines and steel mills). After a heavy recession in the 1970s and 1980s the region today focuses on tourism. This result also raises the question of to what extent H2FC demonstration activities can be used in a political agenda for improving a region's innovative capabilities in general.

Table 2.3: Distribution of the 16 high activity H2FC regions over the 358 NUTS II regions' score in the European Regional Innovation Scoreboard

Score in the Regional Innovation Scoreboard	Number of high activity H2FC regions
Highest third	10
Medium third	5
Bottom third	1

2.7. Assessing the presence of clusters in H2FC-regions

This section compares the presence of likely future H2FC-related industrial clusters in high-activity H2FC regions. The aim is to investigate whether certain existing clusters are represented more frequently in high-activity H2FC regions than in the rest of Europe.

The analysis is based on the cluster mapping carried out by the European Cluster Observatory. The European Cluster Observatory has carried out cluster analyses in 32 countries, with NUTS II regions as the geographical unit. The analysis defines clusters in accordance with Michael Porter's analysis of employment distribution in North America (Porter, 2003). The American study analysed the geographical distribution of employment in various industries, and found different patterns depending on the type of industry. The industries were grouped into three categories, showing their various geographical profiles:

- Local industries are present in all regions, as they serve local markets. They are not exposed to direct competition across regions and are characterised by lower wages, productivity and rates of innovation. According to the European Cluster Observatory, local industries account for around 57% of all employment in Europe.
- Traded cluster industries experience advantages in choosing their location, and serve markets across regions. They have a tendency to 'cluster together', and are characterised by above average wages, together with higher productivity and levels of innovation. The cluster sector accounts for about 37% of European employment.
- Natural resource-based industries are located close to the deposits of the natural resources they exploit, and are therefore also geographically concentrated, but for other reasons. Around 5% of the European workforce is employed in natural resource-based industries.

From the perspective of creating a hydrogen economy in all parts of society, all three industry groups will be affected. Local industries will be affected, either as users of new hydrogen products or as retailers. The natural resource-based industries will be affected, as hydrogen is not an energy source in itself, but needs to be produced using fossil energy sources, bio resources or similar. But, in the development phase of a new technological trajectory, the most important industrial actors should be found within the Traded Cluster Industries.

The European Cluster Observatory has divided the 'Traded cluster industries' into 38 cluster categories (see www.clusterobservatory.eu). They have categorised a cluster's strength in terms of size, specialisation and focus, so as to measure sufficient critical mass to develop the type of spillover and linkages that create positive economic effects. In the Cluster Observatory's evaluation, a cluster present in a given region receives between one and three stars, depending on the strength of the cluster. However, in our study we do not distinguish between the number of stars, but only focus on whether or not a cluster is present in the given region.

We have calculated a Cluster Quotient (CQ) for each of the 38 clusters. The CQ is a measure for collocation of H2FC activities and clusters. The CQ compares the proportion of clusters (in the same cluster category) located in the 16 high activity H2FC regions to the proportion of the total number of clusters (in the same cluster category) in all the 258 regions (see equation).

The Cluster Quotient is thus calculated as:

CQi = (Ai/B)/(Ci/D);

Where:

i is a cluster category according to the Cluster Observatory, e.g. Automotive

Ai is the number for i clusters in all high activity H2FC regions

B is the number of all high activity H2FC regions (=16)

Ci is the number of all i-type clusters (e.g. automotive) in all regions analysed by the Cluster Observatory

D is the number of all regions analysed by the Cluster Observatory (=258)

A CQ>2 shows that the clusters are more frequently located in the high-level H2FC regions than in the rest of Europe. Table 2.4 shows the calculated CQ for the 38 clusters in Europe.

First and foremost, it is important to keep in mind that Table 2.4 reveals a statistical measure for collocation of H2FC activities and clusters. The CQ does not measure whether or not there is a causal relationship between certain clusters and H2FC technology. Furthermore, clusters are analysed by studying the concentration of employment in industrial sectors. Employment with relevance for H2FC is most likely to be in companies' R&D departments, and comprises a relatively small part of the total workforce. R&D departments are often located where companies have their headquarters, or where there is a critical mass of skilled workers. Therefore, we assume that this collocation measure can provide us with some information about the clusters that play a role in H2FC development.

In general, Table 2.4 reflects the result from the above analysis of the correlation between highly active H2FC regions and the regional innovation scoreboard. Clusters with a high CQ (>2) generally score higher in the indicators that make up the innovation scoreboard (human resources in science and technology, participation in life-long learning, public and private R&D, patent applications, employment in medium-high and high-tech manufacturing) than clusters with a CQ<2. Table 2.4 therefore confirms that an overall well-functioning innovation environment is important for regions' engagement in H2FC activity.

Table 2.4: Cluster Quotient

Cluster Category	CQ	Cluster Category	CQ
Medical Devices	4,7	Business Services	2,1
Publishing	4,4	Building Fixtures	2,0
Distribution service	4,3	Constr. Materials	2,0
Analytical Instruments	3,9	*Tobacco*	1,9
IT	3,9	*Education*	1,6
Biopharmaceuticals	3,1	*Leather*	1,5
Power generation and transmission	3,1	***Heavy Machinery***	1,4
Chemicals	3,1	*Finance*	1,4
Sporting	2,9	*Agricultural*	1,4
Production Tech.	2,9	*Textiles*	1,3
Aerospace	2,9	***Transportation***	1,3
Communications equipment	2,9	*Fishing*	1,3
Forest products	2,8	*Hospitality*	1,2
Lighting	2,8	*Metal*	1,1
Plastics	2,7	*Footwear*	0,9
Entertainment	2,4	*Apparel*	0,8
Jewellery	2,4	*Furniture*	0,7
Oil and Gas	2,4	*Food*	0,7
Automotive	2,4	*Construction*	0,7

H2FC technology is still at a stage where its relevance for many of the established clusters is limited. We have identified nine cluster categories that most likely play a role in the development and improvement of the technology. The nine clusters are highlighted in Table 2.4 and presented in detail in Table 2.5, which shows the nine cluster categories, examples of industries and some examples of companies involved in H2FC development.

Of the nine clusters with high relevance for H2FC technology, seven have a CQ higher than 2. Only transportation and heavy machinery have a CQ less than 2.

Transportation covers inventories and logistics, and distinguishes itself from the other clusters by being a service sector, providing actual transport and not the technology for transportation. The transportation sector will be among the large end-user groups of H2FC-based transportation technology. Heavy Machinery clusters are located in 4 out of the 16 H2FC clusters, so the results indicate, not surprisingly, that this cluster does not play a leading role in the regional H2FC activities

Table 2.5: Cluster categories with interest to H2FC development

Cluster categories	Industry examples	Examples from European H2 and Fuel Cell Technology Platform's NEW-IG members
Oil & Gas Products and Services	refineries	Statoil Hydro ASA, Gaz de France, Shell Hydrogen BV, Total France, Intelligent Energy, ILT Technology
Automotive	motor vehicles and components	Daimler, Adam Opel GmbH, Volkswagen, Cento Ricerche Fiat, AVL List GmbH, Volvo, Rolls Royce Fuel cell system, RiverSimple LLP, Intelligent Energy,
Power Generation and Transmission	generators	Siemens, E.ON Sweden AB, EWE AG, GAMESA Corporacion Tecnologica, Intelligent Energy, Ceres Power Ltd.
Heavy Machinery	tractors, locomotives	Wärtsilä Finland, Gruppo Sapio, Ansaldo Fuel Cells, Nucellsys
Chemical Products	chemicals, industrial gases	Linde Gas, BASF Fuel Cells GmbH, ILT Technology, BP International
Production Technology	tanks	Topsoe Fuel Cells, Nucellsys,
Transportation and Logistics	freight, air transport	Rail Safety and Standard Boards
Aerospace	APU on aircraft	Intelligent Energy, EADS Deutschland
Communications Equipment	portable applications, mobile, computers	

Chemicals (3.1), Power generation and transmission (3.1), and Oil and gas (2.4) are three clusters that are particularly relevant to the production and distribution of hydrogen. Automotive (2.4), communications equipment (2.9), aerospace (2.9), and production technology (2.9) are clusters with an interest in the various application options H2FC offers. The CQs show a high collocation between H2FC activities and these clusters.

This result can be explained by taking the market maturity of H2FC technologies into account. Firms interested in developing and demonstrating H2FC technologies in this early phase are seeking business opportunities to produce these technologies and provide the hydrogen, whereas firms that could potentially become end-users of such technologies (such as transportation) are likely to become involved at a later stage of the market development of these technologies.

Clusters most unlikely to support the development of H2 and fuel cell technologies such as Footwear, Furniture and Processed Food (beer, dairies, glass packages/wrapping) have a CQ < 1. This also seems quite natural; firms in these sectors are only likely to become end-users of H2FC technologies when they are fully matured and competitive with other energy technologies.

In summary, a positive correlation has been found between the presence of clusters assessed to be H2FC-friendly and the high-activity H2FC regions. This indicates that specific clusters may play a role in driving the development of H2FC technology. However, the most important result of the study of Cluster Quotients seems to be a confirmation of the correlation between innovative regions (hosting innovative clusters) and H2FC technology development. An institutional set-up with favourable conditions for innovation is therefore seen as extremely important in promoting innovation activities in the field of H2FC.

This study of the role of regions in H2FC development has a preliminary character, and needs to be followed up by more in-depth studies. In particular, studies of the relationship between certain clusters and H2FC technology would be of interest. A study of the institutional set-up at the regional governance level and how to improve this through innovation policies would also be very interesting, and would be fruitful for the regional engagement in H2FC development in the future.

2.8. Conclusions

In the introduction to this article we raised a number of research questions. In the following section we will try to answer these questions and discuss their implications for energy and regional policy.

First of all, we can conclude that geography and cluster aspects seem to matter in establishing a European H2FC technology innovation system. It is clear that some regions are more active in the formative phase of H2FC innovation systems than others.

Regions with the highest level of H2FC activities are found in various places in Europe, and, in many cases, the clustering of activities in neighbouring regions matches the location of partnerships or co-operative H2FC initiatives. In southern Scandinavia, the region matches the location of the 'Scandinavian Hydrogen Highway Partnership' (SHHP). The federal state North-Rhine-Westphalia in Western Germany might benefit from the activities carried out by the 'Fuel Cell and Hydrogen Network NRW'. In northeast Spain, there is the Aragon hydrogen initiative started by the Spanish Ministry of Industry in 2002. And in the case of northern Italy, there have been a number of projects carried out over the last decade – in Lombardy: the Zero Regio project in Mantova, the Bicocca Project in Milan, and the Arese project in Arese; and in Tuscany: the HBUS project in Florence and the Arezzo project.

These geographical patterns of H2FC activities indicate that some European regions are building up critical-mass in the field of H2FC.

Secondly, the relationship between the early adoption of H2FC activity and existing hydrogen production capacities and pipeline infrastructure in regions is weak. Indeed, small projects can be carried out with on-site hydrogen production and do not require existing production or pipeline infrastructure. So the latter should not be seen as prerequisites for engagement with H2FC. However, the existence of production capacities and infrastructure is no doubt a positive factor for the implementation of large-scale projects and the development of H2FC clusters.

Thirdly, it can be concluded that regions which are very active in pursuing H2FC deployment are typically also generally innovative regions. This finding is consistent with endogenous growth theories and thus confirms the hypothesis that innovative regions can more easily engage with and advance in H2FC technology. Less innovative regions may, therefore, need specific support schemes to help them engage with H2FC. However, such support should be subject to the condition that the less innovative region in question disposes of some other success factors (e.g. hydrogen production infrastructure) which promise to make the investment a rewarding one. In any case, it is important to be aware of the extent of the hydrogen chain and that efforts are needed at all stages. It is as yet too early to tell where the breakthrough will occur that can make hydrogen competitive with incumbent technologies. Less innovative regions might be engaged in development paths which could lead to breakthroughs in niche markets that can improve the overall technology. It is therefore not recommendable to cut-off less innovative regions from funding sources.

Fourthly, the most active regions in the field of H2FC are characterised by the location of innovative clusters – a fact which confirms the importance of an overall well-functioning innovation system for the development of emerging technologies. Furthermore, some of the industrial clusters located in the highly active H2FC regions can be characterised as favourable for the development of H2FC. This relationship is particularly strong for clusters in chemical products, power generation, production technology, oil and gas, and automotive and aerospace technology – a fact which reflects the early stage of H2FC market development. In fact, investment in other H2FC applications depends on the advances in hydrogen generation and fuel cell technology. The relative importance of industries that provide end-use applications (such as transportation) is likely to increase at a later stage in the formation of the market for the technology. The decision of local and/or European-level authorities on whether to support a regional initiative should, therefore, take the specific regional industrial cluster structure and the general stage of market development into account.

This article has merely provided a preliminary insight into the economic geography of H2FC development. Additional studies of the character of regional innovation systems and how they can facilitate H2FC development through innovation and cluster policy are needed to pave the way for a hydrogen economy. Another interesting issue this article has revealed is that of the benefits and synergies the agglomeration of activities in neighbouring regions seems to have for H2FC development. This relationship also requires further study before qualified policy implications can be drawn.

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CHAPTER 3
REGIONAL KNOWLEDGE BASES AND TECHNOLOGICAL RELATEDNESS

by

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ABSTRACT

The evolutionary turn in economic geography has proposed that regional diversification is a path dependent process where new industries grow out of pre-existing industrial structures through technologically-related localized knowledge spillover. This paper examines if this also applies for industries developed around emerging radical technology. I develop a new measure for technological relatedness between the knowledge base of the region and that of a radical technology, namely fuel cells. It is demonstrated that even in the case of high degree of radicalness and discontinuity, knowledge generation is still cumulative in its spatial and cognitive dimensions, corroborating the evolutionary thesis.

3.1. Introduction

Discussions of the emergence of new regional industrial paths have gained renewed interest in the field of economic geography. Over the last couple of decades the field of economic geography has experienced what has been called an ‘evolutionary turn’ (see e.g., Boschma and Martin, 2010, Boschma and Martin, 2007, Grabher, 2009, Martin and Sunley, 2006, Essletzbichler and Rigby, 2007) inspired by the field of evolutionary economics (Nelson and Winter, 1982, Freeman, 1994). This turn has brought about a renewed interest in the question of how we can explain the emergence of new industries and their spatial manifestation as a process of regional path dependency (Martin and Sunley, 2006). Boschma and Frenken (2011b) argue that technological relatedness, understood as cognitive proximity, enhances knowledge transfers and sharing from pre-existing regional activities to emerging industrial activities within regional borders. Thus technological relatedness becomes an important enabling factor for the creation of new variety and formation of new regional industrial paths (Boschma and Frenken, 2011b, Neffke et al., 2011a).

