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Innovations in fuel cells and related hydrogen technology in Norway – OECD Case Study in the Energy Sector

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Preface

This report presents the results of an analysis undertaken by NIFU on innovations in fuel cells and related hydrogen technology in Norway. This country study is part of a larger effort jointly organized by the OECD's Working Group on Technology and Innovation Policy (TIP) and IEA's Committee on Energy Research and Technology. Organized as a Focus Group, a number of national case studies have been made on different energy technologies and energy sources, fuel cells and related hydrogen technology being the foremost of these. In addition to Norway, Japan, Italy, France, Canada, UK, Korea and USA have also made similar national studies on these subjects. The work in the Focus Group was lead by USA, represented by Dr. Inja Paik from the US Department of Energy. In 2004, OECD will publish a synthesis report on innovation policy aspects, based on contributions from the various national studies.

In December 2002, the Research Council of Norway awarded NIFU a contract to do the country study of Norway. As work with the study progressed in 2003, results were presented to a committee in the Research Council of Norway, under the leadership of Mr. Hans-Otto Haaland. The other members of this committee were his colleagues, Mr. Jon Hekland, Mr. Trond Moengen and Ms. Trine Paus.

At NIFU, the study was carried out by a small team of research scientists organized as a project under the leadership of Dr. Helge Godø, who worked closely together with Dr. Lars Nerdrum in collecting data and analyzing these in an innovation perspective. The results of this constitute a substantial part of this report. The main data collection and analysis was done from February to October 2003. The report also includes a bibliometric analysis of Norwegian publications on fuel cells and related hydrogen technology (cf. chapter 5.1.2), by NIFU's Dr. Antje Rapmund. In addition, the report presents an analysis of Norwegian patents (cf. chapter 5.1.3) by Mr. Stian Nygaard. When the project began, he was a graduate student at the University of Oslo, planning to do a master's thesis on this subject. For this reason, he became a member of the project team. The project has benefited from Dr. Magnus Gulbrandsen, who served as an advisor. During the project, a number of presentations at conferences and meetings have been made, in addition to writing three progress reports. The project has also benefited from information given by a large number of informants, for which we would like to express our gratitude.

Oslo, December 2003

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Director

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Summary: Innovations in fuel cells and related hydrogen technology in Norway

Norway has a potential for increasing its energy production by developing innovations, both in fossil fuels and in new, renewable energy sources. In this, innovation activities in fuel cells and related hydrogen technologies are important, in particular development of hydrogen technologies. This is the topic of this report, which presents the results of a country study organized by a Focus Group in OECD's Working Group on Technology and Innovation Policy (TIP) in cooperation with IEA's Committee on Energy Research and Technology, in 2003.

Innovation activities

The current Norwegian portfolio of innovation activities related to fuel cells and hydrogen technology consists of approximately 100 RD&D (research, development and demonstration) projects and activities. As most of these extend over many years with variable budgets reflecting the intensity of activities and adjustment of plans as the projects progress, it was difficult to split the economic figures in annual entities. However, in summing up all the budgets of this current (multi-annual) national portfolio, the following figures emerged:

- total: NOK 570 millions (approximately US$ 80 millions)
- private sector funding: NOK 440 millions (approximately US$ 61 millions)
- public funding: NOK 130 millions (approximately US$ 18 millions) – most of these are funded by the Norwegian Research Council.

The ratio of public funding to private sector funding is 1:3.4, or, private sector's share of the national portfolio is 77% in terms of funding. Considered as a share of the revenues generated by the Norwegian energy sector (in 2002: US$ 62 billions), the size of funding of RD&D in fuel cells and hydrogen technology is small, possibly an indication of underinvestment.

