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System failure, innovation policy and patents: Fuel cells and related hydrogen technology in Norway 1990–2002

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Abstract

The empirical focus of this article is technological innovation activities in the emerging field of fuel cells and related hydrogen technology in Norway from 1990 to 2002. In this period, four comparatively large-scale research and development projects and a number of smaller projects aimed at development of fuel cells technology were undertaken, resulting in many inventions that were subsequently patented. Although this creativity may be considered an indication of success, only one of the projects became successful in an innovation perspective. All the large projects were initiated and funded for divergent political and economic reasons. An important reason in the late 1980s was the prospect of using Norway's abundant supply of natural gas in fuel cells for electric power generation. The large R&D projects that attempted to develop fuel cells based on natural gas as energy source failed. In contrast, the successful project was undertaken by military R&D, i.e. in a different system of innovation than the projects that failed. Analysis of these cases points to the importance of a systemic approach to innovations—and to policy making. One challenge for policy makers is to decide how they should promote this development which is crucial for the vision of a future "Hydrogen Economy", i.e. what kind of policy incentives should be introduced to spur efficiency in technological development and diffusion. Theoretically, many options are available; however, understanding the innovation dynamics in this sector is fundamental for making choices. In this article, focus will be set on policy aspects using an innovation systemic approach to analyze development of fuel cells and related hydrogen technology in Norway.

Keywords: Fuel cells; Hydrogen; Innovation policy; Norway

1. Introduction

In visions of a future "Hydrogen Society", new energy systems based on hydrogen and fuel cells have captured the imagination of many political leaders, industry executives and environmental activists, as evident in the *IPHE—International Partnership for Hydrogen Economy*[1] promoted by the current Bush administration in USA and a number of other large scale research, development and demonstration (RD&D) programs. One challenge for policy makers is to decide how they should promote this development, i.e. what kind of incentives should be introduced to spur efficiency in technological development and diffusion. Theoretically, many options are available; however, understanding the innovation dynamics in this sector is fundamental for making choices. In this article, focus will be set on policy aspects using an innovation systemic approach to analyze development of fuel cells and related hydrogen technology in Norway.

In 1838, the Welsh lawyer William Robert Grove (1811–1896) invented fuel cells, but only during the last decades this technology has attracted real interest in terms of RD&D and resources for further development. In spite of many successful achievements in these endeavors, there are still numerous non-trivial obstacles

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[1]Cf. http://www.usea.org/iphe2.htm for more information.

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and problems ahead that will require considerable R&D effort.

Fuel cells and use of hydrogen may be considered as potentially radical innovations because of a number of reasons,[2] such as

- no emission of carbon dioxide (green house gasses) and other pollutants—and no noise,
- an alternative source of energy that will make society less dependent on fossil fuels—and capricious supplier nations,
- provide new ways of configuring energy systems in order to increase reliability and make societies less vulnerable.

Hydrogen technology[3] and fuel cells are inter-related technologies, so that important innovations in one of these fields have implications for the other. Due to its emerging character however, this technology has not been widely studied, especially not from an innovation standpoint. Emerging technologies, or potentially radical innovations such as fuel cells and related hydrogen technology may be subject to market failure, i.e. the market is not capable of developing the technology through coordination of resources between private and public actors. This means that "sometimes there are reasons to complement the market and capitalist firm through public intervention" (Edquist et al., 2004, p. 429). In order to develop and promote a novel technology, policy makers may support and initiate large technological programmes. An important aspect in the analysis is therefore on the role of the government in enabling or constraining firms' possibilities for innovation. In a systemic approach to innovations, a main tenet is that innovation occurs as a result of interaction between actors within the 'innovation system', i.e. in a country, a region, a sector, or a technological field.

The empirical focus of this article is technological innovation activities in the emerging field of fuel cells and related hydrogen technology in Norway from 1990 to 2002. In this period, four comparatively large-scale research and development projects and a number of smaller projects aimed at development of fuel cells technology were undertaken, resulting in many inventions that were subsequently patented. Although this creativity may be considered an indication of success, only one of the projects became successful in an innovation perspective. All the large projects were initiated and funded for divergent political reasons. An important reason in the late 1980s was the prospect of using Norway's abundant supply of natural gas in fuel cells for electric power generation. This was envisioned as an attractive alternative or supplement to gas turbine power plants with high emission of green house gases. For decades, Norway's inability to develop an industry or a domestic market using natural gas from the North Sea has been (and still is) an unresolved policy issue. The large R&D projects that attempted to develop fuel cells based on natural gas as energy source failed. In contrast, the successful project was undertaken by military R&D, i.e. in a different system of innovation than the projects that failed. As these results emerged, the energy sector was deregulated, in Norway as in many other OECD-countries. As a result, public innovation policy became more market oriented; innovation had now become a matter for the markets to "pick winners", not policy makers. Subsequently, public support for RD&D on fuel cells and hydrogen technology was scaled down. Analysis of these cases points to the importance of a systemic approach to innovations—and to policy making.

Based on this, this article will attempt to elucidate the following questions:

- What characterized fuel cells and related hydrogen technology innovation activities in Norway during this period covered by the patent analysis?
- How can variation be maintained and duplication avoided in a national innovation system, or is a sectorial system approach more fertile?
- What is the role of a national innovation system in an international (e.g. European) context?