This paper contributes to this scope of economic geography literature in three ways. Firstly, it is unclear to what degree localization of radically new industries, based on radical technology development, is likewise driven by technologically related knowledge spillover from pre-existing regional economic activities. Since radical technology is characterized by high degree of discontinuity in production and marketing systems and strong dependency on knowledge produced in R&D departments (see Freeman, 1994, Freeman and Perez, 1988) some scholars have argued (Storper and Walker, 1989) that new industries experience relative ‘freedom’ to locate in a large number of regions. According to Storper and Walker, locational freedom is achieved because new industries are less constrained by specific locational resources and rely to a higher degree on their own creative ability to generate or attract a supportive local environment than is the case for established industries. A refinement of this argument has been made by Boschma and van Der Knaap (1997) and Boschma and Lambooey (1999) who argue that the spatial indeterminacy of new industries are limited to regions with useful and beneficial generic resources. Hence, the major contribution of this paper is through empirical analysis of the localization of the radical fuel cell technology, to investigate and clarify whether or not radical technology development takes place in regions with technologically related generic resources.

Secondly, following Boschma and van Der Knaap’s (1997) argument that localization of new industries is triggered by a set of localized generic resources, an additional objective of this paper is to enlarge our understanding of the character of such resources. Boschma and van Der Knaap distinguish between general and specific resources and claim that new industries only benefit from a certain combination of generic resources, such as basic knowledge and skills. Previous research has shown that in the case of the automotive industry, the presence of related industries in certain regions was in fact beneficial for the early localization of the British car industry (Boschma and Wenting, 2007). And Neffke et al. (2011a) have shown that industries are more likely to enter regions with technologically related industries, and that existing industries are more likely to exit regions where other industries are not technologically related. In this paper I do not focus on classes of industries but investigate the presence of a portfolio of technologically related knowledge fields that together adds up to the knowledge base of the fuel cell technology. By decomposing the availability of generic resources into specific knowledge fields relevant to the fuel cell technology, the analysis becomes more detailed in its measure of technological relatedness. This enables the analysis to reveal the importance of specific knowledge fields (over others), and to distinguish between degrees of technological relatedness.

Thirdly, this paper develops a new way of measuring technological relatedness based on the (evolving) knowledge base of a nascent technology area. The main dataset is a regionalized database of patent applications filed under the Patent Cooperation Treaty (OECD, June 2010) which makes it possible to measure fuel cell patenting and fuel cell technologically related patenting for a sample of European regions. Where patent activity is seen as a proxy of knowledge production and hence, works as a measure of competences and skills that are present in a given region within specific knowledge areas. Eight knowledge fields that form part of the fuel cell knowledge base are identified as fuel cell related knowledge, and the same database makes it possible to measure the level of knowledge production within these eight knowledge fields for each region over a 15 years period. This is a much more precise way of measuring technological relatedness than industrial classes have allowed previously. Additionally, although patent data has been criticized for its many shortcomings, another clear advantage of measuring knowledge fields as an alternative to industry classes is the possibility to analyze localization patterns of emerging technology, which often drowns in industrial classification systems.

The paper focuses on the emerging fuel cell technology which is an environmentally friendly energy technology. A fuel cell is an electro-chemical device that generates electricity based on a chemical reaction between oxygen and hydrogen. Fuel cell technology is radical because it has the potential to replace incumbent energy technologies and as such result in technological discontinuities (Garcia and Calantone, 2002). It functions as an entirely new chemical process of energy conversion and consequently builds upon a new set of scientific and technical principles which requires the buildup of a new knowledge base (Bourgeois and Mima, 2003, Avadikyan et al., 2003). Since early 1990s fuel cell technology development has gained a momentum in its technical achievements and is 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 core developers of fuel cell stacks and fuel cell systems such as electrical battery manufacturers or new specialized firms (Bourgeois and Mima, 2003). And in later years, also firms further downstream have increasingly been involved in fuel cell technology development mirroring a diverse range of application opportunities and markets within stationary power, automotive, and portable equipment.

The paper is structured as follows. In the next section the theoretical conceptualization the paper builds on is unfolded. This section begins with a brief distinction between incremental and radical innovation and the concept of 'radically new regional industrial paths' is defined. Then the processes of early industrial localization are discussed distinguishing between the 'window of locational opportunity'-interpretation and the concept of 'regional branching'. Section 3 describes some characteristics about the fuel cell technology and Section 4 introduces the data, method and model used, including a thorough description of the measure of 'technological relatedness'. Section 5 presents the results and the concluding Section 6 sums up the findings and point in the direction of future research.

3.2. Theory and Conceptualization

3.2.1 Radically new regional industrial paths

Let us first briefly define the very object this paper focuses on: emerging regional industrial paths based on radical technology. Which in short is defined here as new industries that build around a radical technology and emerges within the borders of a given region.

Although a plethora of definitions of innovation types is used in innovation studies (Garcia and Calantone, 2002) a simple distinction between incremental and radical technological change is widely accepted to capture the main variations. Incremental innovations occur continuously and are cumulative of nature within technological trajectories (Nelson and Winter, 1982, Freeman, 1994, Dosi and Orsenigo, 1988). They take place within firms or within clusters of firms that are closely linked to each other and hence, in a geographical respect, perceived to be strongly influenced by preexisting patterns of economic activities

(Boschma and Van der Knaap, 1997). In other words incremental changes to products and processes take place where firms are located and are often driven by learning by doing and learning by using mechanisms.

On the other hand, radical innovations often lay the ground for totally new products or processes generating paradigmatic changes (Dosi, 1982, Dosi, 1988a). Radical innovations are discontinuous of nature and are argued to spur new industries or firms to emerge which have the potential to disrupt incumbent industries and firms. In that respect radical innovation is usually perceived to cause discontinuity in the economic system and by evolutionary economic geographers to cause instability in the economic landscape (Boschma and Van der Knaap, 1997). It also follows that in the early stages of radical technological innovation, uncertainty is very high (Freeman and Perez, 1988) and the technology requires years of developments and improvements.

When new industries emerge based on a radical technology it forms what is here called a radically new industrial path. This paper is concerned with where in space the new industrial path is located, and hence terms it radically new regional industrial paths. A new industry may emerge in a number of regions at the same time or slightly separated in time. However, in this definition of radically new regional industrial paths it is important to highlight that the new industry builds on radical technology development and as such is not only new to the region but *new to the world*.

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

3.2.2 Early industrial localization through locational freedom

The discontinuous nature of radical technology has caused economic geographers to argue that the spatial formation of new industries occurs relatively independently from economic structures and practices (Storper and Walker, 1989). Storper and Walker (1989) argue based on the WLO-concept[8] (Scott and Storper, 1987) that localization of new industries is rather independent from

[8] 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. 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).

preexisting industrial structures. The presumption is that an emerging industry that bases its development on a radical technology has such unique requirements that any preexisting locational conditions will hardly meet them (Storper and Walker, 1989, Boschma, 1996). Instead, it is claimed that when a new industry emerges, firms experience a level of 'locational freedom' to locate in a large number of places because their future depends to a higher degree on their own ability to shape a supportive environment (e.g., labor skills, suppliers, buyers) than on a set of specific localized resources. Accordingly, leading firms in emerging industries are to a larger extent dependent on its capability to create its own favorable locational conditions than on specific initial conditions provided by the existing settings in a region. Although, Storper and Walker do point out that the locational freedom has limits and that we won't see new industries develop in relatively unidustrialized regions (Storper and Walker, 1989) their overall argument is towards a high degree of spatial indeterminacy of new industrial localization.

Hence, the main shortcoming of the WLO framework is that they do not pay much attention to the possibility that new industries are linked to already existing industrial structures in a region as a result of regional path dependency. Contrary to the WLO-approach's emphasis on spatial indeterminacy, Boschma and other's later work modifies this understanding and suggests that new industries' spatial emergence is not an entirely accidental process (Boschma and Martin, 2007, Boschma and Frenken, 2011b). 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.

This is much in line with Perez and Soete's (1988) prominent paper on developing countries' capability to catch up in technology. They argue that four components influence the cost and capability of firms in a given country, or in this case a region, to enter a technological trajectory. The four components consists of fixed investments costs; scientific and technical knowledge; skills and experience (in management, production, marketing etc.); and a set of locational advantages. These components are likely to vary depending on the nature of the technology and on the stage of technological evolution understood as phases in the technology's lifecycle (Perez and Soete, 1988). In the introduction phase, which is in focus for this paper, the level of scientific and technical knowledge, and the level of locational advantages (externalities), in order to be able to enter the emerging technological trajectory are relatively high. Whereas the initial fixed investment costs and experience and skills in managing, production, marketing etc. are assumed to increase with a higher level of maturity of the technology. Perez and Soete argue, just as Boschma (2007), that it is *"(…) absurd to assume that a firm can start with zero previous knowledge"* (Perez and Soete, 1988, 466).

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

Clearly, building new industries in regional economies is a complicated matter, and cannot be ascribed to the regional composition of knowledge fields alone. 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 (Lundvall, 1992, Dalum et al., 1999). Other factors of institutional, cultural, political, and social character influence the development of new technological trajectories by creating favorable conditions for the technology e.g. inducing knowledge diffusion among actors in the region, and providing economic incentives to invest in R&D. This is also the case for fuel cell technology development (Madsen and Andersen, 2010). Such factors are clearly of immense importance and I suggest by no means any deterministic relationship between the knowledge base of a given region and the emergence of a new industry. Nevertheless, this paper is dedicated to enquiries into the cognitive dimension of technological development, which is obviously a crucial element in the early years of a technology's evolution. In fact it is plausible to argue that specific localized knowledge required to enter a technology is a prerequisite for a region to succeed in the development of new regional industrial paths based upon radical technology.

3.2.3 Regional branching, an evolutionary approach

Boschma and Frenken (2011b) employ the evolutionary metaphor, 'regional branching', to illustrate that new industry grow out of the existing industrial structure within a region. Regional branching happens either 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.

The concept of regional branching builds on two ideas from the field of economic geography. First and foremost, that knowledge tends to spill over in spatial proximity rather than globally, as shown by the literature on localized knowledge spillover (Audretsch and Feldman, 1996b, Feldman, 1999, Jaffe et al., 1993, Anselin et al., 1997, Maurseth and Verspagen, 2002). Several localized mechanisms[9] are argued to induce knowledge spillover locally leading 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.

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

Empirically 'regional branching' has found support from a number of studies when it comes to exploring the concept of regional path dependency in general, but has received less attention in trying to understand the 'place dependency' (Martin and Sunley, 2006) of radical industrial paths. Previous studies have shown how regions develop along coherent industrial paths: Neffke, Henning, and Boschma (2011a) demonstrate how Swedish regions develop along a somewhat coherent industrial path where industries have higher probability to enter regions where the regional industrial structure is technologically related to that industry, and existing industries without relatedness to the region's industry have higher probability to exit. And Essletzbichler and Winther (1999) demonstrate that Danish regions develop along different technological trajectories in the food processing industry. When it comes to the case of how radically new industries build on competences from old industries, Klepper and Simons' study (2000) demonstrates that successful television producers were experienced radio producers prior to entering the television industry indicating high level of complementarity in competences and routines between the two industries.

[9] Neffke et al (2011a) 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 fuel cell technology development.

Similarly, the study of Boschma and Wenting (2007) confirms that technological relatedness to the regional knowledge base plays a large role in the localization of the British car industry, and that the process in particular was driven by spinoffs from related industries.

The objective of this paper is twofold: First, to test whether or not regions branch as a consequence of technological relatedness between preexisting regional generic resources and new radical innovations. Radical innovations build on a new set of scientific and technical principles (Arthur, 2009) which breaks with incumbent technological trajectories and lays the seeds for the creation of new paths. However, once the scientific and technical principles are discovered and the new technological trajectory takes shape by the buildup of a new knowledge base, actors draw on complementary knowledge assets from related disciplines and activities in order to improve its functionality. Because of the localized channels of knowledge transfers, the argument of this paper is that regions with knowledge bases technologically related to the emerging knowledge base of a given radical technology have higher probability to branch into industrial paths that build upon that particular radical technology.

A second objective is to enlarge our understanding of the character of such regional generic resources. It is claimed that new industry development benefits from a certain combination of generic resources, such as basic knowledge and skills (Boschma and Van der Knaap, 1997). In the analysis that follows the nature of these resources is decomposed beyond industrial classes. But first, the fuel cell technology is described in more detail in the next section.

3.3. The case of fuel cell technology

Fuel cell technologies are seen as one of many alternatives to replace incumbent fossil-fuel based energy technologies. Fuel cells are somewhat generic in the sense that there is potentially a wide range of application opportunities across a variety of sectors (e.g. vehicles, combined heat and power systems, back-up units, auxiliary power units, laptops, mobile phones, hearing aids etc.). Among its positive environmental effects are its high fuel efficiency and that the exhaust from a fuel cell is pure water, providing both local and global environmental benefits above the incumbent technologies (provided that the fuel is produced from renewable energy sources).

It is important to highlight following five characteristics about the fuel cell technology when trying to understand the localization patterns of the new industry. First, its knowledge base is highly complex and serves therefore as a good example of a modern, emerging technology. Dibiaggio and Nasiriyar (2009) show that the fuel cell knowledge base became more and more complex up until

2002 as the number of new knowledge fields and new combinations of using distinctive knowledge fields kept rising.

Second, there are today several types of fuel cells, which indicate that a dominant design has not yet been ‘decided’ upon. The different types of fuel cells vary in their advantages depending on the application option; however, studies (Brown et al., 2007) indicate that an *elimination* process has begun keeping the PEMFC (Proton exchange membrane fuel cell) and the SOFC (Solid oxid fuel cell) in the field of interest for most companies. In this analysis the different types of fuel cells are analyzed together, even though there might be slight differences in the respective knowledge bases, mainly as a result of the use of different electrolytes e.g. knowledge about ceramics play a larger role in SOFC development where polymer compounds are important for PEMFC development. In any case, the lack of a dominant design indicates that the technology is in its very early development stage.

A third characteristic is that fuel cell technology, for some applications, is 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 fuel cells 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 the demand side is characterized by a strong policy drive expressed in visions such as ‘the hydrogen economy’ (Rifkin, 2004). 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.

3.4. Method, data and the model

The general idea of this paper is to investigate the relationship between the knowledge base of a given region and the localization patterns of the emerging industry developing based on the radical fuel cell technology. The intangible nature of knowledge makes it clearly difficult to measure its quantity (or quality for that matter) in any direct way (Foray 2004). Patent statistics is a widely used approach in quantitative studies to measure levels of competences for different units of analysis (see e.g. Patel and Pavitt, 1997 (for large firms), Zucker et al., 2007 (for regions)). The limitations in using patent data to measure knowledge production have also been widely criticized, although the critique has mainly targeted the use of patents to measure innovation. Here, I only discuss the limitations in using patent applications as a source of knowledge production.