The innovation system

In Norway, one may observe at least three segments in activities related to RD&D of fuel cells and hydrogen technology, each segment having its own agenda and strategy. Some of these may be characterized as innovation oriented, others as having focus which to some extent may be useful in innovation activities:

- *Industry*, mainly large oil and gas companies and electrical utility companies, that invest in RD&D related to fuel cells and related hydrogen technology-activities. There are few SMEs in Norway in this field, and Norway does not have an automobile manufacturing industry. In other OECD countries such as Japan, Germany, Korea and USA, the automobile industry plays an important role in fuel cells development.
- ***R&D and scientific community,*** which pursue agendas set by the development and technology itself, i.e. a few, comparatively small R&D organizations, highly specialized in a few niche areas, driven by a knowledge agenda,

- *Government,* specifically the ministries responsible for energy, industry and transportation, but also various agencies affiliated with the government, such as research funding agencies, which has given fuel cells and related hydrogen technology some priority and attention. After the deregulation of the Nordic energy markets in the 1990s, government has, until recently, been less active in terms its innovation strategy leadership role.

Main conclusion

From a national innovation system perspective, one may characterize these segments as decoupled; they constitute what may appear as a weak national innovation regime. In innovation policy, the government may play a key role, either in terms of political and strategic leadership, or by its capability to implement strategies. In 2004, the government is expected propose a number of policy initiatives designed to promote RD&D in new, renewable energies, in particular fuel cells and hydrogen technology.

1 Introduction: Fuel cells and hydrogen technology as innovations in Norway

1.1 Background and context

This report gives an account of the results of a project undertaken by NIFU – the Norwegian Institute for Studies in Research and Higher Education – on innovation activities in fuel cells and related hydrogen technology in Norway. This country study is part of a larger effort jointly organized by the OECD's Working Group on Technology and Innovation Policy (TIP) and IEA's Committee on Energy Research and Technology. In this, a number of country studies have been made in 2003, on different energy technologies and energy sources, fuel cells being one of these. In addition to Norway, Japan, Italy, France, Canada, Germany, Korea and USA have participated with country studies, the latter designated as the lead country. The participating countries have agreed to use a common analytical approach, National Innovation Systems (NIS), and a common methodology.

1.2 A framework for the case study – OECD's aims and *goals*

According to OECD[1], the overall purpose of this case study is to perform a critical examination of the energy innovation system. The focus will be on assessing the impacts of deregulation, ICT and questions related to green house gas emission that have transformed the energy sector in terms of innovation processes and R&D productivity, and examination of their policy implications. The latter is perceived as important for policy decisions related to private/public partnerships, intellectual property rights and R&D funding. For this purpose, the OECD has initiated case studies in the energy sector. The case studies will analyze a number of energy technologies, such as: clean coal, photovoltaics, oil and gas, nuclear, electricity, energy efficiency and renewable energy, and finally, fuel cells. The latter is the topic of this report, i.e. a case study of innovations related to fuel cells and hydrogen technology in Norway.

In planning the case studies, a common framework and approach was adopted for undertaking the country studies. The framework consists of three key components:

- Examination of the energy technology innovation system,
- Evaluation of the effectiveness of the innovation system including the estimation of energy R&D productivity, and
- Delineation of policy implications.

[1] Cf. "Proposed case study on innovation in the energy sector", DSTI/STP/TIP(2002)3, 30 October 2002.

For each component, a number of steps were specified in terms of issues and relevant data for these. Below, these key components will be briefly explained because they are important for understanding the focus, aim and structure of this study, and how the study was carried out.

Examination of the energy technology innovation system

In terms of this key component, examination of the energy technology innovation system, the following topics were identified:
- Drivers of innovation
- Knowledge creation, diffusion and exploitation
- Public-private partnerships
- Intellectual Property Rights - IPR
- Effects of globalization
- Systemic influences on innovation

For each topic listed above, a number of questions were posed. In addition, the analysis should evaluate recent trends in the following areas and how they may have influenced or altered the innovation system:
- Regulatory reform
- Adoption of ICT
- Environmental concerns
- Other changes, such as market environment.

Because the questions stated above are fundamental for the design of the empirical part of the study, these guided a substantial part of the data collection procedure of the study, i.e. who or what are the relevant sources of data for answering the questions posed by the topics, and how to collect or elicit the relevant data. An important empirical approach in this became mapping of various networks in the Norwegian fuel cell and hydrogen innovation community. This will show how and to what extent people and organizations are interrelated – and to what extent these networks are connected to international networks. Chapters 2, 3 and 4 of this report will set focus on the topics of this key component.