In the article, the following sections will attempt to elucidate these questions:

- Section 2 presents the analytical framework based on systemic approaches to innovations,
- Section 3 presents the mapping of the innovation system for fuel cells and related hydrogen technology in Norway 1990–2002,
- Section 4 presents a patent analysis and explains actor relations and interaction between them in developing fuel cells and related hydrogen technology,
- Section 5 discusses some policy implications of the empirical material,
- Section 6 presents some concluding remarks.

2. Systemic approaches to understanding innovation

In innovation theories, using systemic approaches for understanding how innovations emerge—or explaining why some potential innovations fail to emerge—have

[2]This question is not beyond dispute; some analysts suggest that the environmental and economic benefits of fuel cells are not large. Cf. article "Questions about a Hydrogen Economy", in *Scientific American*, May 2004, by Matthew L. Wald.

[3]With hydrogen technology we mean producing and storing hydrogen for use together with fuel cells.

gained recognition. The fertility of this reflects a recognition that innovations evolve because of a complex set of interrelated factors and dynamics, i.e. innovations are systemic. However, in spite of this common basic understanding, in analysis and explanations, analysts focus on different system aspects.

2.1. Conceptual frameworks for analyses of innovation systems

Four somewhat related conceptual frameworks are relevant for a systemic approach to innovations:

- *NSI—National Systems of Innovation*, which have primary focus on the nation, i.e. a ''macro''-level approach to innovation systems (Lundvall, 1992; Nelson, 1993).
- *SSI—Sectoral Systems of Innovation*, with a primary focus on a industrial–technological sector and its population of firms, i.e. a ''meso''-level approach to innovation (Malerba, 2002; Edquist et al., 2004).
- *R/LSI—Regional/Local Systems of Innovation*, where a region or other sub-national entities are analyzed in terms of innovations (Braczyk et al., 1998).
- *TS—Technological Systems* , in which the focus is set primarily on explaining how technology-based innovations and related emerge and evolve, e.g. railroads, electric grid, telecommunication systems, etc. (Carlsson and Stankiewicz, 1991; Hughes, 1983)

In addition to these, some theorists have recently suggested that supranational frameworks may be relevant because of globalization processes, as evident in the notion of an *ESI—European Systems of Innovation* (Niosi, 2002) because this conceptual framework capture some innovation dynamics that are not adequately analyzed and explained in SSI and NSI. In addition to these systemic approaches, analyses on innovations based on patent data have strong supporters. Based on assumptions that patents are indicators of technological creativity and innovation activities, and that analyses of these provide quantified data on the size and scope of such activities; adherents of this approach will maintain that they are relevant and provide adequate data for analyses of innovation systems.

Although all approaches provide valuable insights and explanations of innovation systems, in this article we will compare analysis of Norwegian development of fuel cells and related hydrogen technology patents with analyses using systemic approaches to innovations. In this the focus will be set on NSI and SSI—and to some extent ESI. In the latter, analysts suggest that EU's Framework Programme for research and technology development and other EU policies have gradually contributed to an integration process in which Europe may be considered as an innovation system, hence making the conceptual framework of ESI fertile. ESI may not be an important consideration for large countries, but for smaller countries such as Norway, the developments in EU have gradually gained significance.

In an emerging and promising new technological field such as fuel cells and hydrogen technology, we will argue that the two systemic approaches of NSI and SSI provide divergent analyses that have some significance for innovation policy goals: Whereas a NSI perspective on innovation policy would provide support for a horizontal, general innovation policy, a SSI perspective provides insights that enable policy makers to tailor policy measures more directly to specific technological and industrial policy goals. Furthermore, because of this, a SSI perspective is more compatible with an ESI-perspective. Secondly, we will argue that the general tendency towards deregulation and liberalization in most OECD-member countries has had a detrimental impact on innovations in the energy sector, more so in this sector than in other sectors. Whereas a SSI perspective—particularly by adopting some of the insights from TS—may explain this and other salient aspects related to innovation regimes of a particular sector more distinctly, other approaches, such as NSI or patent analyses are either too general or too particularistic to provide fertile, relevant insights. Thirdly, although we argue that a SSI approach is more fertile than others for explaining innovation-oriented activities in energy technology, this results in policy dilemmas for which analysis does not provide clear-cut recommendations for a small country such as Norway. The policy dilemmas may be spelt out like this:

- *Variety* vs. *focus*: Using a systemic perspective, should policy be designed to encourage variety when developing emerging technologies, or do large technological programmes require that all available competence be concentrated in one programme? Factors such as national size and national industry sector characteristics are relevant in this discussion. In a systemic perspective, this question may be analyzed as a distinction between normal competition (variety), or as a system failure (lack of interaction).
- *National interests* vs. *international integration:* As technology development and economic systems are becoming increasingly international, using a national innovation system (NSI) approach may impose analytical constraints that make this approach less relevant for policy. Reflecting this, the conceptual framework of a *European Systems of Innovation* (Niosi, 2002, p. 213) may be more fertile and relevant than the approach represented by NSI—National Innovation System perspective in some important respects.

2.2. Innovation policy issues

Innovation policy may be understood as a set of incentives (funding, regulatory and legal initiatives, education, etc.) provided by governments and public authorities in order to encourage innovation processes in a society or for specific goals that society wants to attain. There are numerous types of policies that a government may enact in order to attain goals related to improving industry, promotion of new technology development, etc. Two somewhat contrasting versions of innovation policy exist:

- *Horizontal,* or general innovation policy, which "puts the emphasis on non-interventionism and signals that the focus should be on framework conditions rather than specific sectors or technologies" (Lundvall and Borrâs, 2003, p. 16). In this, the notion of market failure justifies public support of higher education, patenting and R&D as important issues in innovation policy.
- *Systemic* or targeted innovation policy, implying "that most major policy fields need to be considered in light on how they contribute to innovation" (Lundvall and Borrâs, 2003, p. 17). Innovation policy then encompasses science and technology policy, and support for specific technology programs, including the diffusion of a technology and the commercialization phase.