Using patent applications as a measure for knowledge production will always be an imperfect measure for several reasons. First, patents are codified knowledge whereas a high proportion of knowledge produced in firms, universities, and research institutes are tacit. However, following Patel and Pavitt (1997) the two forms of knowledge are complementary rather than substitutes. For example, tacit knowledge is needed to understand and absorb information from patent applications and vice versa. Second, a lot of knowledge production with scientific and technical content is not recorded by patent applications. And third, using the count of patent applications tends to obscure the variations in the quality of knowledge covered by patents (Zucker et al., 2007). Nevertheless, for the purpose of this study patent applications are considered to be the most appropriate measure, given its relative homogenous, detailed, and consistent recording of knowledge production.

3.4.1 Data

The OECD, REGPAT database, June 2010 is the main data source used. The OECD, REGPAT database, June 2010 is a comprehensive attempt to regionalize patent applications filed under the Patent Co-operation Treaty (PCT) at international phase designated to the European Patent Office. A general reason for choosing PCT applications is that they are considered to contain least country based bias, because they represent international patent applications.

For the specific case of fuel cell patenting, the PCT dataset is preferable for two reasons. As in other fields patenting is a highly used strategy for firms to protect their knowledge assets in the fuel cell field (Avadikyan et al., 2003, Arechavala-Vargas et al., 2009). Because of the technology area's immaturity and the immense uncertainty about what the future brings, firms who have invested heavily in this new technology are extremely concerned about protecting their knowledge.[10] Due to the technology's early stage of evolution, firms do often not have ready products (applied knowledge) or skills in manufacturing; technological knowledge is their main asset.

Second, due to the fact that firms within the fuel cell industry see themselves as global players[11] it is appropriate to assume that they make use of the PCT system

[10] This concern is not only about the technological knowledge, but also information on suppliers and collaboration partners, which most fuel cell firms do not want to reveal.

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

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 et al., 2009).

The OECD REGPAT has regionalized the addresses of both applicants and inventors into two hierarchical territorial levels: Territorial Level 2 (TL2) and Territorial level 3 (TL3)[12]. In this study the sample of analysis refers to 250 NUTS2 regions across Europe, which corresponds to TL2[13]. 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.

3.4.2 Identifying the knowledge base of fuel cell technology

The main interest is to define and measure (1) fuel cell knowledge production for a given region, a given year; (2) the knowledge base of fuel cell technology defined as a set of knowledge fields indicating technologically related knowledge fields; and (3) the frequency of each of the fuel cell-related knowledge fields in all non-fuel cell knowledge production for a given region, a given year. First, the knowledge base of fuel cell technology (2) is defined.

To identify the fuel cell knowledge base all patents classified in accordance with the International Patent Classification (IPC)[14] system covering fuel cell technology has been extracted from the dataset. This is done rather precisely by using IPC-main groups (7-digits), H01M008 ("Fuel cells, manufactures thereof"). The analysis focuses on the period 1992-2007; 1992 is the year where the main patenting (and development) activity in fuel cell took off, and 2007 is the latest complete year in the database. Total for this period the dataset contains 8,572 fuel

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

[13] Due to lack of some regional data (mainly Governmental expenditures on R&D, used as control variable) only regions from following countries are included: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, 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.

[14] 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 digits), Main groups (7 digits) and Subgroups (9-digits).

cell patent applications[15] defined by the IPC-code H01M008. This paper concentrates on the regional dynamics of fuel cell development in Europe and limits therefore the analysis to patent applications filed by inventors localized in a sample of European regions counting 2,429 patent applications.

To measure the knowledge base of fuel cell technology I identify a set of knowledge fields that together form the technological knowledge base of fuel cell technology. These are identified by IPC-codes that are co-classified with the European sample of fuel cell patent applications. A patent application is often assigned with more than one IPC-code reflecting every single knowledge fields the patent covers. These knowledge fields are somehow involved in the generation of fuel cell knowledge. Therefore there is a good reason to assume that knowledge fields (IPC-codes) which are co-classified with fuel cell patent applications form part of the fuel cell knowledge base.

The co-classified knowledge fields are aggregated at the level of subclasses (4 digits)[16]. This shows that 312 out of 628 possible IPC subclasses are co-classified with the IPC-code for fuel cells. However, a large share of the 312 IPC subclasses occurs only a few times over the whole period, so to keep the analysis relatively simple only IPC-subclasses with a share >1 pct. has been included as forming part of the fuel cell knowledge base. Table 3.1 provides a description of the eight knowledge fields[17] that together form part of the fuel cell knowledge base and their relevance for fuel cell technology.

The composition of the knowledge fields at different times can be seen in Figure 3.1. The first column illustrates the distribution for all years 1992-2007, and the remaining five columns show the variation in three year periods. The figure illustrates that the knowledge base 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.

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[15] 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.

[16] 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.

[17] Originally, this approach to identify the knowledge base of fuel cell technology revealed 13 knowledge fields with a co-classification-share > 1. Because a correlation matrix revealed correlation coefficients higher than 70% for 6 of the knowledge fields (B01D, B01J, C01B, C08G, C08J, C08L), these were joined into the overall knowledge field of ‘Physical and chemical processes’ to avoid causing multicollinearity in the model.

Table 3.1: Eight knowledge fields that together compose the knowledge base of fuel cell technology in the years 1992-2007

IPC-code	IPC name	Knowledge field	Relevance for fuel cell	Share**
*B01D, B01J, C01B, C08G, C08J, C08L**	*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 fuel cell.	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 fuel cell development, since converting chemical energy into electrical energy is the key function of fuel cells.	23.1 %
H01B	*Cables, conductors, insulators, selection of materials for their conductive, insulating or dielectric properties*	**Cables, conductors, insulators**	The fact that fuel cells generate electricity makes electrical conductors, conductive materials, cables, insulators, etc., very central to the development of fuel cells.	4.3 %
C25B	*Electrolytic and electrophoretic processes for the production of non-metals, apparatus therefor*	**Electrolytic processes**	Electrolytic processes are the inversed reaction of what takes place in the fuel cell. In electrolysis, electricity generates gases, 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 is strongly related to fuel cell applications in the transport sector. Since fuel cells generate electricity, applied knowledge in vehicles will lie within this knowledge field.	2.0 %
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 fuel cell involve testing and measuring, as well as analyzing the effects of various materials, which are particularly 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 fuel cells. Circuit arrangements and systems for energy storing are considered to be supportive arrangements.	1.3 %

Source: OECD REGPAT, June 2010, and WIPO for International Patent Classifications

* This knowledge field is the sum of six subclasses, since the correlation between them is >0.70 and would cause collinearity in the regression.

** The share indicates how large of the total co-classifications belong to the specific knowledge field.

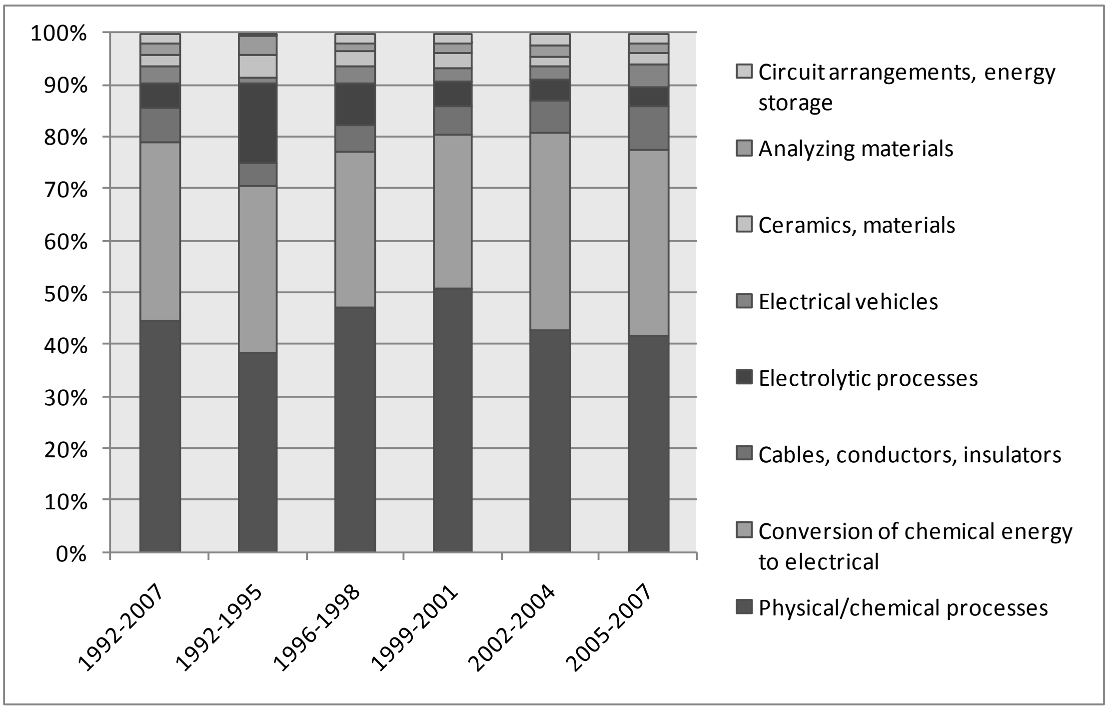

Figure 3.1: Composition of the fuel cell knowledge base over time
Source: Own calculations based on OECD REGPAT, June 2010

The identification of the fuel cell knowledge base provides at the same time the identification of knowledge fields that are technologically related to the emerging fuel cell industry. The level of knowledge production within each of these eight areas for each given region for each year serves as the independent variable and is described in more detail below. First the dependent variable, the level of fuel cell knowledge production (1), is defined.

3.4.3 The dependent variable –fuel cell knowledge production

The dependent variable in the analysis is fuel cell knowledge produced in given regions at given times. It is measured as fuel cell patenting activity (FCpt) filed under the Patent Corporation Treaty, and defined as above (all patent applications with IPC-code equal to H01M008, "Fuel cells and manufactures thereof"). The patents are ascribed at the regional level using a non-fractional count. In the OECD REGPAT database the fractional count takes into consideration that for each patent application several inventors with different regional residence may be behind the invention, and hence only ascribe a fraction of each patent application to the specific region where the inventor resides. However, I argue that knowledge is a non-divisible asset and since the purpose of this study is to measure knowledge production at the regional level, I use non-fractional counts, i.e. in the occasion where multiple inventors from different regions are behind a patent application the same patent application has been assigned to each of the regions involved.

Since fuel cell technology is yet an immature technology, the number of FCpt for some regions, in particular in the early period are small. Therefore FCpt is calculated as the sum of three consecutive years for each region for each year in the period 1992-2007. In this way, the model also takes into account the time for fuel cell related knowledge to be absorbed and utilized in generation of fuel cell knowledge.

3.4.4 Independent variable – technological relatedness

The independent variables are measures of fuel cell related knowledge for each region. Based on the knowledge base of fuel cell technology (the eight knowledge fields identified in Table 3.1), two measures of regional assets in fuel cell related knowledge fields have been calculated. The first measure of fuel cell technological relatedness (FC-TR) is basically eight measures indicating the level of knowledge production within each of the identified knowledge fields for each region for each year. It is calculated for all non-fuel cell patent applications, i.e. all fuel cell patent applications have been withdrawn from the database before aggregating the frequency of patent applications within the selected IPC-subclasses. Two further steps have been taken in preparing the FC-TR measures. Since regions differ in their total level of knowledge production (all patent applications filed under the Patent Cooperation Treaty regardless of IPC-codes) a first step has been made to make FC-TR comparable by relating the knowledge produced within each of the eight knowledge fields to the total patent activity of the region. This is a way of controlling for large differences that exists between regions' level of knowledge production and which could explain the differences in levels of fuel cell knowledge production.[18] Second, following Zucker et al (2007) the figures are computed by cumulating counts for all previous years, and discounting by 20 % annually to reflect depreciation of knowledge.

The second measure of fuel cell technological relatedness (FC-TR-DIV) indicates the diversity among the eight knowledge fields. FC-TR-DIV is calculated as a categorical variable taking the values 0 to 8, 0 if none of the fuel cell related knowledge fields are present, and 8 if all of them are present in a given region a given year. The higher FC-TR-DIV is, the higher degree of diversity within fuel cell related knowledge characterizes the knowledge base of a region. In this way FC-TR-DIV can be interpreted as an indicator of the degree of technological

[18] It is not possible to control for total level of patenting by including it as a control variable, because that would cause multicollinearity in the model. A 'variance inflation factor' analysis of the dataset showed that the variable 'total patent count' exceeded the value 12.

relatedness between a region's knowledge base and a certain technology, in this case fuel cell technology.

A number of controls have furthermore been included:

Governmental Expenditures on R&D (GERD)

Availability of public R&D expenditures is likely to affect the production of fuel cell knowledge, thus Governmental Expenditures on R&D (GERD) at the regional level (NUTS2) is included as a control. At the same time a high level of GERD is likely also to affect the total level of knowledge production in a region. In fact GERD is strongly correlated with total number of patents (0.76) so this is assumed to be a good additional control for both the availability of public R&D funding in a region and the total level of knowledge produced (patented). Data was downloaded from Eurostat, however, for some regions data were not comprehensive and it has been necessary to extrapolate for missing years.

Population

A population measure has been included to control for the size of the region, since it is assumed that larger regions will generate more knowledge.

Lagged dependent variable

Furthermore a lagged dependent variable (LAG.1 FC) was included to account for the effect of fuel cell knowledge produced in foregoing years. The lagged dependent variable was constructed in similar ways as the FC-TR measure, i.e. cumulated counts for all previous years, and discounting by 20 % annually to reflect depreciation of fuel cell knowledge.

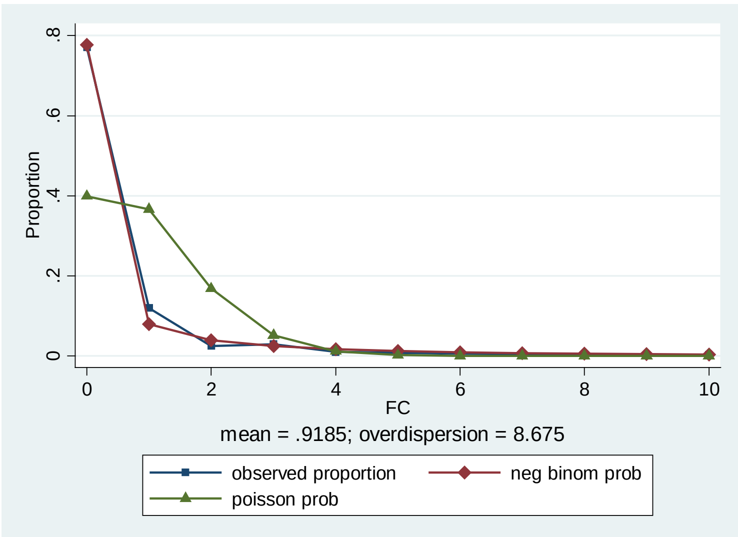

Figure 3.2: Distribution of observed proportion and its fitness to poisson and negative binomial, respectively.