Evaluation of the effectiveness of the innovation system

The second key component, evaluation of the overall effectiveness of the innovation system, is challenging for a number of reasons. However, the country studies were encouraged to collect data using a framework developed by the US Department of Energy (DOE)[2]. An extension of this second key component is to undertake an R&D productivity analysis in terms of R&D investments, increased energy production, and decreased cost of

[2] Cf. *Energy Research at DOE: Was it worth it? – Energy Efficient and Fossil Energy Research 1978 to 2000*, Washington: National Academy Press, 2001. The Appendix D, "Measuring the Benefits and Costs of the Department of Energy's Energy Efficiency and Fossil Energy R&D Programs" gives the details of this approach, which is based on a number of case studies. (Department of Energy, 2001)

production and other economic payoffs, such as the market share. Chapter 5 of this report addresses these questions.

Delineation of policy implications

The third and final key component requires delineation of policy implications for a number of topics:

- Energy and environment,
- R&D funding,
- Public/private partnerships in pre-competitive technology development,
- Intellectual Property Rights (IPR) management,
- Other policy areas of interest to participating countries.

However, an overarching issue for all these topics is related to the question of systemic imperfections, which also relates closely to the concept of NIS, cf. next section.

For Norway, being a nation possessing vast offshore natural gas reserves (200 years of supply according the Norwegian Petroleum Directorate), fuel cells have a substantial future potential, both commercially and in terms of environmental issues related to carbon dioxide emission, and more generally in terms of national economic strategy. In particular, important policy issues involving potentially large investments in infrastructure (e.g.: natural gas→ hydrogen→ fuel cells) and plants are involved.

1.3 The concept of NIS and "Dynamising NIS"

In 2002, the OECD published a booklet, *Dynamising National Innovation Systems*, in which National Innovation System (NIS) is a key concept (OECD, 2002a). The concept of NIS as an acronym for "National Innovation Systems"[3] was initially coined by Bengt-Åke Lundvall (Lundvall, 1988, 1993) (now at the Aalborg University in Denmark), in works he published in the mid-1980s. As a proponent of an evolutionary economic approach informed by the theoretical works of Chris Freeman (Freeman & Perez, 1988) and Joseph Schumpeter, Lundvall developed the concept of NIS based on ideas from the German 19th century economist Fredrich Liszt's on "national production systems" and Eric von Hippel's seminal work on informal technical collaboration among engineers and technicians. The latter lead to a cornerstone in his theoretical framework for NIS, i.e. the importance of user-producer relationships (the market) in the shaping of NIS.

Although NIS as a concept has an extended usage, giving a precise definition of this appears to be difficult. In an attempt to do this, Niosi et al. (Niosi, Saviotti, Bellon, & Crow, 1993) tentatively favours this definition:
"A national system of innovation is the system of interacting private and public firms (either large or small), universities, and government agencies aiming at the production of

[3] Some analysts use the term "National Systems of Innovations" – NSI. This is equivocal with NIS.

science and technology within the national borders. Interaction among these units may be technical, commercial, legal, social, and financial, inasmuch as the goal of the interaction is the development, protection, financing, or regulation of new science and technology".

A more general, abstract definition is provided by Richard R. Nelson and Nathan Rosenberg, who define NIS as "..a set of institutional actors that, together, plays the major role in influencing innovative performance" (Nelson & Rosenberg, 1993). In their explanation of this, they indicate that the question of "national" is unresolved, however, because innovation and industrial policy is of great concern for national policy makers, the nation as an entity is of relevance. A similar argument may be found in Maureen McKelvey's analysis, who, in discussing the problems associated with defining the role of the nation in the innovation system claims that: "Despite these problems, nations do still constitute an interesting, meaningful and useful level of analysis" (McKelvey, 1991), however, innovation processes are becoming more and more internationalized.