Adherents of a horizontal, general innovation policy advocate state intervention for making improvements in the functioning of markets; they believe that competitive markets will spur the rate of innovation (Edquist et al., 2004). Inherent in this is the notion of variation and selection processes—and that market competition will encourage these processes most efficiently. From an evolutionary perspective variation means to increase the technological choices available. This ensures diversity and reduces uncertainty of a new technology by providing several technological trajectories. Accordingly, variation and selection will enhance the possibilities for developing a successful technology (selection through market processes). Critics suggest that this type of policy may promote duplication of efforts, rather than increasing variation. Consequently, competitors will invest in development of the same type of technological options. From a systemic perspective this may be considered as a form of system failure, because competition creates non-cooperative interaction between the actors. Although competition may be important for securing variation, also strong links (cooperation) between actors is also crucial. This raises the issue of to what degree should firms compete and cooperate, and what effect has country size (small country means more scattered resources and less variation) in this respect? This relationship between variation and competition will be discussed further in the policy analysis. However, adherents of a general, horizontal innovation policy believe that policy should not "pick winners"—this should be done by the market, the choice made by markets are always most efficient and best. In contrast, using a SSI perspective, this approach may provide support for policies that are more selective and targeted.

3. Mapping out the innovation system for fuel cells and related hydrogen technology in Norway

3.1. Introduction: four large fuel cells projects

Spanning over two decade, from the middle of the 1980s to the end of the 1990s, four comparatively large fuel cells development projects were undertaken in Norway. Three of these were aimed at development of a solid oxide fuel cell (SOFC) using natural gas as feedstock. The fourth fuel cell project, *Hugin*, was part of a larger military project for development of an unmanned submarine. Initially, there was just one, single SOFC-project known as *NorCell*. This project was formally started in 1988 (the R&D began earlier) and ended in 1991. At this point, one of the participants of the project, the state-owned oil & gas company Statoil, split out and established its own SOFC-project, *Mjøllner*.[4] Simultaneously, the original NorCell-project evolved into a new project called *NorCell II*. The details of these four projects will be elaborated first, followed by an analysis of the patents that emerged out of these projects.

3.2. Initial push: Norway's gas "problem" and the menace of Soviet submarines

The initial NorCell project obtained funding because of its goal developing a technology (SOFC) using natural gas as feedstock that would provide much higher energy efficiency than conventional gas turbine power plants, a topic closely related to Norway's gas "problem". Most of the natural gas produced on the Norwegian continental shelf is exported; the almost absence a domestic use of natural gas has been a political issue for more than two decades. The military submarine development project Hugin had its background in the Cold War, when military authorities alleged that submarines from unidentified nations (e.g.

[4] In Nordic mythology, "Mjølner" was the name of the hammer that Thor used as his weapon. It is believed that the word also means crushing. It is difficult to know what kind of symbolic meaning Statoil attached to naming its project with a slightly different spelling (Mjøllner instead of Mjølner).

Soviet) were hiding in Norwegian fjords. To counteract this, the Norwegian military R&D establishment FFI initiated development of an unmanned surveillance submarine powered by fuel cells technology. With the fall of the Berlin Wall, this project was turned into a civilian project and is considered successful, as will be explained below in the presentations of the four projects.

3.2.1. NorCell I

Starting up in May 1988, the objective of this project was to develop and demonstrate planar SOFC technology. In addition to support from the public research funding agency NTNF, the project was supported by industrial partners, Norsk Hydro, Saga (a Norwegian oil company that was taken over by Norsk Hydro in 1999), Statoil and Statkraft, the latter being Norway's largest electric utility company, owned by the Norwegian state. The project was carried out at the R&D organization SI in Oslo, in collaboration with the Centre for Material Science at the University of Oslo. At the time, the forefront of R&D in fuel cells was in England and USA. Starting more or less from scratch, the researchers in NorCell used both scientific and technological literature and patents as information sources when they began working on developing the fuel cells.

3.2.2. NorCell II

NorCell II started in September 1991, 2 years before the initially planned completion of the first NorCell project. In reality, NorCell II represented a reorganization and expansion of the first NorCell project: Statoil had left the project and the Norwegian metal manufacturing company Elkem joined the project, bringing with them its US-based subsidiary Ceramatec. According to Elkem, Ceramatec had received funds for undertaking R&D on fuel cells from the US Department of Energy and the Gas Research Institute[5] in USA, this vouching for their high quality. The final project report from 1995 states that the NorCell II project had been terminated at the end of 1994, and that some of the goals of the project had not been achieved. However, the project did make some achievements in that it was able to construct, operate and test a 1.4 kW SOFC ("The Oslo Demo") and meet the single fuel cell performance goals. When Elkem withdrew from NorCell II in 1994, the rights of the new knowledge and technology were patented in USA to Ceramatec, but Hydro has some partial ownership in four patents that can be labeled as SOFC patents.

According to the final report from NorCell II, the cooperation with Ceramatec in USA was considered difficult because of differences in work culture in the two R&D teams, however, the reports states that Ceramatec continued to work with SOFC-development in a new partnership establish with the US firm Babcock & Wilcox, a subsidiary of McDermott International.