3.4.5 The model

The analysis is carried out on a balanced panel data set comprised of the years 1992-2007 and 250 European NUTS2 regions.

Since the dependent variable is a running aggregate of three consecutive years and I include a lagged dependent variable, the panel covers in fact only 13 three year periods and independent variables for the years 1993-2005. Most of the regions have a relatively low count of FCpt while a smaller tail has much higher counts. FCpt is clearly a limited dependent count variable which suggests that the appropriate model is a count model such as the Poisson or negative binomial model, following Hausman et al (1984). While the Poisson model requires the variance of the dependent variable to equal its mean, the distribution of FCpt (see Figure 3.2) reveals clear overdispersion – a violation of the mean-variance equality restriction. This suggests using the negative binomial model that allows for heterogeneity on the mean.

Table 3.2: List of variables for 172 nuts2 regions, years 1993-2005

List of variables	**European NUTS2 regions**				
	N	Mean	S.D.	Min	Max
Fuel cell patenting	2236	1.36	4.67	0	82
Fuel cells (FCpt) (consecutive three yrs)	2236	4.61	14.16	0	232
FC TR					
Physical/chemical processes	2236	46.52	96.19	0	1,022
Conversion of chemical energy to electrical	2236	1.96	4.99	0	63
Cables, conductors, insulators	2236	1.61	3.98	0	73
Electrolytic processes	2236	0.60	1.95	0	39
Electrical vehicles	2236	0.59	2.41	0	34
Ceramics, materials	2236	3.65	7.28	0	73
Analyzing materials	2236	22.60	40.43	0	500
Circuit arrangements, energy storage	2236	1.38	3.73	0	60
FC-TR-DIV	2236	3.85	1.91	0	8
Controls:					
R&D exp.	2236	953.08	1,280.95	8.72	16,216.1
Population	2236	2,092,832	1,593,828	263,056	11,400,000

In order to control for unobserved heterogeneity we run the model with fixed effects. Introducing fixed effects to the model builds on the assumption that there are some time independent regional effects that correlate with the explanatory variables. Moreover, a Hausman test (1978) confirmed our choice over the random effects. The fixed effect has another consequence for the model because it only includes groups (regions) with FCpt values >0. Hence, the model drops 76 groups (regions) and the analysis is carried out on the remaining 172 regions.[19] Each variable (See list of variables in Table 3.2) is therefore measured for each year 1993-2005 for each of the remaining 172 regions, hence N = 13 years x 172 regions = 2236.

3.5. Results

Table 3.3 shows the results of the negative binomial regression with fixed effects on the relationship between (1) controls, and (2) the FC-TR measure and the dependent variable FCpt. Model (1) confirms that Governmental R&D expenses are positively correlated with the level of fuel cell knowledge production (FCpt). However, the size of the region measured by population reveals a negative relationship. This could be due to the fixed effect, but running the same model with random effects show similar results. This could be an indication that fuel cell knowledge production takes place outside the most populated regions. The signs and significance for both controls are confirmed in Model (2) and (3).

The overall results revealed in model (2) show that fuel cell knowledge production (FCpt) is higher in regions with fuel cell related knowledge fields, although, some knowledge fields are more important than others. In total, five out of eight technology areas have a positive significant impact on the regional production of fuel cell knowledge, hence indicating a positive spatial relationship. The technology fields: 'chemical or physical processes', 'conversion of chemical energy into electrical energy', 'cables, conductors, insulators', 'materials e.g. ceramics', and 'analyzing materials' all have a positive significant association with the production of fuel cell knowledge in the consecutive three years. All these knowledge fields are central to the functioning of fuel cells. The two former refers to the main processes taking place in the core of the fuel cell: chemical process of energy conversion. The third knowledge field indicates the importance of knowledge in conductive materials to assure a high efficiency in the fuel cell's

[19] NUTS 2 codes for the 76 regions the model drops because of no fuel cell patenting activity: AT32, AT34, BE34, BE35, CZ02-CZ08, ES11-ES13, ES53, ES62, FI13, FI1A, FR21, FR83, GR11-GR14, GR21, GR22, GR24, GR25, GR41-GR43, HU21-HU23, HU31, HU32, IE01, ITC2, ITD1, ITD2, ITF2, ITF4-ITF6, ITG2, NL11, NL23, NL34, NO07, PL11, PL21, PL31-PL34, PL41-43, PL51, PL52, PL61-PL63, PT11, PT15, PT18, SE21, SE33, SK01-SK04, UKF3, UKJ4, UKK3

production of electricity. The knowledge field ‘ceramic materials’ is mainly of importance for solid oxid fuel cells where the electrolyte is made of ceramics. The last positive significant knowledge field, ‘analyzing materials’ refers mainly to determination of materials’ physical and chemical properties and makes the developers capable of monitoring, and testing any technological progress.

Table 3.3: Regional fuel cell technologically related knowledge stock effects on fuel cell patenting, negative binomial regression with fixed effects for European regions (NUTS2), 1992-2007

	(1)	**(2)**
CONSTANT	11.627 (1.759)***	3.677 (2.081)*
LAG.1 FC		0.010 (0.001)***
FC-TR:		
CHEMICAL OR PHYSICAL PROCESSES		**0.486 (0.103)*** **
CONVERSION OF CHEMICAL ENERGY INTO ELECTRICAL ENERGY		**1.492 (0.644)** **
CABLES; CONDUCTORS; INSULATORS;		**5.532 (1.256)*** **
ELECTROLYTIC PROCESSES		-1.441 (2.399)
ELECTRICAL VEHICLES		-2.079 (2.801)
CERAMICS; MATERIAL		**1.301 (0.544)** **
ANALYZING MATERIALS		**2.547 (0.195)*** **
CIRCUIT ARRANGEMENT; STORING		2.466 (1.812)
R&D (LOG)	1.101 (0.076)***	0.620 (0.085)***
POPULATION (LOG)	-1.267 (0.139)***	-0.557 (0.163)***
N (Regions)	172	172

*** P < 0.001, ** P < 0.05, and * P < 0.1

Three knowledge fields show no significant relationship to the production of fuel cell knowledge. First, the knowledge field of ‘electrolytic processes’ reveals no significant relationship. Since electrolysis is the inversed chemical process of what takes place in the fuel cell, this could indicate that the two fields have started growing into two independent technological trajectories concurrently with an increased specialization. Second, the field of ‘electrical vehicles’ is not significant to production of FC knowledge. This might indicate that most development within electrical vehicles takes place independently of fuel cell development because most electrical vehicles rely solely on batteries as the energy converter technology. In some cases fuel cell systems are perceived as sub-systems to the electrical vehicles, but the contrary does not apply. Hence, electrical vehicles knowledge is not necessarily spatially associated with fuel cell knowledge. The knowledge field of ‘circuit arrangements, and storing’ is a third field that shows no significant relationship to fuel cell knowledge production. The reason could be that circuit arrangements and systems for energy storing have the character of being mere supportive arrangements to the core functions of the fuel cell.

Table 3.4: Regional fuel cell technologically related diversity (FC-TR-DIV) effects on fuel cell patenting, negative binomial regression with fixed effects for European regions (NUTS2), 1992-2007

	(3)
Lag1_DV	-0.001 (0.001)**
FC-TR-DIV:	
1 out of 8	0.299 (0.348)
2 out of 8	0.258 (0.344)
3 out of 8	0.6560 (0.342)*
4 out of 8	0.818 (0.344)**
5 out of 8	1.128 (0.347)***
6 out of 8	1.192 (0.349)***
7 out of 8	1.398 (0.352)***
8 out of 8	1.667 (0.359)***
Constant	13.842 (1.932)***
R&D (LOG)	0.891 (0.095)***
Population (LOG)	-1.386 (0.156)***
N (Regions)	172

*** $P < 0.001$, ** $P < 0.05$, and * $P < 0.1$

Table 3.4 shows the results of the third model running the analysis on fuel cell technological related diversity (FC-TR-DIV) measure. The results confirm that the more knowledge fields that are represented in a region, i.e. the larger diversity of fuel cell related knowledge fields, the larger probability to generate fuel cell knowledge in the following three years.

Model (3) shows in fact that regions with three or more fuel cell related knowledge fields have a significant higher probability to generate fuel cell knowledge, and that the correlation coefficients are increasing by the number of knowledge fields present in a given region. This indicates that the higher degree of technological relatedness between the regional knowledge base and that of an emerging industry, the higher the probability is of a new industry to emerge in that region.

3.6. Conclusion

The objective of this paper has been to pursue the evolutionary thesis that regions develop along technological trajectories also in the case of radically new industrial paths. The main contribution has been to test empirically if the creation of new regional industrial paths is driven by knowledge spillover processes enhanced by technological relatedness to preexisting regional economic activities, which the findings support.

Secondly, the objective has been to enlarge our knowledge on the character of such location specific resources. Previous studies have made use of industry classifications, but the great advantage of the current study is it provides more detailed proof of the relationship between a region's knowledge base and its technological relatedness to an emerging technology. The empirical results can be summarized by the following two points: 1) the analysis points towards specific technologically related knowledge fields which are significantly co-located with the generation of fuel cell development, and 2) it reveals that the higher degree of technological relatedness present in a given region, the higher probability is there for a region to branch into fuel cell technological development.

Thirdly, the paper has developed a new measure of technological relatedness using regionalized patent databases, which seems to have certain advantages, in particular, when studying new technology areas that are not recognized by industrial classification systems (e.g. NACE).

One central question these findings arise is what causes the evolutionary processes of the creation of new variety at the regional level. The results here suggests that this process is highly localized in space (at least within borders of NUTS2 regions) but does not reveal how much of this process can be ascribed to firm diversification (specific firm-bound scientific and technical knowledge), spinoffs, or to locational advantages causing positive externalities. Boschma and Wenting (2007) show that spinoff processes play a larger role than locational economies in the early years of industry development. If future research can provide further evidence of such character it will be extremely valuable for understanding the evolutionary development of new industries and their spatial manifestation.

The results also raise questions of more fundamental character: the level of discontinuity of radical technological change and its implications for new regional industrial paths. As was pointed out in Section 2, the discontinuous nature of radical technology has caused economic geographers to argue that new (radical) industries develop independently from preexisting industrial structures. The findings of this paper suggest that even in the case of radical technology development, knowledge production is also highly cumulative and build on preexisting localized scientific and technical knowledge resources, which imply that the emergence of radically new industrial paths is highly place-dependent (Martin and Sunley, 2006).

These findings also have interest of more practical character. Today, we often see regional governments across the world launching innovation policies that seek to promote new high-tech clusters, such as fuel cells (through hydrogen community strategies), or other high-tech areas such as IT, biotech, nano-technology etc. This study, together with other similar studies, suggests that in doing so building upon pre-existing regional resources might show to be a more sustainable starting point for regional innovation policy.

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CHAPTER 4
THE MECHANISMS OF REGIONAL BRANCHING

by

Anne Nygaard Tanner

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 industry and the degree to which the underlying logic of these mechanisms is ‘technological relatedness’. It is concluded that the actors currently dominating the emerging fuel cell industry are either large incumbent multinational enterprises (MNEs) or smaller dedicated fuel cell 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 fuel cell technology. Large MNEs that integrate fuel cell systems into application diversify vertically upstream. However, they build less on technology competences that are related to the core scientific principle of the fuel cell. 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.

4.1. 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). Emerging industries, however, also have the potential to cause drastic changes in a region's economic structure, especially if they cause existing industries to disappear.

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'[20], 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., 2011a) and for the emergence of radical fuel cell technology across European regions (Tanner, 2011). However, the emerging literature on 'regional branching' has a number of shortcomings, which are the focus of this paper.

First, it has been put forward that we lack a thorough understanding of the mechanisms that catalyze regional branching (Neffke et al., 2011a). 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 takes a step toward 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 fuel cell industry, and ii) to what degree is the underlying logic of these mechanisms 'technological relatedness'?

Second, studying the emergence of a new industry in 'real time' offers the opportunity to refine the conceptualization of regional branching. It is argued that the concept of regional branching is constrained in its explanatory power of

[20]In this paper, regional branching is used interchangeably with regional diversification. However, the concept of regional diversification differs in content from its use in the 1970s and 1980s, where the literature was concerned with how a region could create economic stability by being optimally diversified across the primary, secondary, and tertiary sectors, respectively) (Wood, 1984).

emerging industries because it tends to ignore other knowledge-producing actors, such as universities and research institutions, and their role in inducing the development of new industries. In contrast, regional branching has thus far been applied very narrowly as a process that has its origin in the pre-existing regional industry (Boschma and Frenken, 2011a, Neffke et al., 2011a). However, it is evident and well proven that the pre-existing industry is not the only knowledge resource in a region. According to the national and regional innovation system framework (Lundvall, 1992, Cooke, 2001, 2004), in addition to the pre-existing industry (knowledge-exploiting actors), a regional knowledge base consists of knowledge-exploring actors such as universities and research institutes. In particular, in the creation of new knowledge-intensive industries, universities and research institutes have been shown to play a significant role (see e.g. Zucker et al., 1998, Audretsch, 2001). In this paper, I initiate a discussion of the role of universities and research institutes in regional branching processes.

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 industry. The emerging fuel cell 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 fuel cell 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, Conte et al., 2004). 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 fuel cell is an electrochemical device that generates electricity based on a chemical reaction between a fuel, usually hydrogen, and oxygen. The scientific principle of fuel cells have been known since William Grove discovered it in 1839. Fuel cells have also been used in NASA spacecraft programs since the 1960s and 1970s. However, its wide scale potential was recognized due to progress in a number of related scientific fields, such as material science, chemistry, and nanotechnology. These and other knowledge fields play a key role in the development of fuel cell technology 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, 1988b, p. 1126).