Within OECD, the concept of NIS has been successful in terms of creating a theoretical framework for innovation policy analysis and understanding, as evident in a number of publications, conferences, focus groups, seminars, etc. on this topic, in particular within the aegis of OECD's Working Group on Technology and Innovation Policy. In this, the attention has increasingly become oriented towards finding policy recommendations, i.e. finding prescriptive solutions to the challenges posed in creating innovation policies, as demonstrated in the recent report *Dynamising National Innovation Systems* from 2002. The report states that implementation of the NIS approach is "..not an issue of deriving a grand design" (OECD, 2002a), instead that it "..constitutes a knowledge-based, comprehensive structural policy". The report claims that in this, there are two sets of structural problems:

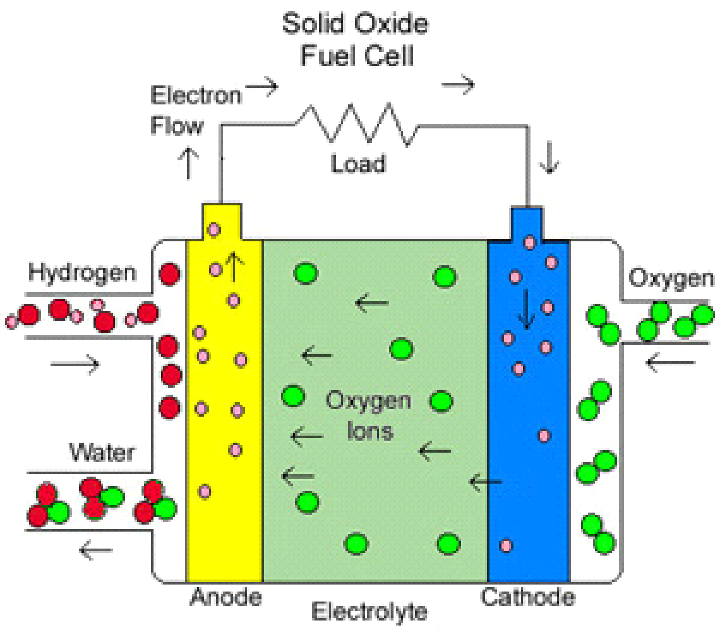
- an efficient configuration or structuring of the constituent parts of the innovation system,
- the structure of the innovation process itself, in particular the link between knowledge flows and improved economic performance.

These general policy questions guide the case study that will be presented in the following chapters. Following the aims and steps described in the section above, the case study's goal is to provide a contribution towards resolution of some of the structural problems identified by the OECD report *Dynamising National Innovation Systems*. In addition to these goals, there are stakeholders who expect that the study will provide insights of interest to sectorial and industrial policy issues, in particular development of R&D strategy options relevant for the promotion of renewable new energy sources and systems. In particular, the US has expressed interest in a methodology that will focus on the economic rationality of making public R&D investments in innovation activities directed at development of new energy sources and technologies.

1.4 Brief description of fuel cell technology: history, basic technology

A fuel cell may be described as a technical device that generates electricity by chemical conversion of energy embedded in an external input source, most commonly hydrogen (H_2), although methanol, ammonia and synthetic gas from oil, coal or biomass material may also be utilized. The chemical process resembles that of electricity generation in batteries, however, in a fuel cell, the reactant is not stored inside the device (as in a battery), but supplied from an external source. A number of different types of fuel cells exist; these are basically differentiated in terms of the materials used for anodes, cathodes and electrolyte, these three elements being fundamental in all fuel cells. The figure 1.1[4] is a simplified depiction of a *solid oxide fuel cell,* or *SOFC*. The other types of fuel cells are:

- alkali fuel cell – AFC
- proton exchange membrane fuel cell – PEMFC
- phosphoric acid fuel cell – PAFC
- molten carbonate fuel cell - MCFC



Figur 1.1: *Basic components and process of a solid oxide fuel cell (SOFC)*

Each single fuel cell generates a small amount of electricity, typically less than one volt. For this reason, in order to increase the energy output from fuel cells, a number of individual fuel cells are usually stacked or piled together. Still, because the conversion of energy is direct, high energy efficiencies may be obtained from fuel cells, usually in the range from 40% to 80%, depending on the type of fuel cell and their operating

4 Source: fuelcells.si.edu/images/ pafcpem4.jpg

temperatures. By comparison, energy generated by an internal combustion engine is 30% or less. The different types of fuel cells have different characteristics, or salient features. Thus developed units of MCFC have proved to provide high energy efficiency (60-80%), with proven high electricity output (more than 2 MW), however, they are, like most fuel cells, expensive in terms of output energy price and operationally complex. Still, there is a growing market for commercial fuel cells based energy systems, as evident by the success of the Canadian fuel cell manufacturing company Ballard[5], which offers "power packs" of various sizes to consumers and communities.