3.2.3. Mjøllner

The main reason for Statoil's exit from NorCell (or, non-participation in NorCell II) in the early 1990s was that it wanted to concentrate all its resourced to development of its own, proprietary planar SOFC, in the Mjøllner project. At the time, Statoil's strategy was to evolve from oil & gas into a generalized energy company and in this electricity generation was important. In their judgment, the possibility of developing a commercially viable planar SOFC was so promising that they would be able to do this alone—and much faster than in a cooperative R&D consortium. The R&D in the Mjøllner project was done by approximately 25 engineers and scientists, which was large in a Norwegian R&D context. In 1998, Statoil attempted to establish alliances with major electro-technical equipment manufacturers in Europe (Daimler-Bentz, AEG, Siemens, Ahlstrom, ABB, etc.), so that these could develop further and manufacture the type of planar SOFC that Statoil needed for its power plants. However, Statoil did not succeed, for a variety of reasons.

3.2.4. Hugin

The one successful fuel cell development emerged from a project for developing an unmanned submarine, i.e. underwater vehicle, called Hugin.[6] The R&D was done at FFI (Norwegian Defence Research Establishment), with Statoil, a Norwegian oil and gas company, as a partner in the final stages of this development. Initially, the Hugin project began during the cold war, in the late 1960s and early 1970s. At that time, military authorities alleged that hostile submarines were trespassing into the Norwegian coast, hiding in the fjords and spying on Norway. As a counter-measure, Norwegian defence authorities wanted to develop mobile acoustic surveillance technology operating on the sea floor. Energy supply for these units represented an obstacle, but FFI came up with the idea of using sea-water batteries, i.e. semi-fuel cells. After the cold war, FFI in a joint venture with Statoil developed a semi-fuel cell for a submarine that had a long operating capability (1000 h). This solution was incorporated in the Hugin 3000 submarine which was licensed to the Norwegian manufacturing company Kongsberg–Simrad, who subsequently successfully commercialized this. Hugin is now used for mapping and surveillance of the seabed, in

[5] Its name is now GTI—Gas Technology Institute of Des Plaines, Illinois in USA, cf. homepage: http://www.gastechnology.org/. By entering "Ceramatec" in the search machine of GTI, references to 14 reports were obtained, most of these on SOFC, written in the 1990s.

[6] "Hugin" in ancient Nordic mythology was one of God Odin's two ravens. The other one was "Munin". Hugin and Munin were Odin's scouts or surveillants. Hugin means "thought" or "mind".

Table 1
Patents by assignee and class

Assignee	Patent class					
	Fuel cell	Storage	Production	Membrane	Material	Total
Kværner		8	21			29
Statoil	7					7
Sintef				2		2
IFE		2				2
FFI	10					10
Norsk Hydro			3		2	5
Others	3					3
Total	20	10	24	2	2	58

particular inspection of underwater oil and gas pipelines—a distinctly non-military application. In addition to the patents obtained by FFI and Statoil, Siemens was involved in one patent in this project. Using hydrogen peroxide and seawater as fuel, the Hugin project developed what is called semi-fuel cells, for generating power for the propulsion and other functions in the Hugin submarine.

3.3. Analysis of Norwegian patents on fuel cells and related hydrogen technology

In innovation studies, patents are used as empirical evidence in analysis in a number of different theoretical approaches. The assumption in these is that patents reflect important aspects in a system of innovation, and may be used for analysing the science and technology base to a nation during a period of time. In addition, the evolution of technological knowledge may also be traced by a patent analysis. This refers to the fact that the patents identified give a picture of the technical capabilities that exist in the system of innovation for fuel cells and related hydrogen technology in Norway during this period. This is important for the analysis on the technological fields that the actors are specialized in, or if there exists some division of labor between the firms in the innovation system. In this way, a patent analysis may provide insights into the formal and informal networks that provide knowledge interaction that constitute a system of innovation.

This section will now present an analysis of patent activities in fuel cells and related hydrogen technology in Norway in the period 1990–2002. The patents were gathered from the Delphion database and which were applied for between 1990 and 2002 in EU, USA or Norway. The patents were divided into technological categories:

- fuel cells,
- hydrogen storage,
- hydrogen production,
- membranes,
- new materials.

The purpose is to give an overview of assignees and inventors, the technological field they are patenting in, the relationship between the identified actors, and identifying the formal and informal networks. Table 1 gives an overview of patents by assignee and class.

The data collected showed that eight firms or institutes obtained one or more patent related to fuel cells and related hydrogen technology. The patents were categorized according to the technological category. In the next step, possible links between the assignees were investigated to determine the extent of co-patenting and the distribution of assignees and citations in patents. In the following, a presentation will be made of patents according to technological categories shown in Table 1.

In the data collection, focus was set on the collecting material on the following aspects:

- patent application area,
- knowledge sources that were important in the making of the invention, and
- citations in the patents.

3.3.1. Fuel cells

In the period 1990–2002, 20 patents on fuel cells assigned to Norway were obtained. They belong to four firms and one private person. The patents emerged from the four comparatively large R&D projects, as described in the previous section. As explained earlier, only one of these (Hugin) may be characterized as a success in an innovation perspective.

3.3.1.1. Hugin. In the successful project Hugin, FFI obtained 10 semi-fuel cell patents. The originality of these patents is high because only three refer to previous patents. The patents referred to are in large part patents from the USA, to patents attributed to Lockhead, US Navy, Globe Union and Westinghouse Electric Corp., but also the military in Canada and Statoil in Norway (co-operation) have been cited. Statoil has two patents that can be traced to the Hugin project, neither of them have any references to previous patents. Also Siemens and Alcatel have one patent each that can be connected to the Hugin project.