Technological change in the field of fuel cell 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 fuel cell knowledge base (Tanner, 2011, Dibiaggio and Nasiriyar, 2009), which requires a broad scope of in-depth and interdependent competences (Hellman and van den Hoed, 2007). 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 fuel cell industry is currently characterized by a mix of young dedicated fuel cell firms and large incumbent multinational enterprises (MNEs) (Brown et al., 2007, Hellman and van den Hoed, 2007, Pilkington et al., 2009, Nygaard, 2008). 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 fuel cell and hydrogen-related activities (Madsen and Andersen, 2010, Musiolik and Markard, 2011, Mans et al., 2008, Bourgeois and Mima, 2003,).

Aside from a number of qualitative case studies of hydrogen and fuel cell cluster initiatives (Holbrook et al., 2010, Mans et al., 2008, Amesse et al., 2003, Hodson et al., 2008, Hodson, 2008), the emergence of the fuel cell 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 fuel cell 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 fuel cell patent applications and characterizes a variety of regional economies that are involved in knowledge production in the emerging field of fuel cells. Second, the analysis examines the different types of regional branching mechanisms by focusing on the actor with the largest share of fuel cell patents for each region. It is concluded in Section 5 that the actors currently dominating the emerging fuel cell 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 fuel cell technology, whereas more downstream firms that integrate the fuel cell systems into applications build less on technology competences that are related to the core scientific principle of the fuel cell. The downstream firms diversify vertically upstream. As predicted, university research plays a significant role in some regions, while the role of smaller dedicated fuel cell developers is important in other regions.

4.2. 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, Menzel and Fornahl, 2010, Fornahl et al., 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, 1988b, 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 (Day et al., 2000).

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' (Andersen, 2011).

4.2.1 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., 2011a). Neffke et al. (2011a) 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 fuel cell technology, the more likely the region is to branch into the emerging fuel cell field.

4.2.2 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, namely firm diversification and spinoffs.

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[21], a firm may diversify into technologies that are not related to the knowledge base of the firm. This process

[21] I use the concept of vertical diversification here, which is very similar to the concept of 'vertical integration' (see e.g. Macher and Mowery, 2004); however, the concept of vertical diversification underlines that the firm changes its direction of search (knowledge base).

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.

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 (Moore, 1996, 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, in the case of radical, emerging industry, likely to be the primary mechanism for regional branching under certain specific conditions, only. 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.

4.2.3 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 several 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, purposeful 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 (Martin and Sunley, 2006, Garud and Karnøe, 2001).

A more accommodating aspect of emerging industry development is the regional and national institutional settings that support and sustain the development of new industries. In particular, developing "green innovations" may require higher institutional support than innovations that are more easily brought to markets.

Finally, supportive actors such as universities, governments, and interest organizations that make up the regional innovation system (Cooke, 2001, 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.

4.3. Method

This study focuses on a selection of European regions that make up the majority of fuel cell knowledge production approximated by patent applications. The analytical strategy is as follows. First, European NUTS2[22] regions with the largest shares of fuel cell patenting between 1993 and 2007 are identified. Second, the largest fuel cell patenting players for each region are identified, and third, the largest players' development paths into the emerging fuel cell 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 (OECD, 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 (Ter Wal and Boschma, 2009). The International Patent Classification (IPC) system is used to identify patent applications with fuel cell content. The IPC-code 'H01M008' refers to the classification of "fuel cells, and manufacture thereof". This method defines fuel cell patent activity rather narrowly[23], which is consistent

[22] European NUTS2 regions are defined as "basic regions for the application of regional policies" within a threshold of 800,000 and 3 Mio inhabitants (European Communities, 2007). However, there are large differences between NUTS2 regions as some fall outside the threshold and others do not have any jurisdiction to implement regional policies. Still, NUTS2 regions are preferred above NUTS1 and NUTS3 for the spatial mapping of new industries.
[23] Thus, the sample only includes patent applications that have a primary fuel cell relevant content. Patents with a more secondary relevance for fuel cells are not included in this sample, such as material development that is relevant for many other types of electricity converters, including

with the purpose of this study, that is, to identify actors with core development activities.

Once the fuel cell 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[24]. 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 fuel cell 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 fuel cell technology and/or industry and with companies from each node in the fuel cell value chain, that is, upstream, downstream and core fuel cell system developers. Additionally, a few interviews were conducted with representatives from regional hydrogen and fuel cell organizations. The interviews were based on a semi-structured model that addressed the firms' history, its state-of-the-art regional activities, and its linkages between existing industry structure and the new industry.

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batteries and hybrid cells; tank devices with a possible but not limited application option in fuel cell vehicles; or principles of handling different heat sources that are not restricted to specific fuel cell development issues.

[24] Note that it is quantity rather than quality of knowledge production that is measured. Moreover, the production of knowledge as measured by patents does not necessarily correspond to where the knowledge might be used due to transactions of intellectual property rights between firms across regional and/or national borders.

4.4. Analysis

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

4.4.1 The framing of fuel cell industry emergence

Fuel cell technology and the emerging industry that evolves around it belong to a wider platform of innovations that is referred to as 'green innovations' (Cooke, 2010). The green potential of hydrogen fuel cells 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 great interest in the fuel cell industry has culminated in the concept of a 'hydrogen economy' as a substitute to the fossil-fuel based economy, with hydrogen serving as the major energy carrier rather than oil and coal (Rifkin, 2004). The realization of a hydrogen economy may seem far away, especially following the lowered expectations that followed the hype in the beginning of the 2000s. However, none of this seems to have weakened the interest and efforts in developing the technology (Ruef and Markard, 2010).

The characteristic feature of fuel cell 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 fuel cell 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 fuel cell 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.

4.4.2 The diversity of regions branching into the emerging fuel cell industry

Analogous to other studies on the spatial distribution of high-tech patenting (Feldman and Lendel, 2010), fuel cell patenting is concentrated in a small group of regions (see Table 4.1). Out of a total number of 271 NUTS2 regions, 189 regions have a share in the 2165 fuel cell patents applied for between 1993 and 2007. During the same period, 80% of the patents are recorded in 42 regions, and 60% of the total fuel cell patent applications are applied for by 6.6%, or 17, of the 271 NUT2 regions. This confirms a clear pattern of concentration of fuel cell knowledge generation in a low number of regions.

Table 4.1: Development of the distribution of fuel cell patent applications across European NUTS2 regions

Number of NUTS2 regions	Total fuel cell 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	1297	60	76.3	68.3	49.8
1993-1997					
189	209	100	1.1	0.0	3.6
42	175	83.4	4.2	1.1	6.6
17	151	71.9	8.9	8.7	8.5
2003-2007					
189	1035	100	5.5	1.5	11.5
42	793	76.5	18.9	12.6	18.8
17	547	52.9	32.2	28.0	23.4

Own calculations based on OECD REGPAT, December 2010

However, the development during this period reveals a diminishing spatial concentration. The share of fuel cell patent applications recorded by the 17 most active patenting regions decreases from 72% in the first period (1993-1997) to 52.9% in the second period (2003-2007). As this is still considered the fluid phase, the period reflects increasing entry, mirroring a decreasing concentration.

Figure 4.1 illustrates the geographical distribution of the 17 regions that account for 60 % of fuel cell 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 fuel cell patenting regions. Four other countries have NUTS2 regions that are among the most fuel cell 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 fuel cell 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.

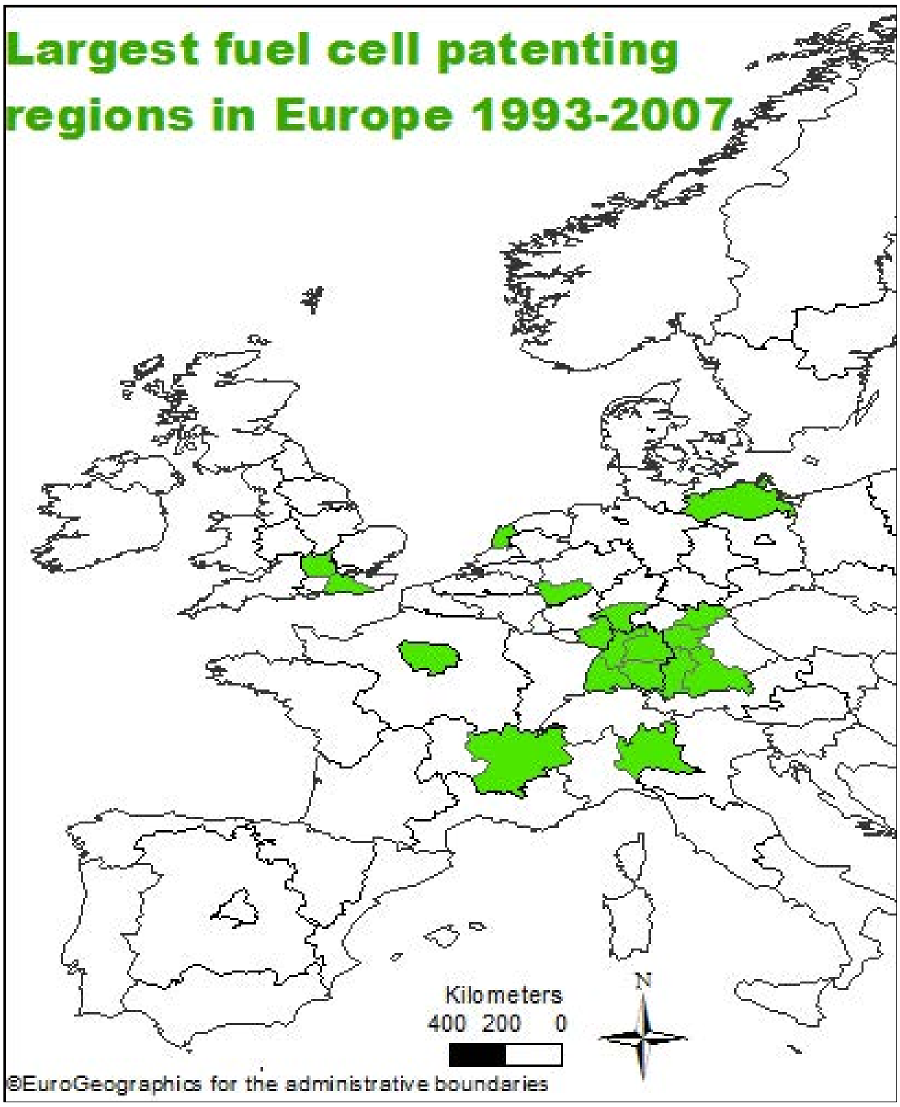

Figure 4.1: The largest fuel cell patenting regions in Europe, 1993-2007, Source: OECD REGPAT, Dec 2010.

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 fuel cell patenting regions already had employment shares in high-tech sectors that were much higher than 4.4 % in 2000 (see Table 4.2). 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.

Table 4.2: Regions with total patent applications, European high-tech employment, and fuel cell patents per 10,000 high-tech employees, 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: Own 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.

Although the total level of fuel cell knowledge production is important, a comparison of the largest fuel cell regions based on a relative measure can indicate how productive the regions are in fuel cell knowledge generation. Table 4.2 shows the ratio of fuel cell patents per 10,000 high tech employees. The relative measure of fuel cell 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 fuel cell knowledge generation accounts for a minimal share of its high-tech patents. Considering the most patent-productive regions, column 5 in Table 4.2 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 fuel cell patents, except for Upper Franconia with 35.8 and Mecklenburg-Western Pomerania with 33.6 fuel cell patents. The latter two produce, respectively, 16.6 and 13.6 fuel cell patents per 10,000 high-tech employees.

In particular, it is interesting that Mecklenburg-Western Pomerania is among the most productive places in fuel cell 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 fuel cell 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.

4.4.3 Regional diversification mechanisms

Table 4.3 displays the number of total fuel cell patent applications, patenting entities, mean per patenting entity, and the share of university patents and the largest patenting entity for each of the largest fuel cell patenting regions over a fifteen-year period. [25] The largest fuel cell patenting regions are characterized by housing either a large anchoring MNE, a smaller dedicated fuel cell system developer, or a university or research institute. According to the narrow definition of fuel cell knowledge, the actors all have development activities within the core of fuel cell technology. However, the different actors are related to the fuel cell value chain in different ways (see Table 4.4 for a description of the fuel cell value chain).

[25] The figures are calculated based on where the inventors, who have produced the patented knowledge, reside. Because it is often the case that more than one inventor is involved in the same patent application and they do not necessarily live in the same region, the numbers are aggregated based on regional shares. Hence, the data reveal where the inventors behind the patent applications live, which is obviously not necessarily the same region as the applicant (firm or university) is located, but it is assumed that it is within commuting distance to the applicant. Hence, large firms may be the dominating applicants in several neighboring regions even though they are only located in one region.

Table 4.3: 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.	Largest Patenting entity Entity name
Stuttgart	Baden-Wuerttemberg	47	4.6	14%	25%	DAIMLER
Karlsruhe	Baden-Wuerttemberg	31	1.5	25%	23%	FREUDENBERG GROUP
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 FUEL CELLS
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

Table 4.4: The fuel cell value chain based on Nygaard (2008)

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**

i) The abbreviations refer to the types of fuel cells such as proton exchange membrane fuel cell (PEMFC), solid oxide fuel cells (SOFC) and direct methanol fuel cells (DMFC), which are the most common fuel cell systems today.

Upstream fuel cell component developers

Upstream in the fuel cell 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 fuel cells 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 fuel cells and may work for many types of applications.

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 fuel cell 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 fuel cells (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 fuel cell field by developing complete MEAs for proton exchange membrane fuel cells (PEMFC). Johnson Matthey's fuel cell development activities date back to the 1950s, when they focused on alkaline fuel cells for the NASA space program and phosphoric acid fuel cells for large stationary power stations. Since 2000, however, Johnson Matthey's fuel cell activities have been organized in the subsidiary Johnson Matthey Fuel Cells Ltd. in partnership with Anglo Platinum, which owns 17.5%, and the company is now focused on MEAs for PEMFC.[26]

BASF has also had experiences in another type of fuel cell, namely, the direct methanol fuel cell (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 fuel cell-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 fuel cell 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 fuel cell technology field. However, both BASF and Johnson Matthey have moved a step downstream and developed the core component of the fuel cell (MEAs), where the electrochemical reaction actually occurs.

Dedicated fuel cell system developers

Further downstream in the fuel cell value chain are the fuel cell system developers where sub-systems and components are integrated into a fuel cell system. This segment is represented by three smaller companies in our sample, namely, SFC

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

Energy AG, New Enerday, and Nuvera Fuel Cells Europe. These are dedicated fuel cell system developers that differ from one another with respect to the type of fuel cell they develop and their market approach, which often has a niche character.