Historians of technology claim that fuel cells were invented in 1838 by the English lawyer William Robert Grove (1811-1896), this in the course of Grove's development of a new type of battery[6]. Following this, a number of scientists designed new types of fuel cells, gradually improving the knowledge and technology of fuel cells. A milestone in this was reached in 1893, when Friedrich Wilhelm Ostwald (1853-1932) was able to provide a successful explanation of how fuel cells work, i.e. the electro-chemical roles of various elements in a fuel cell and how these generate electricity. Another important person in the history of fuel cells is Francis Thomas Bacon (1904-1992) who successfully developed an alkali electrolyte fuel cell. The results of his work were licensed to Pratt & Whitney in their space craft fuel cell used in the Apollo space mission. In a historical perspective, the invention of fuel cells coincided with the invention of telegraphy by Samuel Morse (1837). However, their subsequent evolution are different, an aspect which is significant in an innovation perspective.

1.5 Brief description of technological challenges

The interest in fuel cells and the use of hydrogen as a potentially important future source of energy has increased steadily during the past decades. This interest also includes other types of new, renewable energy sources, such as wind mills, photovoltaic power generators, etc. The reason for this is plain: Traditional fossil fuel sources are finite, these will inevitably be depleted. In this process one may reasonably expect that the price of fossil fuels will gradually increase because of increasing scarcity and costs of production. Simultaneously, the world's energy consumption is increasing rapidly; both developed and developing countries are using more and more energy, in particular fossil fuels. This development exacerbates the problems associated with emission of climatic gases and pollution. In this perspective, fuel cells are attractive. Fuel cells represent "a clean technology" because it may generate energy from renewable resources. Governments and national energy policy makers, together with environmentally concerned individuals and organizations have for a long time promoted fuel cells because of this, however, this interest is now shared with an increasing number of industrial firms and sectors, of which

[5] Cf. for more information on Ballard: http://www.ballard.com/

[6] For further information, cf Smithsonian Institution – http://americanhistory.si.edu/csr/fuelcells/origins/

the automobile manufacturing industry may be considered as strategic for the promotion of fuel cell technology. The reason for this is a number of attractive aspects associated with fuel cells:

- high energy efficiency
- only water and damp is emitted
- silence
- renewable resources are used as source energy, notably hydrogen
- a high degree of potential freedom in configuration and design of technological solutions and infrastructures based on fuel cells,
- this potential freedom may promote new, flexible ways of constructing energy supply systems in society based on a number of different energy sources.

However, in spite of these attractive aspects, there are a number of factors that inhibit the diffusion of fuel cell technology. Perhaps most important is the cost: Fuel cells are, compared with conventional energy sources, still expensive: "Depending on the feedstock and production and distribution methods used, the cost of a kilogram of hydrogen can be four to six times as high as the cost of a gallon of gasoline or diesel fuel. (A kilogram of hydrogen is the energy equivalent of a gallon of petroleum-based fuel.)"[7] (Burns, McCormick, & Borroni-Bird, 2002). In addition, there are a number of other hurdles and barriers:

- fuel cell technology has not become "stabilized", the bulk of the technology is still at experimental, prototype stage, although some fuel cell based power systems are commercially available, such as the "power packages" manufactured by the Canadian firm Ballard,
- the infrastructure for a fuel cell based energy system is still highly inadequate, in particular a systems and technology for distribution and storage of hydrogen,
- apart from a few companies, the manufacturing, mass-production industry is lacking, the automotive industry has not yet made commitments to adoption of fuel cells in vehicles,
- the "grand design" of a "hydrogen society" has not yet been developed, in spite of numerous scenarios and visions.

Thus, in a perspective of innovation, one may claim that fuel cells are still inventions because the diffusion of fuel cells has not yet "taken off", it is still a rare, exotic and expensive technology. However, fuel cells have a potential of becoming a radical technological innovation. This may be a significant policy matter.