3.3.1.2. NorCell and NorCell II. No Norwegian patents could be traced directly to the Norcell project, however, four patents assigned by the US firm Ceramatec, which participated in Norcell, originated in this project.[7] Somehow the patents obtained by the project in USA became Ceramatec's property during NorCell II.[8] The researchers in Norcell used both articles and patents as information sources when they started their own R&D. Some patents by Westinghouse could be labeled as "classics" and there were the "bible", some early articles[9] from the USA. In these articles all the different fuel cells types were tested and measured. The knowledge involved in the Norcell project was indirectly transmitted to NorECS and SINTEF. NorECs as Norwegian Electro Ceramics AS is a company that was started by researchers from the Centre for Material Science at the University of Oslo and which have a trademark on Probostat,[10] which is a measurement cell for electrical properties and permeability studies at high temperatures.

3.3.1.3. Mjøllner. Five patent applications are directly linked to the Mjøllner project, and Statoil assigns all of them. Several of the employees in Prototech were inventors on Statoil's patents and had leading roles in the development process. Using the knowledge from Mjøllner to further develop a SOFC, Prototech works with development of fuel cells for clients such as the energy company BKK in Bergen. Statoil's patents from the Mjøllner project refer to patents from firms in different countries. In these, Sanyo Electric Co. Ltd. in Osaka in Japan is most frequently cited for previous patents in SOFC, followed by Westinghouse Electric Corp. in Pittsburgh in the USA, Sulzer Hexis AG in Winterthur in Switzerland and Dornier GmbH in Germany.

3.3.2. Hydrogen storage

Development of storage systems and technologies for handling hydrogen is crucial for the future prospects of fuel cells diffusion because of inherent physical properties of hydrogen: In terms of volume, hydrogen at room temperature demands approximately ten times more space compared to gasoline. Although the volume of hydrogen may be somewhat diminished by compression and low-temperature storage, this is still a non-trivial technological challenge. Like gasoline, hydrogen is also highly explosive.

Eleven of the patents identified were related to hydrogen storage, as shown in Table 1, of which Kværner obtained nine. Most of the patents were related to inventions made somewhat serendipitously in a project, the "Kværner Carbon Black and Hydrogen Process." In this project, Kværner invented special varieties of carbon black that may be used for storage of hydrogen. The inventors were all employees in Kværner's R&D department in Trondheim. The initial intention of the projects was to develop a solution for handling residual gas produced in the first separation process when the mixture of oil, gas and water comes out of wells on offshore oil production platforms. Because this gas cannot be flared off (prohibited), Kværner intended to develop a process technology that would crack the gas into hydrogen and carbon so that the hydrogen could be used as an energy source, while the carbon could be transported onshore. This did not work in practice, but the process gave good qualities of carbon (carbon black). This process produces no emissions, while the traditional process for producing carbon black is extremely polluting. Kværner is still doing R&D on the carbon black process in their research center in Trondheim. They cooperated with SINTEF, and IFE, but only marginally in the beginning.

Institute for Energy Technology (IFE) has obtained two patents on hydrogen storage in carbon materials that are similar to Kværner's. The IFE patent "Hydrogen storage in carbon material" has eight references to previous patents, one of these to a Kværner patent on carbon nano-tubes which can be used for storing hydrogen. IFE also cites seven other patents, six from USA and one from Germany.

3.3.3. Hydrogen production

In this field, Kværner, having 21 patents on hydrogen production, is also dominant. These patents are also related to the "Kværner Carbon Black and Hydrogen Process" described earlier. In a factory built

[7]Ownership to these four patents is shared with Norsk Hydro, a firm which also participated in the Norcell project.

[8]One of the partners in the project, Norsk Hydro, has retained some user rights to these patents.

[9]The most important articles: S.S. Penner (Ed.), Assessment of Research Needs for Advanced Fuel Cells, Pergamon Press, New York, 1986. US Congress, Office of Technology Assessment, OTA-TM-0-37, US Government Printing Office, Washington, February 1986. K. Kinoshita, F.R. McLarnon, E.J Cairns, Fuel Cells—a handbook, US Department of Energy Report DOE/METC-88/6096, May 1988. A.J Appleby, F.R Foulkes, Fuel Cells Handbook, Van Nostrand Reinhold, New York, 1989.

[10](http://www.norecs.com The Probostat can be used for testing and building of cells for studies, characterization and testing of electro ceramics, fuel cell components, membrane materials, etc. The inventors are considering patenting the invention.

in Canada in 1999, this process, which made possible co-production of hydrogen and carbon was licensed to the factory by Kværner. However, the factory is now closed due to economic problems and a wish to consolidate around the company's key area. In Kværner's patents, US patents from Hydrogen Consultants, Inc., Air Products and Chemicals, Inc., and Columbian Chemicals Company are cited, in addition to references to some European patents.

In addition to Kværner's patents, Norsk Hydro also has obtained three patents related to hydrogen production by electrolysis. Electrolysis is a process for production of hydrogen from water using electricity. The electricity separates water into hydrogen and oxygen. It is in principle a reverse fuel cell. Norsk Hydro Electrolysers is a world leader in water electrolysis that and participates in a project in Iceland on hydrogen filling station for automobiles. Norsk Hydro Electrolysers cooperates with several international firms and EU projects in development of a hydrogen electrolyser, which points to the increasing importance of European system of innovations (ESI).