The three dedicated fuel cell system developers have followed different paths into the fuel cell field. New Enerday, with approximately 10 employees, is a firm spinoff based in Mecklenburg Western-Pomerania. This small firm has the majority of the fuel cell patents 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 fuel cell 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 fuel cell technology systems that were built upon its related core competences in heating and auxiliary electrical arrangements. However, in 2010, Webasto sold off the fuel cell development activities, and New Enerday was 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. SFC Energy was founded in 2000 based on Dr. Manfred Stefener's promotion of electrode structures for direct methanol fuel cells. SFC Energy produces fuel cell systems (DMFC) to leisure markets, off-grid and defense organizations. Since 2003, SFC has shipped more than 20,000 fuel cell systems to a range of niche market segments, and it has grown to approximately 100 employees.[27]

Nuvera Fuel Cells Europe was originally the Italian electrochemistry Group De Nora's fuel cell subsidiary. De Nora Fuel Cells 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 fuel cell system developers focus on assembling the system and, hence, rely heavily on suppliers of fuel cell 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.

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

System integrators: The application of fuel cell systems

Closest to the markets are the system integrators that incorporate the fuel cell system into a complete product. Examples include automobiles, combined heat and power systems, laptops, and hearing aids. In the largest fuel cell 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 fuel cell drive systems for the propulsion of vehicles. All three, however, can be said to diversify vertically upstream into the field of fuel cell technology.

The automotive manufacturers' interest in fuel cell technology was initiated by the Canadian Ballard Power System's breakthrough at the end of the 1980s, which reduced the cost of a fuel cell 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 fuel cell technology provided greater potential because of the higher energy density level obtainable with high-pressured hydrogen as fuel. However, moving into the field of fuel cell technology has not been uncomplicated for Daimler, as their core competences are technologically centered on the internal combustion engine (ICE) and the skills associated with the mechanically moving part in this type of engine. In the fuel cell, the core scientific principle is very different, and there are no moving mechanical parts in the fuel cell-powered engine. Therefore, Daimler did not have a high level of in-house capabilities that was technologically related to the core scientific principle of the fuel cell. According to Dr. Jörg Wind, Daimler AG, Daimler first had to establish a basic understanding of the fuel cell 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, fuel cell 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 fuel cell 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 fuel cell stacks and systems, respectively. The fuel cell stack developer and producer is the 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 fuel cell system integrator and developer NuCellSys, which is located in Nabern, near Daimler's headquarters in Stuttgart.

Table 4.5: Firm diversification along the fuel cell value chain

Upstream	2	3	Downstream
Freudenberg Group			
Johnson Matthey →	Johnson Matthey Fuel Cells Ltd.		
BASF →	BASF Global Fuel Cell and Research Centre		
		New Enerday	
		SFC Energy	
		Nuvera Fuel Cells ← - -	
		- - →	**Renault**
	AFCC ←	NuCellsys ←	**Daimler**

Arrows indicate direction, dashed line=strategic alliance, italic= spinoffs

In sum, Table 4.5 illustrates the diversification paths the different firms have followed. The Freudenberg Group has diversified horizontally into the fuel cell field, but it has not diversified along the fuel cell value chain. BASF and Johnson Matthey have, on the other hand, moved downstream in the fuel cell value chain and are currently developing MEAs for PEMFC. Renault builds on a strategic alliance with Nuvera Fuel cells in delivering fuel cell systems, while Daimler has diversified vertically upstream and, by maintaining control of the two subsidiaries, is in control of most of the fuel cell value chain.

A measure of firm's fuel cell-related competences

For four MNEs[28], it has been possible to calculate a specialization index[29] for a five-year period (1988-1992) prior to the time when the development in fuel cell technology exploded (see Table 4.6). The last row shows the percentage of the total fuel cell knowledge base that is embraced by the particular knowledge field.[30]

[28] It is not possible to calculate the specialization index for the other large MNEs - Freudenberg Group and Renault S.A.S - as their patent portfolio filed under the PCT during the years 1988-1992 was too small. The same holds for the smaller fuel cell system developers.

[29] The specialization index (S) is a measure that indicates a firm's technological specialization for a number of fuel cell-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.

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

The table indicates that the large MNEs build on different fuel cell-related competences and that this corresponds with their position in the fuel cell value chain. As described above, BASF and Johnson Matthey are engaged upstream in the fuel cell value chain; they build on their in-house capabilities within chemical and physical processes that are at the core of the fuel cell technology. This is illustrated by the fact that BASF and Johnson Matthey are specialized in the knowledge fields that make up 29 % (see Table 4.6) of the fuel cell knowledge, thereby indicating a high degree of technological relatedness to the fuel cell knowledge base.

Table 4.6: Technological Specialization index for selected MNEs in the period 1988-1992

	Fuel cell knowledge base								
	Total fuel cell-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	-	12.7	-	-	5.15
Siemens	-	-	-	1.32	-	6.29	-	-	4.98
BASF	1.45	2.42	-	-	2.13	-	-	-	-
Johnson Matthey	2.17	2.41	-	-	-	-	-	-	-
Share of FC knowledge base	66%	29%	23.1%	4.3%	3.4%	2%	1.7%	1.4%	1.3%

Source: OECD REGPAT December 2010. For definition and identification of fuel cell 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 less knowledge about electrochemistry and fuel cells in particular. This is also shown by the results from the patents analysis in Table 4.6, thus Daimler had to enhance in-house competences (absorptive capacity) to be able to understand the technology.[31]

[31] In fact, Daimler was able to build on some fuel cell specific competences from the aircraft manufacturer Dornier, acquired in 1985. However, these were peripheral to the company and had to be integrated before their knowledge became an asset to Daimler’s fuel cell effort (Ernst, 2007)

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).

4.4.4 The role of universities in the creation of fuel cell industry

A final result from Table 4.3 that should be emphasized is the role of universities and research institutes. As is seen in column five in Table 4.3, there are significant variations in university shares between the largest fuel cell patenting regions ranging from 2% to 67%. According to this, it is evident that some regions' fuel cell activities are mainly driven by university research. This is the case for Freiburg in Baden-Wuerttemberg (44%), Cologne in North Rhine-Westphalia (67%), Rhône-Alpes (58%), and North Holland (63%). In these regions, the largest patenting entity (columns six and seven) reflects the high university share and is either a research institute or a university.

High levels of university knowledge production may serve different functions in supporting the build-up of new industries within regions because of the different types of knowledge transferring channels between the university and the industry (Feldman et al., 2002). These include sponsored or collaborative research projects, patents and licensing, educated skilled labor, social networking, and university spinoffs.

Until recently, education in hydrogen and fuel cell technology at the university level has been rather sporadic (e.g., summer schools, short courses). Thus, most training has occurred internally within the fuel cell and hydrogen companies.

Hence, the two major knowledge transferring channels that have characterized the role of university and research institutes in relationship to fuel cell development have been collaborative research projects and university spinoffs.

Both large MNEs and smaller dedicated fuel cell system developers rely heavily on collaborative research with universities and research institutes. For example, New Enerday in Mecklenburg Western-Pomerania collaborates closely with the Leibniz Institute for Catalysis at Rostock University and the University of Applied Science in Stralsund. Similarly, in a Danish context, Topsoe Fuel cell, a subsidiary of the global catalyst supplier Haldor Topsoe A/S, established a close partnership with Risø DTU in 2000 when Topsoe expressed an interest in developing SOFC.

Spinoffs from universities and research institutes constitute another knowledge-transferring mechanism that has a direct impact on regional branching processes. This is the case for SFC Energy, though there are many more university spinoffs that the paper's methodological approach has been unable to highlight (see also Upstill and Symington, 2002). For instance, in North Holland, the Dutch spinoff company InDEC B.V. was founded in 1999 based on research activities carried out at the 'Energy Research Centre for the Netherlands' (ECN). ECN developed some SOFC components that had market potential. When the market potential was realized, the production was separated from the research activities, and these activities later became the basis of InDEC's activities (Brett et al., 2006).

Consequently, university knowledge may play an important role in further supporting regional branching processes, particularly in complex, knowledge-intensive emerging industries such as the fuel cell industry. An embryonic industrial interest in a new field such as fuel cells may in fact encourage universities to assign more resources to the field, which in turn creates a greater foundation for new business ideas in a particular region (Vargas and Holbrook, 2010). However, for universities and research institutes to function as core catalyzing mechanisms for regional branching processes, other studies suggest that the region should be characterized by an entrepreneurial culture (Feldman, 2001). In other words, a region must be equipped with an institutional and infrastructural support system that, together with an entrepreneurial spirit, can secure exploitation of the generated knowledge before a region may benefit from high shares of university knowledge.

4.5. Discussion and conclusion

This paper set out to investigate the mechanisms through which regional branching into the emerging fuel cell industry operate. The analysis was performed on a profile of regions (17 NUTS2 regions) representing 60 % of all fuel cell 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 fuel cell industry but a segment, nonetheless, that provides qualitative insight into the various types of actors that have initiated regional branching processes in the fuel cell industry. In addition, our sample turned out to have firms well distributed along the fuel cell value chain, which provides unique insight into the heterogeneity of the actors currently constituting the fuel cell industry.

The results depict an industry that is dominated by large MNEs that diversify vertically along the fuel cell value chain and by smaller dedicated firms that concentrate on developing and assembling fuel cell systems. The dedicated fuel cell 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[32]. Hence, based on the sample of firms, firm diversification seems to be the dominating mechanism through which regional branching operates in the emerging fuel cell industry.[33] 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 fuel cell 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 fuel cell technology builds on a new knowledge base that draws strongly on electrochemical disciplines. According to Dosi's (1988b) 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 fuel cell knowledge base, downstream MNEs have had fewer competences that were technologically related to the core principle of the fuel cell. 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).

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[32] New Enerday is a spinoff founded on Webasto's subsidiary Enerday's activities, and Nuvera Fuel Cells was originally a subsidiary under the Italian De Nora Group.

[33] In a way, the sample of actors represents the surface soil in a soil profile (to maintain the geographical terminology), and as such, this study says little about the undergrowth of actors that represent the underlying layer. These may be characterized by higher levels of spinoffs. Nevertheless, almost 60 % of all non-university patenting in the sample regions are ascribed to the large players we have investigated.

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 fuel cell 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 fuel cell firms and large multinational firms 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 fuel cell industry, their inherited routine-based behavior of acting globally through a net of subsidiaries is passed on to the knowledge-producing activities within fuel cell 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.

Finally, the analysis identified four regions where university and research institutes played an important role for producing new knowledge within fuel cell technology. This may propose expanding the concept of regional branching to also include universities and research institutes. For instance, by reformulating the concept of regional branching as new industries that grow out of regional knowledge bases that encompass both knowledge-exploiting actors (pre-existing industry) and knowledge-exploring actors, such as universities and research institutes.

CHAPTER 5
DISCUSSION AND CONCLUSION

5.1. Introduction

In the preceding three chapters, I have analysed the localisation of the emerging hydrogen and fuel cell industry with a strong focus on the knowledge dynamics at the heart of new industry foundation. The importance of knowledge and in particular of the creation, use, and diffusion of knowledge in the current economy has been emphasised by many scholars (Foray, 2004, Lundvall, 1992, Lundvall et al., 2002) and is considered to be central to creating technological change (Dosi, 1982, 1988b). The three chapters have focused on understanding the spatial relationship between pre-existing knowledge resources and the creation of new economically valuable knowledge based on a new, radical technology. Whereas Chapter 2 explored the degree of co-location between some broad regionalised measures of economic activity and hydrogen and fuel cell demonstration activities, Chapter 3 and 4 described more systematic research on the level of technological relatedness between localised knowledge resources and the emerging fuel cell industry.

The findings from all chapters point in the same direction: radical emerging industries develop where they do because the process of learning (creating new knowledge) is cumulative and builds upon technologically related knowledge competences. In other words, the spatial origin of new industries strongly depends on the accumulation of technologically related knowledge resources in space. These findings give rise to a number of discussions of their implications for our understanding of the spatial context of industry emergence, as well as for regional innovation policy. This chapter is devoted to reflections on these implications, as well as on the limitations of the findings.

5.2. Discussion of findings

5.2.1 A summary

Chapter 2 focused on the location of hydrogen and fuel cell demonstration activities, including a measure for regions' interest in becoming a 'hydrogen community'. This chapter highlighted the importance of regional innovation systems that are geared to create new knowledge. We found a positive relationship between regions that are generally perceived as high-functioning innovation systems and a high level of hydrogen and fuel cell demonstration activities. This relationship indicates that innovative regions can more easily develop highly complex technological systems. Possible reasons for this difference include the easier access to and flow of knowledge and financial resources. Moreover, Chapter 2 gave the first indication of a positive relationship between a region's industry structure and the localisation of hydrogen and fuel cell demonstration activities, although we did not find a strong positive relationship to pre-existing hydrogen production and infrastructure facilities.

We cautiously interpreted the findings in Chapter 2 to be indications of the importance of institutional support for the development and demonstration of hydrogen and fuel cell technology. Together with the findings of a possible relationship to the pre-existing industrial structure, this exploratory piece of research highlights the need for more thorough research into the role of both elements.

In the subsequent research, however, I chose to focus only on the influence of pre-existing local knowledge and technological resources on the emergence of new technology. It is reasonable to argue that new industries should be primarily the products of these factors and that the institutional environment will rarely trigger a new industry to emerge (Martin, 2010, Boschma and Frenken, 2009). Beyond the basic institutions, such as markets, property rights and a judicial system that are prerequisites for the development of economic activity (Boschma and Frenken, 2009), the institutional environment is in general perceived to play an either enabling or constraining influence on the emergence of new technologies or industries (Martin, 2010).

Chapter 3 adopted the evolutionary economic geography perspective and examined whether the creation of new economic variety in fuel cell technology was influenced by the regional knowledge base. To this end, I developed a new measure of technological relatedness based on OECD's regionalised patent data. This tool made it possible to investigate the degree of technological relatedness between the emerging fuel cell technology and the regional knowledge base. The findings confirmed the evolutionary hypothesis that knowledge generation, also in the case of radical technology development, is cumulative in its spatial and cognitive dimensions. This research is important for its support of the evolutionary thesis of regional path-dependent development, even in the case of new path creation. This paper, however, shed no light on the mechanisms through which regional branching may occur. Those mechanisms were explored in Chapter 4.