1.6 Data collection and analysis

This country study of Norway was organized as a project consisting of nine interrelated tasks, each task being distinct in terms of activities, methods and goals. Three of these

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7 L. D. Burns, J. B. McCormick and C. E. Borroni-Bird, "Vehicle of change", *Scientific American*, October 2002, p. 49.

tasks resulted in working documents; these documents have served as a platform for this report:

- Helge Godø, Antje Rapmund, Lars Nerdrum and Magnus Gulbrandsen, *Pilot project report: Innovations in fuel cell technology in Norway – OECD Case Study on Innovation in the Energy Sector,* NIFU U-notat 2/2003, (Godø, Rapmund, Nerdrum, & Gulbrandsen, 2003)
- Antje Rapmund and Stian Nygaard, *Bibliometric and patent analysis of Norwegian research on fuel cells 1990-2002,* NIFU U-notat 19/2003,(Rapmund & Nygaard, 2003)
- Lars Nerdrum and Helge Godø, *Mapping Norwegian RD&D in fuel cells and related hydrogen technology – in an innovation policy perspective*, NIFU U-notat 20/2003.(Nerdrum & Godø, 2003)

In the study, a number of different sources of information and data were used. These may be broadly grouped into five categories:

- *Open sources* such as found in published reports, official government documents, scholarly books and journals, newspaper articles and web publications, etc. Whenever these sources are used, references will be made in the text.
- *Bibliometric data* elicited from ISI, providing names of institutional affiliation of the authors with a Norwegian address, cf. chapter 5.1.2 of this report (Rapmund & Nygaard, 2003).
- *Patent data* elicited from patent data bases, on inventors having a Norwegian address, cf. chapter 5.1.3 of this report (Rapmund & Nygaard, 2003).
- *RD&D project information* from Norwegian companies, research funding agencies, research institutes and organizations, on activities in fuel cells and related hydrogen technology,
- *Interviews* with key informants related to the activities above.

Of these sources of information and data, the last two will be explained below because these are closely linked, and, more significant, data and information collected by these contributed substantially to a number of findings in the project. As a starting point for data collection, the following three sources were used:

- A list of members of the *Norwegian Hydrogen Forum*[8] and an article published by this organization in their newsletter (mostly in Norwegian), *H_2Info*, no 2, 2002[9], providing information on RD&D-activities in the member organizations,

8 Cf. www.hydrogen.no. NHF's home page describes itself as a "not-for-profit organization to promote the environmental benefits of using hydrogen as a carrier. Members are Norwegian companies, universities/colleges, and research institutions with an interest in hydrogen".

9 This article was published in Norwegian with the title "Hydrogenaktiviteter i Norge" ["Hydrogen activities in Norway"], downloaded from http://www.hydrogen.no/h2info/h2info_2002_02.htm - 23 pages of printout.

- Information from FORIS, the project management data base of the Research Council of Norway on all current projects on fuel cells and related hydrogen technology funded by the research council,
- Names of Norwegian organizations, companies, projects, etc undertaking RD&D on fuel cells and related hydrogen technology identified in miscellaneous sources, such as newspapers, specialized newsletters, web-sources, etc.

In addition to identifying the relevant actors, analysis of these sources provided information on RD&D-activities (research, development and demonstration-activities), however, some sources more rich with information than others. All the information found was transmitted to spreadsheets. Thus, a rudimentary data matrix was constructed. Due to lack of information on important categories, we decided to do a survey of the organizations and ask them about their project portfolio on fuel cells and related hydrogen technology activities. Based on names in the data matrices, a list consisting of names of 19 organizations was made, as shown below. All these were approached and interviewed by telephone. In addition we made visits to two of these. In the survey, a simple interview guide was used, asking questions on the following topics:

- the number and size (i.e. head count, projects, funding) of activities with an innovation focus,
- tasks and goals – who does what for what purpose,
- alliances and networks of cooperation,
- results and benefits obtained from the innovations (if any) – in terms of commercial benefits, social and environmental benefits, and knowledge benefits.

Because of this open approach, we were able to elicit much and rich information from the key informants. During the interviews, notes were taken, and these were used in typing reports immediately after the interviews. The interviews became an important source for many parts of the analyses presented in this report.