3.3.4. Membranes

As technology, membranes may be considered generic because they have numerous applications; however, in this context they are interesting because they may be used both in fuel cells and for gas separation, such as in production of hydrogen from natural gas. There are five patents on membranes in the material. Three of these belonged to SINTEF. Two of the patents make references to other patents: The first one to a patent obtained by Ford Global Technologies, Inc., in USA. The second patent has several references: Five references are made to Bend Research, Inc. in USA. In addition, the patent refers to Membrane Technology & Research, Inc. and Vapor Technologies, Inc., both from USA, and to two Japanese companies: Anelva Corporation and Orient Watch Company, and, finally, to the German 'Forschungszentrum Julich Gmbh.'

3.3.5. Other patents

In the patent material, there were two remaining patents related to glass ceramic material that may be used in fuel cells, but also has other areas of application, i.e. it has a generic character. These patents were obtained by Norsk Hydro. In the patent, references are made to other glass ceramic material patents by Corning Incorporated and one reference to the RCA Corporation, both companies in US. In addition, one reference is made to Matsushita Electric Industrial Co., Ltd of Japan.

4. Patents and the system of innovation

In this section, the focus will be set on knowledge flows and interactions involved in the patents presented above. The focus will set the actors in the system of innovation through formal and informal mechanisms, such as inter-firm research projects, personal networks between inventors and other people, and career patterns, i.e. how knowledge and expertise have moved around following various careers. Knowledge interaction is an important aspect for diffusion of knowledge in the SI. This approach is interesting because innovation is increasingly understood as an interactive process of learning and diffusion of knowledge.

4.1. Patents, networks and interactions

Fig. 1 represents the Norwegian innovation system in fuel cells and related hydrogen technology by showing the actors in this and the relationships between the actors that have patented, in the period 1990–2002. In this figure, which is based on information elicited on the 58 patents in the dataset, the actors (individuals, organizations or firms) are represented as circles. The size of the circle is somewhat proportional to the number of patents each actor holds, i.e. large circle indicates large number of patents, small circles few or only one. The relationships between the actors are represented as lines with variable thickness: The thick lines represent a direct co-operation in joint projects resulting in patents; the narrow lines depict a project cooperation not resulting in patenting. The relation expressed in form of the dotted line indicates direct contact between inventors or employment in different firms/institutes.

The results from the analysis showed that the most significant interactions were between the actors in the fuel cells projects, and the R&D on hydrogen production and storage. The interactions found in the Hugin

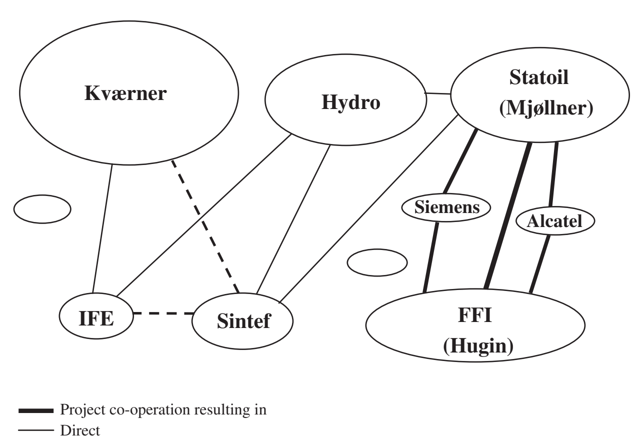

Fig. 1. Patents and relations in Norway 1990–2002.

project are expressed in Fig. 1 with thick lines. Statoil and FFI, and to some degree, Siemens and Alcatel cooperated on this project which resulted in many patents. The Norcell project did not involve any patenting in Norway, therefore it is expressed with a narrow line between Hydro, SINTEF and Statoil who cooperated on this project. The Mjøllner project cooperation resulted in patents for Statoil, which gave Prototech permission to use these rights. Although Kværner and IFE did joint R&D on hydrogen storage, they have not patented together. IFE cites Kværner's patent, but not the other way around. The relation between Kværner and SINTEF is that an employee in Kværner co-authored an article with people from SINTEF.

Although modest in the patent analysis presented earlier, Fig. 1 indicates that SINTEF constitutes a central node in the depicted network. This supports an interpretation that SINTEF played an important role even if they did not obtain many patents.

Although SINTEF is the largest research organization in Norway, it works as a sub-contractor for client firms and organizations; inventions made by SINTEF are usually patented by their clients. SINTEF was a project leader and the main contributor in the Norcell project from 84 to 89, and they also did contract R&D for Statoil's projects, for Kværner and together with IFE on hydrogen storage. The lines in Fig. 1 show a relation to Kværner (co-authorship and R&D cooperation), to IFE (R&D cooperation on H2 storage), and Statoil. These connections supports the interpretation that SINTEF is a much more important actor in the innovation system than the patent analysis indicates, however, in a patent analysis perspective, its position may seem diminutive.

4.2. Knowledge flows in patent citations

In submissions of patent application documents, citations or references to other patents or to science articles may be made in order to justify novelty and utility of the invention, or in order to make distinction from relevant "prior art." In patent analysis, this type of information is used as source for what is called *citation analysis*, which, by applying methods analogous to bibliometric analysis, attempts to trace knowledge flows and identify related networks. Citation analysis may elicit what kind of external knowledge inputs that was important in the process of developing the invention. However, critics warn that this type of information is not reliable because in a patent application process, citations are primarily used opportunistically for the purpose of making a successful patent claim—and not for knowledge flow analysis and research. In addition, using patent citations as indicators of knowledge flows may be deceptive because citations are inserted into the patent application for strategic reasons. According to one inventor interviewed: "Especially the US Patent Office in USA brings up old patents from the 60's and say that this invention is already patented. And it is not even close to our patent. The citations are there, due to necessity, and not because they provided some profound insight for the patent." Still, patents are used by many firms as a source of information when they venture into a new field, or for keeping the firm up to date in a particular technological area. In this sense, patents as indication of knowledge flows may be fertile, but this is not necessarily reflected in the citations in patent applications. Thus data on citations must be used with caution because these are often stated opportunistically, i.e. in order to obtain a patent. These aspects will be the topic in the next part.