The knowledge base of a region is an analytical expression of knowledge, education, on-the-job training, competences and skills that people possess and utilise to generate new knowledge. In most cases, human resources are organised in firms, universities, or research institutes and are pooled together for a common purpose – to solve technical or scientific problems, for example, or to increase firm performance. Hence, Chapter 4 began with an interest in uncovering the drivers of early diversification into fuel cell technology, as seen in the previous chapters. The analysis was based on an alternative methodological approach that made it possible to focus on a variety of regional economies and actors with high shares of knowledge production in fuel cell technology. The analysis identified a number of large MNEs and a smaller number of dedicated fuel cell system developers and *tracked* the paths of each into the emerging fuel cell industry. These findings contribute both to a clarification of the mechanisms of regional branching and to an understanding of the industrial dynamics of the emerging fuel cell industry. In Chapter 4, firm diversification is found to be the dominant mechanism of regional branching into fuel cell technology. Additionally, I conclude that firms diversify vertically along the fuel cell value chain in order to build up specific knowledge competences that will make them capable of *mastering* the new technology; however, the findings revealed that the degree to which firms build on internal technologically related competences vary. Upstream firms appear to possess competences with a higher degree of relatedness to the fuel cell knowledge base than downstream firms. This pattern suggests other explanations for regional branching besides the availability of technologically related knowledge resources, which are discussed in more detail in the next section.

5.2.2 Discussion and implications

In the preceding chapters this thesis has focused on investigating the relationship between pre-existing knowledge resources in regions and the spatial emergence of an industry. The purpose has been to determine the extent to which industry emergence is embedded in geographical territories. Such inquiries would shed light on the factors underlying the formation of new industries in regional economies and help to resolve the dispute, introduced in Chapter 1, over the role of ‘chance events’ in the emerging field of evolutionary economic geography. This thesis offers some clarification of this issue.

The findings in this thesis support the idea that new industries are place-dependent. Most notably, Chapter 3 confirmed a positive relationship between regions’ pre-existing knowledge resources and the emergence of a new industry. More interestingly, the evidence supports the theory that the higher the degree of technological relatedness between a regional knowledge base and the knowledge base of an emerging industry, the greater the probability that a region will diversify into that particular industry. As a consequence, the combination of different knowledge resources increases the chances that a region will diversify. The more possible knowledge resources are available in a given region, the greater the chance of branching. Thus, these results confirm interdependence between industrial paths in emerging technological paradigms. This result confirms that industries do not only produce new space; space also produces new industry. Consequently, this thesis lends support to the claim that industries are place-dependent (Martin and Sunley, 2006, Martin 2010).

This finding also confirms the evolutionary hypothesis that cumulative knowledge production, as Dosi (1984) proposes, increases the notional possibilities of technical solutions provided by scientific progress. Many of the technical solutions that are needed in the fuel cell technology today are highly complex; these problems have become solvable because of the accumulation of knowledge over long periods of time in certain key fields of the fuel cell knowledge base. For example, significant progress has been made in material science, chemistry, and nanotechnology over the last several decades; this progress contributes considerably to solving technical issues in fuel cell systems today. The findings indicate that the accumulation of this knowledge in specific regions allows the actors in those regions to advance in fuel cell technology. Consequently, these results confirm the hypothesis of the window of locational opportunity: accumulated generic resources influence the location of new industries. The question remains to what degree the presence of generic resources form part of the explanans of industries’ spatial emergence. And to what degree pre-existing knowledge resources interplay with other issues such as human agency and institutions, or whether the explanans is in accordance with the WLO approach; determined to some degree by chance. I return shortly to discussions about the WLO perception of chance events; first the thesis’ findings on human agency and institutions is discussed.

Besides regional knowledge dynamics, this thesis explores the presence and importance of human agency: risk-taking actors who are willing and able to implement and exploit an emerging technology (Dosi, 1982). These actors’ entrepreneurial (or intrapreneurial) activities shape emerging industries, and as a consequence, the industries induce changes in the economic landscape. Where the risk-taking actors are located, new industries emerge and influence the regional economies by building up specific fuel cell assets based on generic accumulated knowledge resources. Consequently, the emergence of new industry impacts the economic landscape.

Conversely, an interesting finding from Chapter 4 revealed that actors diversifying into the emerging fuel cell industry do not necessarily build on firm-internal resources that are technologically related to the core of fuel cell technology, though such resources are not totally absent. Nevertheless, other factors are needed to explain the selection of an emerging technology not based on firm diversification caused by technologically related resources to the emerging industry (i.e., economies of scope). In Chapter 4, it was suggested that these factors include changes in the institutional environment that are expressed in a long-term need for green energy technology. In addition, a lack of existing capabilities results from the technology's immaturity. The latter, together with a need to control and align incentives along the value chain, caused firms to diversify vertically upstream, although they did not possess core competences proximate to the fuel cell knowledge base. An understanding of such industrial dynamics is needed to explain the emergence of new industry in regions.

Thus, both industrial dynamics and institutional factors may contribute to reducing the role of chance in explaining industry emergence as suggested by the WLO-model. Institutional influence is an important element of Dosi's (1984) account of selection mechanisms under weakened market selection. Institutional factors guide search and selection in the earliest stage of a technology's evolution. Such institutional triggers are contained in the WLO model's connotation of "chance" (Boschma and Lambooy, 1999). There are two reasons that institutional influence is associated with chance in the WLO-model. First, there are multiple opportunities for influence at technological bottlenecks, shortage or abundance of input, shocks in prices or supplies, changes in demand and/or relative prices, or conflicts (Dosi, 1988a). Second, many institutional factors are omnipresent, and it is difficult to predict which triggers will induce industry development in any particular region (Boschma and Lambooy, 1999). Hence, institutional factors are resistant to predictions and generalisations. According to the WLO model, this trait excludes them from having any explanatory value; however, this conclusion is faulty. Institutional factors that seem fuzzy and contextual may still have explanatory value. It is the author's belief that institutional influence and industrial dynamics can increase the explanatory power of evolutionary thinking in economic geography on industry's spatial emergence. Such factors should be included in future studies on industry emergence. I will return to this theme shortly.

In sum, it is clear that localised knowledge resources alone cannot explain the spatial emergence of new industries. As argued in Chapter 1, new industry development results from a complex set of variables that develop interdependently under the influence of history and the nature of the given technology. To reduce this web of interrelated causes to 'chance events' is, conversely, deeply unsatisfactory. By arguing that generic knowledge resources are important in regional diversification into emerging industry, this thesis reduces the role of chance. Generic technologically related resources improve the propensity for new industries to emerge in a given region. Furthermore, the thesis indicates that the role of institutional changes and risk-taking actors in creating new industry will improve our understanding of how new industries come into being and in what sense these events are place-dependent.

Policy implications

Another reason that it is unsatisfactory to disclaim the role of institutional influence and reduce emergence drivers to incomprehensible chance events is that policy makers are subsequently left empty-handed with no tools to promote new industries. As illustrated in Chapter 1, numerous regions have regional strategies to develop 'hydrogen communities' by encouraging network (cluster) organisations. It was noted that such strategies have little theoretical foundation. The findings in this thesis have expanded the bases for regional innovation policy to promote new industry development.

By showing that technologically related competences are a prerequisite, or at least that they increase the likelihood that regions will engage in fuel cell technology development, I lend support to the idea that regional authorities should take the regional industrial base into consideration when designing new cluster policies. A long-term approach, however, may increase the regional knowledge base through research activities at universities and research institutes. Combined with a strategy to encourage entrepreneurial activities, such initiatives may also positively impact a region's ability to renew itself in the long term.

5.3. Future research

The research conducted in this thesis has increased our understanding of the embedded nature of emerging industries in geographical territories, with particular attention being given to regional knowledge dynamics; however, a comprehensive understanding of the drivers, including institutional factors, which induce new industries to emerge is still lacking. Future research should address this question;

in particular, it would be useful to determine systematically which types of institutional factors are important for the emergence of new industries, and during which period in the industry life cycle different types of institutions matter.

Furthermore, this research supports studies of industry emergence based on a comparative approach. Research on other emerging industries' territorial embeddedness would support and strengthen these results if they confirm the findings of this thesis. If, however, such research established differences between industries, then we would need to search for other drivers of the emergence of industries in space.

Finally, this research has also raised questions that are more limitedly related to the findings of the papers in this thesis. Below, I sketch an outline of some of the most straightforward ideas for future research that emerge from this research.

5.3.1 Local nodes in global networks?

In this thesis, it has been suggested that fuel cell knowledge production tends to be local, but this conclusion was generally built on the assumption that knowledge tends to spill over locally rather than globally (Audretsch and Feldman, 1996a, Jacobs, 1969, Antonelli, 2001, Marshall, 1890, Glaeser et al., 1992). For instance, in Chapter 2, we assume that co-location of hydrogen and fuel cell activity with particular hydrogen and fuel cell-friendly clusters may indirectly reveal a linkage between the two. In Chapter 3, we assume that the increase in fuel cell knowledge production is caused by the local knowledge base without establishing the direction of the knowledge flows (or, in other words, the spatial origin of the knowledge the fuel cell knowledge production builds on). Chapter 4, however, supports to a certain extent the localised nature of knowledge production in fuel cell technology development by showing processes of firm diversification and spinoffs that are clearly spatially bounded by the localisation of the pre-existing industry.

Conversely, the fact that MNEs play a dominating role in a majority of the regions casts doubt on the innate localised nature of innovation in the early stage of industry life cycles. The localized nature of young industries' innovative activities has been the prevailing understanding since Audretsch and Feldman (1996a) illustrated that innovative activities tend to cluster in the early stage of the ILC. There are two reasons why the role of MNEs early in industry evolution has implications for this understanding. First, 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 fuel cell industry, their inherited routine-based behaviour of acting globally through a net of subsidiaries is passed on to the knowledge-producing activities within fuel cell development. For example, Daimler taps into knowledge resources located in the Canadian fuel cell industry in Vancouver, *embodies* the knowledge in fuel cell stacks, and transfers this embodied tacit knowledge to its fuel cell system development facility in Nabern, near Stuttgart. The Daimler example is a clear indication of globalized knowledge flows which ought to receive more attention in economic geography.

Secondly, the way that Audretsch and Feldman (1996a) identify the different stages in the ILC is contradicted by the findings in Chapter 4, which consequently undermines their results. Audretsch and Feldman distinguish the different ILC-stages based on the size of the firms and the rate of product innovations such that small firms with above-average product innovations are assigned to the emergent stage of an industry, and large firms with high rates are assigned to the growth stage. This finding is obviously contradicted by the findings in Chapter 4, where large firms play a dominant role in emerging fuel cell technology.

Therefore, there is a need for further research into the local vs. global knowledge flows in the emergence of new industries. To this end, a more promising measure may be the one developed by Neffke et al. (2011b), which uses the age of plants to distinguish between young, intermediate, and mature industries; however, this approach still does not account for the knowledge dynamics that act prior to a commercial breakthrough. To investigate the localised character of knowledge flows in the very early stages of industry emergence, primary data sources seem to be a better empirical instrument. Examples include survey data on regional, national, and international knowledge flows, such as labour flows, patent licensing, acquisitions and mergers, such as that used by Gertler and Levitte (2005) in their analysis of 'local nodes in global networks' based on the Canadian biotechnology industry. Such studies would increase our understanding of local vs. global knowledge input in regional branching processes into contemporaneous emerging industries.

Another issue not investigated in the thesis is the way an emerging industry, such as the fuel cell industry, produces different types of geographies. This problem would be another obvious question for future research. In the next section, I encourage such research by discussing findings that were not included in the three main papers of this thesis.

5.3.2 An emerging industry's footprint on the economic landscape

From an academic and not least from a policy perspective, it is potentially interesting to analyse what type of geographies the emerging industry may create in a given region. Such early indications may give policy makers a tool to support industry-building in the best possible way. For instance, there may be different strategies depending on whether incumbent MNEs or smaller spinoff firms characterise a new industry in a region. Research on this issue may improve regional innovation policies. These policies today are dominated by the idea of creating clusters, which sometimes seem to have little basis in the regional industrial structure (Sölvell et al., 2003).

Markusen's (1996) significant contribution to the industrial district literature is a possible theoretical framework that could shed light on the formation of new geographies based on spatial industry emergence. She distinguishes between hub-and-spoke districts, state-anchored districts and satellite districts besides the familiar definitions of industrial and Marshallian districts. It is not my purpose to go into detail of these concepts here, but only to illustrate how this approach may contribute to understanding the consequences of the emergence of a new industry in a specific regional context. The following example is based on the hub-and-spoke district type.

The hub-and-spoke district is defined by hosting one or two large enterprises that dominate the regional economy and have a strong localised network of suppliers. In the study presented in the previous chapter, Daimler is an example of a hub firm that relies on a dense, localised web of 1^{st}- and 2^{nd}-tiers suppliers. It is, of course, important to note that Daimler's current fuel cell activities are relatively minor compared to its total activities. Nevertheless, the diversification of a large hub into a radical technology field has the potential to stimulate its suppliers to diversify, as well, or the enterprise risks making the regional suppliers obsolete because these are not capable of adapting to the new technological regime. In particular, when the large hub is an MNE and operates internationally, Daimler may find it easier (and cheaper) to find suppliers elsewhere than to wait for the "old" suppliers to adapt. Thus, a further regional branching process depends on the regional suppliers' capacities to adapt quickly to the structural changes of the existing industry.

Stuttgart region has become aware of the challenge faced by the automotive cluster in Baden-Wuerttemberg. Daimler's strategic decision to move into the radical fuel cell technology may eventually disrupt many of its conventional suppliers (provided that the fuel cell potential is realised). The large automotive suppliers, such as The Freudenberg Group and Bosch, have identified the potential of the transition to fuel cell propulsion in the automotive industry early and have searched for possible convergence in its own resources. To illustrate the regional potential to adapt to the emerging fuel cell technology, I have calculated the stock of fuel cell-related knowledge and enterprises, which may support such development (Table 5.1).

Table 5.1: Fuel cell-related knowledge production in the largest fuel cell producing regions 2003-2007

	Total fuel cell-related patents	Largest fuel cell-related patenting entity (share)	Largest fuel cell-related patenting entity	# of entities (business org.)	Fuel cell-related patents per entity
Stuttgart	709	42%	BOSCH	102	6.9
Karlsruhe	704	39%	BASF	407	1.7
Freiburg	280	8%	DEGUSSA AG	107	2.6
Tübingen	183	15%	BOSCH	96	1.9
Upper Bavaria	849	14%	WACKER CHEMIE	181	4.7
Upper Franconia	88	21%	SIEMENS	51	1.7
Middle Franconia	215	54%	SIEMENS	61	3.5
Bavarian Schwabia	120	10%	CLARIANT	54	2.2
Darmstadt	735	13%	DEGUSSA AG	217	3.4
Mecklenburg-Vorpommern	62	38%	NEW ENERDAY	19	3.3
Cologne	662	32%	BAYER AG	535	1.2
Rhineland Palatinate	728	71%	BASF	268	2.7
Île de France	817	7%	COMMISSARIAT A L ENERGIE ATOMIQU	164	5.0
Rhône-Alpes	646	16%	COMMISSARIAT A L ENERGIE ATOMIQU	146	4.4
Lombardy	393	7%	SOLVAY SOLEXIS	70	5.6
North Holland	279	66%	SHELL	47	5.9
Berkshire, Buckinghamshire and Oxfordshire	275	12%	JOHNSON MATTHEY	88	3.1

Source OECD REGPAT, and OECD HAN, own cleaning and consolidating of data, and calculations: The fuel cell-related knowledge base is defined in accordance with the method used in Chapter 3, and subsequently related to the OECD HAN database to point out the patenting organization, following the method used in Chapter 4.