The following organizations and companies were approached and interviewed:

- Institute for Energy Technology (IFE)
- Det norske Veritas,
- Elkem
- Agder College
- Norwegian institute for water research (NIVA)
- Norsk Hydro
- Norwegian University of Science and Technology (NTNU)
- PEM Tech
- Rogaland Regional Research – Rogalandsforskning
- SINTEF
- Statkraft
- Kværner
- Statoil

- Prototech
- University of Oslo
- Stor-Oslo Lokaltrafikk
- Shell Norway
- Norwegian Defence Research Establishment (FFI)
- University of Bergen

As will become evident in the presentation in the next chapters, the collection of data has provided us with an empirical material of sufficient quality to present an overview. However, two factors have inhibited the reporting of data:

- some informants were reluctant to give precise information on their activities, this because they claimed these were business secrets or otherwise sensitive information,
- complexity of project organizations, in which informants were not certain of a number of figures – and for this reason gave us approximate figures and facts on a general level.

However, we are fairly certain all the largest and most significant RD&D-activities in fuel cells and related hydrogen technology have been registered and characterized by the mapping.

1.7 Structure of this report

Generally, the energy policy agenda of Norway reflects the abundance and economic significance of energy. This explains why the agenda is different from nations that depend on energy imports. However, within this framework of energy abundance, there are forces and factors that play an important role for innovations in fuel cells and related hydrogen technologies in Norway. As drivers of innovations, these will be elaborated in the next chapter (*chapter 2*), which will also identify other, related factors, i.e. broad structural and dynamic factors that are important for the emergence of innovations in the energy sector.

Following this, *chapter 3*, will describe and explain the innovation "landscape" of Norway in fuel cells and related hydrogen technology. This will identify the major actors, i.e. firms, organizations, research institutes, etc, in this field and what kind of activities that is undertaken. RD&D, an abbreviation of activities related to research, development and demonstration are important in this.

Because public policy may play an important role in promotion of innovations, this is the topic of *chapter 4*. Until now, Norway has not had a specific, targeted innovation policy for promotion of RD&D in fuel cells and related hydrogen technology; however, there are some general policy measures that may be relevant, as will be explained in this chapter.

Chapter 5 addresses innovation performance in Norway, and makes an assessment of this, in the field of fuel cells and related hydrogen technology. The aim of this is to present an analysis of empirical aspects that are significant in an innovation policy perspective. The chapters consist of a number of interrelated, but separate analyses: First, knowledge profiles and networks based on bibliometric analysis and patent analysis. This is followed by an analysis of some salient structural and institutional aspects, and an assessment of benefits from innovation activities. Finally, the chapter will present a case study of three R&D projects that elucidate important innovation policy and strategy aspects.

The final chapter, *chapter 6*, concludes the report by presenting and discussing some of significant issues relevant for innovation policy and strategy in promotion of new, renewable energy sources, such as fuel cells and hydrogen. In this, the question of innovation systemic efficiency is discussed. The chapter concludes by pointing to the Norwegian innovation "landscape", observing that actors in this pursue strategies that may be considered rational in terms of their own needs and ambitions, however, on a national level, the sum of these may be characterized as incoherent or fragmented, i.e. they are decoupled or only weakly linked to each other. Innovations in new, renewable energy sources are essential for future sustainable development of society. For this reason, there is a need for public policy initiatives that will provide leadership and spur innovation activities.

2 Drivers of innovation in fuel cells and hydrogen technology in Norway

2.1 Introduction

Norway produces an abundance of energy; most of this is exported, either directly as electricity, gas or oil, or indirectly, embedded in products that have been manufactured in energy intensive processes, such as aluminum. Norway has a potential for increasing its energy production even more by developing innovations, both in fossil fuels and in new, renewable energy sources. In this, innovation activities in fuel cells and related hydrogen technologies have an interesting potential. This will be the main topic of this report; however, in order to focus on this, some introductory aspects need to be elucidated.