This part examines the patent citations that were found in the Norwegian patents on fuel cells and related hydrogen technology in the period from 1990 to 2002, i.e. the 58 patents presented in the previous sections. Approximately half of these had citations to other patents. These were mainly to foreign patents (USA, Japan, and EU), however, a few patents made citations of other Norwegian patents on a reciprocal basis: Statoil and FFI made references to each other in patents that emerged from a joint project. In some patents, IFE cites Kværner's patents. One plausible interpretation of these observations is that knowledge flows in innovation activities in Norwegian fuel cells and hydrogen technology is more oriented towards international actors, than national actors. Subsequently, one may ask: Is this due to lack of a national technological foundation and indication of a weakness of the national innovation system? Or do the international orientations of the citations in the patents only reflect a specific pattern of patent behaviour, possibly what may be termed as a patent "application ritual" (i.e. doing what is expected to achieve success in obtaining a patent)? These questions will now be analyzed in order to elucidate what significance patent citations as indications of knowledge flows have in innovation processes.

Many informants stated that a patent profile was used when they were trying to solve problems. In addition, patenting may attract attention from other firms, i.e. as a type of signalling to relevant technology development communities and as a type of marketing or promotion of an invention. The fact that most Norwegian patents that make citations to patents from USA may partially be explained in terms of real or perceived requirements set by the US Patent Office. However, this also reflects realities of the global scene: Firms in USA, Europe and Japan have done most of the R&D in the relevant fields. In addition, Norwegians working with development of fuel cells and hydrogen technology were generally oriented towards the relevant international technology development communities.

An interesting point is that cooperation and citations is being done in an European context. All firms have some form of cooperation with a firm located in EU. Citations in patents were most of all to USA firms, patenting followed the national borders and cooperation was done between European firms. In those patents that were co-patented, all were between Norwegian firms.

An interesting observation is that several of the patents came from a different context than they were originally developed for. Some aspects of technological knowledge are generic and may become important in contexts that were not initially intended. The capability to operate with a broad perspective when doing R&D is especially important for taking advantage of such opportunities. This was evident in Kværner's offshore patent that became the carbon black process, and FFI's semi-fuel cells which were intended for surveillance of submarines during the cold war, now licensed and used in civilian submarines. The unpredictability innovation processes and possibility of serendipity makes management challenging. Because knowledge invented in one sector may have a potential use in another technological field, a broad perspective in doing R&D is important as may provide the firm with multiple options and flexibility.

5. Innovation policy implications

According to a number of informants who were involved in the NorCell projects, the meager outcome of these and Mjøllner was due to lack of a strong strategic leadership on a national level and a lack of long-term commitment by the stakeholders. In claiming this, they point to the accomplishment of large development projects by FFI (the Norwegian Defense Research Establishment) that have achieved success because these have had a strong leadership capable of focusing large resources and maintaining long-term commitment towards ambitious goals, such as evident in the Hugin project that successfully developed a fuel cell for propulsion of small, unmanned submarines. They contend that if the resources used by all the projects had been pooled in one single project, this would have increased the likelihood of making significant achievements. Instead, the projects represented a duplication of effort because they essentially had similar goals and obtained almost similar results, or, more aptly, paucity of results. This typical of a ''native theory'', i.e. how participants in the R&D effort themselves view and explain the world. However, innovation theories may be able to offer alternative interpretations, but these are not equivocal and do not necessarily offer clear-cut interpretations in terms of policy implications. Some aspects of this will now be reviewed.

5.1. Competition and innovation

Contrary to the ''native theory'' presented above, some innovation theorists such as Porter (1990) and his followers claim that competition is essential for providing innovation processes with dynamism. According to this, the situation in Norway with two large, competing projects should be considered beneficial, because the competition would spur the participants to focus on achieving success. A question that emerges from this analysis is how many projects are needed in a national system of innovation for securing sufficient competition? Applying this to a small country such as Norway is something different than applying it to a big economy such as USA, Japan or France. One might ask whether it is reasonable to have several almost identical, large projects carried out simultaneously, or whether it is better to have one project with all the available resources put into that project. This also relates to the distinction between normal competition and system failure, when the system fails to secure sufficient interaction between the actors and the result is that several projects do the same kind of R&D, i.e. inefficiency is fostered instead of efficiency and creativity. Did NorCell and Mjøllner have a climate of normal (healthy) competition that a country should have? Since both failed, this competitive situation was obviously not beneficial for innovation.