Table 5.1 illustrates that the firms with largest shares of fuel cell-related resources are large sub-suppliers to the automotive industry: Bosch, BASF, and Degussa. The possession of fuel cell-related resources may result in an easier adaption to the new paradigm of fuel cell technology. Small and medium-sized suppliers, however, have been characterised by a wait-and-see approach, which may result in a long-term disruption of the Stuttgart automotive cluster.

In a recent analysis carried out by Fraunhofer Institute ISI for Region Stuttgart (Industrie- und Handelskammer Region Stuttgart, 2011), it became clear that the majority of the medium-sised enterprises in Baden-Wuerttemberg are poorly prepared for any upcoming structural changes in the automotive industry. For example, the medium-sised enterprises spend only 2.6% of their sales on development of new technology, the lowest spending level among all automotive suppliers in Germany. Consequently, a further diversification of the regional economy along the trajectory of fuel cell vehicles would require the regional automotive component suppliers to step up and search for possibilities in the new technological regime.

These preliminary indications confirm the vulnerability of hub-and-spoke industrial districts, which Markusen ascribes to their dependency on the large firm's strategy (1996). Moreover, the often-small amount of venture capital available within the district outside the large firms in hub-and-spoke regions may hamper the regional diversification process. Accordingly, access to venture capital resources for the many sub-tier suppliers is crucial for a successful regional diversification process if it is to include the many small and medium-sized enterprises. It is likely that this process will become crucial in supporting and sustaining Stuttgart's process of regional diversification into the emerging fuel cell industry.

Table 5.1 also displays the potential relevant knowledge base, as measured by patenting levels and actors, for the remaining regions analysed in Chapter 4. The table reveals other interesting findings; for example, Cologne has the highest numbers of patenting entities with fuel cell-related competences, and Mecklenburg Western-Pomerania accounts for less than 40 patent applications in fuel cell-related knowledge fields (besides New Enerday's own portfolio) distributed on less than 20 firms in the years 2003-2007 (See Table 5.1). Consequently, Mecklenburg Western-Pomerania may find it difficult to support fuel cell technology.

It is important to recall that the emerging fuel cell industry is still in a pre-commercial phase with few products in the markets and no profitable fuel cell companies. There is no certainty that this industry will ever live up to its wide-scale commercial potential. Consequently, it is also uncertain in what regions the industry will thrive and grow and what regions may at later stages become industrial clusters of fuel cell development that will benefit from localisation economies. Only time will tell.

5.3.3 Technological relatedness and related variety

From a broader perspective, research on related variety (Jacobs, 1969) and 'technological relatedness' (Boschma and Frenken, 2011a), of which this research is a part, has contributed to a dynamic understanding of regional economic development. As such, the evolutionary turn in economic geography has contributed to an enhanced understanding of regional growth paths (Frenken et al., 2007, Bishop and Gripaios, 2010), the role of technological relatedness in agglomeration externalities (Neffke et al., 2011a, Neffke et al., 2011b), related variety in trade linkages (Boschma and Iammarino, 2009), and with this thesis, an improved understanding of the spatial emergence of new industries through technologically related knowledge spillover. This result is encouraging for the emerging field of evolutionary economic geography.

The evolutionary research path in economic geography seems promising and should continue with further investigations of the complex nature of knowledge dynamics, human agency, and institutional influence at the regional level. In spite of a promising path more studies are necessary to understand how regions may renew themselves and escape becoming locked-in to old industrial paths. Such research will further illuminate why particular technologies have led to the creation of industries in particular locations. And expectedly, such research will increase the academic support of regions' efforts in developing regional advantages around an emerging industry.

DANSK RESUMÉ

I dag ved vi meget lidt om, hvad der egentlig driver nye industrier til at lokalisere sig, hvor de gør. Trods en stor interesse fra politisk side om at skabe nye højteknologiske industrier som vi skal leve af i fremtiden, eksisterer der meget lidt forskning, der kan belyse, hvad der har betydning for, hvordan nye industrier opstår. Og ikke mindst forskning, der belyser, hvorfor nye industrier opstår, hvor de gør. Denne afhandling undersøger lokaliseringen af den unge industri, der udvikler sig omkring brint- og brændselscelleteknologi i Europa og søger at forklare, hvorfor vi ser industrien udvikle sig i nogle regioner og ikke i andre.

En brændselscelle er en elektrokemisk enhed der genererer elektricitet baseret på en kemisk reaktion mellem et brændstof, ofte brint, og oxygen. Udviklingen inden for brint og brændselsceller tog for alvor fart i begyndelsen af 1990'erne, som følge af en række videnskabelige og teknologiske gennembrud inden for materialeforskning, kemi og nanoteknologi. Brint og brændselscelleteknologi er en generisk energiteknologi, i den forstand at den kan bringes i anvendelse inden for en række forskellige energirelaterede produkter så som stationære kraftvarmeanlæg, nødstrømsanlæg, biler, gaffeltrucks, bærbare computere, mobiltelefoner, høreapparater osv. I den forstand er teknologien også defineret som en radikal ny teknologi, der har potentialet til at erstatte eksisterende teknologier, fx olie- og gasfyr, forbrændingsmotorer og batterier.

I dag er det fortsat uvist om brint- og brændselscelleindustriens potentiale til at revolutionere energisektoren vil blive indfriet, men hvis det sker, vil det medføre store forandringer i den eksisterende energisektor. Eksisterende virksomheder, måske endda hele brancher, vil opleve at deres interne kompetencer, teknologier, og produktionsfaciliteter er i fare for at blive forældet og miste deres værdi. Nye virksomheder og brancher vil vokse frem og potentielt set skabe forskydninger i det økonomiske landskab.

Spørgsmålene denne afhandling behandler er, hvor den unge brint- og brændselscelleindustri lokaliserer sig og hvorfor industrien lokaliserer sig hvor den gør. Gennem de seneste 20 år har vi set en stigende kommerciel interesse i udviklingen af brint- og brændselscelleteknologier og flere og flere virksomheder har involveret sig i forskellige dele af værdikæden. Den unge brændselscelleindustri består i dag af et miks af mindre nystartede virksomheder og store multinationale virksomheder.

Afhandlingen bygger teoretisk på en innovationssystems-forståelse i kombination med den nyligt fremkomne teoriretning – evolutionær økonomisk geografi. Afhandlingen kombinerer kvantitative og kvalitative forskningsmetoder og udfører analyser på regionalt niveau (meso) så vel som analyser, hvor virksomheder og universiteter udgør analyseenheden (mikro-niveau). Afhandlingen består af tre artikler, der på hver sin måde undersøger produktionen af viden inden for brændselscelleteknologi i dens geografiske kontekst. Disse artikler udgør afhandlingens hoveddel (Kapitel 2-4). Desuden består afhandlingen af en teoretisk indledning (Kapitel 1), der positionerer afhandlingens teoretiske udgangspunkt, og en konklusion (Kapitel 5) som opsummerer og diskuterer resultaterne samt perspektiverer over forskningsspørgsmål, der bør tages op i fremtidige forskningsprojekter.

Kapitel 2 fokuserer på lokaliseringen af praktisk vidensproduktion (læring) inden for brint- og brændselscelleteknologi. Den praktiske vidensproduktion måles på antallet af brint- og brændselscelledemonstrationsprojekter og brinttankstationer. Analysen indikerer en positiv sammenhæng mellem et velfungerende regionalt innovationssystem og praktiske læringsaktiviteter. Desuden giver Kapitel 2 de første indikationer af vigtigheden af, at der er en teknologisk relateret industri tilstede, som den nye industri kan lære af.

Kapitel 3 forfølger hypotesen om at den eksisterende regionale vidensbase kan forklare, hvorfor ny brændselscelleviden bliver generet, hvor den gør. Analysen præsenterer resultaterne af en økonometrisk test, der afslører en positiv signifikant sammenhæng mellem en brændselscellerelateret regional vidensbase og vidensproduktion inden for brændselsceller. Desuden viser analysen at jo mere alsidig den regionale vidensbase er inden for forskellige brændselscellevidensfelter, jo større sandsynlighed er der for at den pågældende region vil diversificere i retning af brændselscelleteknologi. Disse resultater bekræfter at regioners teknologiske kompetencesammensætning er stiafhængig, også når det gælder vidensgenerering inden for radikale teknologier.

Kapitel 4 undersøger hvilke mekanismer, der driver regioners diversificering i retning af brændselscelleteknologi. Analysen i Kapitel 4 kombinerer kvantitative patentdata og kvalitative interviews og undersøger de 17 mest brændselscelleaktive regioner i Europa. Analysen viser, at der er tre vigtige aktørtyper, der driver de udvalgte regioners udvikling i retning af brændselscelleteknologi: i) store multinationale virksomheder som diversificerer vertikalt langs brændselscelleværdikæden, ii) mindre dedikerede brændselscellesystemudviklere, og iii) universiteter og forskningsinstitutioner som spiller en vigtig rolle i nogle regioner, muligvis som vigtige samarbejdspartnere. Analysen viser, at de store multinationale virksomheder er de dominerende aktører, hvilket indikerer at brændselscelleudvikling kræver store langsigtede investeringer.

Afhandlingens resultater bidrager derved teoretisk og empirisk til en større forståelse af skabelsen af nye industrier og deres geografiske lokalitet. Analyserne understøtter den evolutionære økonomisk geografiske hypotese om at udviklingen af nye industrier er stedsspecifik – også når det gælder udviklingen af industrier, der er baseret på radikal teknologiudvikling. Med andre ord nye, radikale industrier udvikles med stor sandsynlighed i regioner der har en regional vidensbase, der er teknologisk relateret til vidensbasen inden for den nye industri. Imidlertid er teknologisk udvikling inden for radikalt nye teknologier ikke kun afhængig af akkumuleret viden, men også af tilstedeværelsen af risikovillige aktører, der har evnen og viljen til at implementere teknologien i nye produkter, der kan skabe værdi på markedet. I den konkrete case der er studeret i denne afhandling, viser analyserne at veletablerede multinationale virksomheder spiller en afgørende rolle i at drive udviklingen. Selvom disse resultater bidrager til en større forståelse af de mekanismer, der fører til nye industriers udvikling, er der fortsat spørgsmål, der skal besvares, før vi har en tilfredsstillende forklaring på nye industriers fremkomst i deres geografiske kontekst.

Det er forfatterens overbevisning, at forskningen præsenteret i denne afhandling er nødvendig for at kunne forstå de fundamentale dynamikker, der driver nye industrier frem. En forståelse som er et vigtigt først skridt på vejen til at understøtte den politiske målsætning om at fremme udviklingen af højteknologiske industrier.

ABSTRACT

This thesis focuses on the emergence of new industries and seeks to understand from where they emerge. Emerging industries are defined as a group of firms that explore and exploit the economic potential of a radical technology. This thesis builds on the innovation system approach, as well as the newly developed paradigm of evolutionary economic geography. The main objective is twofold: i) to examine the mechanisms underlying the origin and emergence of technology-based industry in its geographical settings and ii) to draw attention to industry emergence in the field of economic geography.

This thesis combines quantitative and qualitative research methods, and analyses are carried out at the meso level (with regions as the analytical unit) and at the micro level (with a focus on firms and universities). The thesis consists of three papers, each of which uniquely sheds light on knowledge production within emerging fuel cell technology. The first paper focuses on the location of practical learning activities within hydrogen and fuel cell technology. The results indicate a positive relationship between well-functioning regional innovation systems and practical learning activities. Moreover, this study gives the first indications of the importance of a technologically related industrial base from which the new industry can grow.

The second paper examines whether the pre-existing knowledge base of regions may explain why new knowledge within fuel cell technology is produced where it is. This analysis shows the results of an econometric test that reveal a positive significant relationship between specific fuel cell-related knowledge fields and fuel cell knowledge production. Furthermore, the analysis shows that the higher the degree of fuel cell-relatedness between the regional knowledge base and the knowledge base of the new technology, the higher the probability that a region will diversify in the direction of fuel cell technology. This finding confirms that

knowledge generation in radical technology development is cumulative in its cognitive and spatial dimensions.

The third paper analyses the mechanisms through which such regional diversification takes place. The analysis is based on quantitative patent data and qualitative interviews, as well as insights from various types of documents. The findings reveal three types of actors with important roles in regional diversification, or branching, into fuel cell technology: i) large incumbent multinational enterprises (MNE) that diversify vertically upstream or downstream, depending on their technologically related resources; based on this analysis, these enterprises are the dominant actors; ii) smaller dedicated fuel cell system developers; iii) universities and research institutes, which play a large role in certain regions and may be important collaborative actors.

These findings support the evolutionary hypothesis that emerging industries are place-dependent and that this trait is observed even for industries that emerge based on radical technology development. Radically new industries tend to emerge where the regional knowledge base is technologically related to the knowledge base of the new industry; however, technological change in emerging technological trajectories relies not only on the accumulation of scientific and applied knowledge but also on risk-taking actors who are willing and able to implement and exploit radical technologies. Accordingly, another finding of this thesis indicates that in the case of the emerging fuel cell industry, incumbent multinational enterprises seem to play an important role in developing fuel cell system products. Although these findings contribute to the understanding of the underlying mechanisms behind the spatial emergence of new industries, these results also raise further questions that must be answered before we can claim to have a satisfactory understanding of emerging industries in their geographical context.

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This thesis focuses on the emergence of new industries and seeks to understand from where they emerge. Emerging industries are defined as a group of firms that explore and exploit the economic potential of a radical technology. The thesis builds on the innovation system approach, as well as the newly developed paradigm of evolutionary economic geography. It combines quantitative and qualitative research methods, and analyses are carried out at the meso level (with regions as the analytical unit) and at the micro level (with a focus on firms and universities). The thesis consists of three papers, each of which uniquely sheds light on knowledge production within emerging fuel cell technology.

The findings support the evolutionary hypothesis that emerging industries are place-dependent and that this trait is observed even for industries that emerge based on radical technology development. Radically new industries tend to emerge where the regional knowledge base is technologically related to the knowledge base of the new industry; however, technological change in emerging technological trajectories relies not only on the accumulation of scientific and applied knowledge but also on risk-taking actors who are willing and able to implement and exploit radical technologies.

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