A systemic approach to innovations may offer more succinct interpretations, because the one successful project, Hugin, was not exposed to competition and rivalry. In an SSI-perspective, one would first observe that whereas the successful project Hugin was developed in a military R&D context, i.e. the defense sector, the projects that failed were done in the energy sector. Secondly, although all projects had clear aims in terms of their goals, the energy sector fuel cells projects were abandoned; only the military fuel cells development project was successfully completed. This raises a number of questions; however, the most significant seems to be sector specific differences in technology development environment: Whereas the military sector is not strongly ruled by economic limitations in terms of cost for development of technology, this is a relevant factor in private sector. Thus one may suggest that in the military sector, the willingness to take risks and to do long-term technology development is given systemic support; its part of the culture in which technological supremacy is an important element for creating military supremacy or advantage. Such considerations are generally not so relevant in private sector and far less in the energy sector, which is characterized by low R&D intensity and conservatism. In such an innovation climate, competition may not necessarily be beneficial, nor relevant.

5.2. Policy and strategy for radical innovations

In funding development of potentially radical innovations, R&D policy and strategy has to recognize (and accept) two crucial factors: The temporal aspect and the risk of failures. Economic benefits of R&D aiming at creating a radical innovation may take a long time to materialize, if at all. Still, the "scrap value" of R&D-projects that fail, or are only partly successful, may be significant, if there is a capability of making use of the knowledge gained. Mjøllner and the two NorCell projects may have been mediocre in terms of obtaining an immediate breakthrough for planar SOFCs using natural gas as feedstock, however, the projects provided the people working with these an unique opportunity to learn and create state-of-art technology. One could claim that the downscaling of Norwegian R&D in fuel cells technology development after the projects were finished was unfortunate and premature because this disabled the nation to reap potentially high knowledge benefits from the investments it had made, in the future. This lack of perseverance and long-term commitment disabled the R&D community to leverage the knowledge base it had built up, for pursuing other types of fuel cells technology development, such as PEM or hydrogen production and storage.

In an SSI-perspective, this development is not surprising for two reasons: Introduction of fuel cells would radically disrupt the dominant technological regimes of the energy sector. Secondly, further technology development of fuel cells would require substantial investments in R&D. As these resources were not provided, none of the projects were able to demonstrate convincing potential or results, i.e. the R&D-people had the "burden of proof," but were not given a chance to bring forward their proofs. In the military sector, the Hugin project was developed in an environment that did not require the same type of "proofs" as in the energy sector. With hindsight, it seems evident that the decision to downscale the civilian R&D in fuel cells projects was unwise, in so far as the knowledge base that was established has not been developed further and has gradually become obsolete. In the meantime, other nations have surged forward, making a substantial progress towards developing commercially viable fuel cells. This may also feasibly be explained by salient characteristics of the various sectors that promote these, such as the automobile sector. In an innovation systemic perspective following NSI, the motive for supporting the NorCell and Mjøllner projects could be explained in terms a "market failure," this possibly giving justification for the initial public funding of fuel cells development. The lack of further support coincided with the deregulation of the energy sector and simultaneous shift in R&D policy towards "not picking winners." In contrast, the success of Hugin may be explained by the fact that this project was targeted, i.e. "picked to become a winner." A SSI-perspective explains both outcomes, i.e. why sector aspects contributed to the failure of three projects and the success of one, the Hugin project.

5.3. National vs. international strategy

For a small nation such as Norway, innovation in an uncertain field such as fuel cells and related hydrogen technology requires harvesting knowledge from international sources. Participation in supra-national efforts and EU projects may provide opportunities in this direction. However, this option requires coordination of R&D funding so that it corresponds with the EU programmes. The EU focus therefore seems to be an optimal solution for the actors to engage in stimulating innovation projects and may help to sustain strong national environments in several areas in fuel cells and related hydrogen technology; it will also help in avoiding the problems small countries face when developing technologies that require large technological programmes. The innovation theoretical implication of this is that ESI is more relevant for analysis and policy advice than NSI. Furthermore, that in by-passing the NSI-perspective, one may predict that the SSI-perspective may find strategic compatibility with an ESI-perspective.

6. Concluding remarks

The main objective in this article was to analyze the innovation processes that were evident in fuel cells and related hydrogen technology in Norway in the period from 1990 to 2002. The empirical evidence has shown technological creativity in terms of patents and a significant flow of knowledge as the actors co-operate with other firms in developing technology. As a result, technological capabilities have been built in the area of fuel cells SOFC, a preferred solution for energy production and in combined heat and power production. However, only one of the projects was successful in an innovation perspective. In analyzing this one success—and the other failures—a SSI-perspective seems to offer the most fertile explanations. Thus, the sector focus in SSI on innovations is more relevant both for understanding development of potentially radical innovations such as fuel cells and for policy measures aimed at promotion of radical innovations.

The policy discussion recognized two issues. The first was the problem of variation and duplication in the system of innovation. In the period analyzed, there were two (actually three) projects developing the same technology. Instead of duplication, policy should have encouraged promotion of variety by development of two different technological options. The other policy issue was national interests vs. international integration. In a NSI-perspective, national technology and industrial interests are high on the agenda. This perspective obstructs the significance of international networks and flows of knowledge, which was essential for the Norwegian projects, irrespective of the outcomes. The ability to leverage knowledge in an international community requires complementary national actors to have autonomous capabilities and competence—a free-rider strategy is not really feasible. In Norway there was a strong European orientation which could indicate this, but at the same time a strong concern and willingness for building national competence existed. Whereas a NSI-perspective may downplay the significance of this interdependence between national and international systems of innovations, a SSI-perspective is not hampered by national boundaries. In this, the focus is set on sectors, their dynamics and technological regimes. By doing this, distinct sector characteristics relevant for innovations become more visible. The conclusion is that in this case the ESI—European System of Innovation—perspective combined with a SSI provides analysis with more powerful tools for understanding various dynamics in the innovation process—hence also is more interesting for innovation policy making.

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