Norway's present abundance of energy is due mainly to two energy sources:

- *Hydroelectric power:* With an annual output of approximately 130 TWh, this has until now provided the domestic market adequately with all of its regular, normal demand for electricity (approximately 120 TWh). The surplus is exported to Nordic neighboring countries. Although the per capita consumption of energy is similar to that of other nations in northern Europe in the consumer market segments, the consumption of electricity in Norway is high, but this is due mainly to two reasons:
    - Electricity enjoys a hegemony as an energy source in stationary applications in the public and private market segments, because it has traditionally been inexpensive and convenient.
    - Approximately 2/3 of the electricity produced in Norway is used by industry, of which the electrochemical industry (aluminum melting and manufacturing) is a dominant actor. By this, Norway exports energy embedded in metals and other energy intensive products, e.g. industrial fertilizers, pulp, paper, etc.
- *Offshore oil and gas production:* Since the 1970s Norway has been a substantial exporter of oil and gas from its large offshore oil and gas provinces, as only a small fraction of this is consumed in the national markets. The following facts[10] give an indication of this:
    - In 2002, approximately 160 million tons of oil (including condensates and NLG) were produced, of this 137 million tons crude oil were exported (86%) at a value of NOK 200 billions (approx. US$ 28 billions),
    - In 2002, the production of gas reached an all time high of approximately 68 millions Sm^3 o.e., of this 63 millions million Sm^3 o.e. (93%) were exported at a value of NOK 70 billions (approx. US$ 10 billions).

[10] Source: *Statistics Norway, Oil and Gas Activity – 4th Quarter 2002 – Statistics and Analysis*, Oslo, June 2003, figures 7 and 8, table 25 and 27.

As exploration and production of Norwegian offshore oil and gas has evolved, this sector has brought forward a number of outstanding technological innovations in offshore technology. This will be the topic of a separate country study in the OECD Case Studies of Innovations in the Energy Sector.[11]

As evident in a number of policy documents and political debates related to energy policy and environmental issues, the attitude and interest for developing new, renewable energy sources in Norway has been generally positive. Parallel to many other countries, the "oil shock" of 1973 marked the start of this; however, this interest has never gained momentum beyond being politically correct. One may point to a number of reasons for this, of which the low price and abundant supply of electricity from hydroelectric power plants probably is the most important economic reasons: According to conventional wisdom, there has never be a "business case" for other new, renewable energy sources, apart from building hydroelectric power plants [12]. Until recently, the management "mind-set" of the predominantly state owned energy utilities has reinforced this; traditionally, they have been oriented towards constructions of large, centralized hydroelectric power systems. This technological orthodoxy was for a period also aligned with efforts to build nuclear power plants in the 1950s and 1960s; however, as in Denmark, protests from the public opinion combined with the high costs of this (compared with hydroelectric power) finally defeated these initiatives. In short, the economic and strategic incentives for developing new, renewable energy sources have, until recently, been weak, almost absent. However, this has changed gradually due to the deregulation of the domestic energy system combined with introduction of the Nordic energy market. Another factor that has contributed to a renewed interest in developing new, renewable energy sources is a growing concern that Norway within a few years may experience serious shortage of electric power. The reason for this is that the domestic consumption of electricity has increased over the years; however, the electric power generation capacity has not kept pace with this increasing demand. According to a prognosis published[13] by the Norwegian Water Resources and Energy Directorate (NVE), an annual increase of electric power by 1.2% (which is an assumption of low growth) may create a serious "imbalance" in the Norwegian energy system by year 2015. Mainly for environmental reasons, the prospects for constructing new hydroelectric power plants in order to increase the electric power supply are not feasible. This also contributes to a growing interest in developing new, renewable energy sources – and technologies and infrastructures that may provide these.

These new economic mechanisms, combined with other factors that have emerged recently constitute the present drivers of innovation in Norway in fuel cells and related hydrogen technology – of which the following topics will be elaborated below:

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[11] Cf. Rogalandsforskning/Norregio, *Upstream oil and gas in Norway*, Stavanger 2003.

[12] The success of Denmark in developing commercially viable windmills for electricity power generation has proven the fallacy of this.

[13] Cf.: http://www.energistatus.no/spesialemner/kraftbalansen.htm

- Deregulation of energy markets
- Norway's gas "problem"
- Environmental movements and commitments
- Growing interest in the industry
- Growing concern for the vulnerability of modern society
- Norway's non-OPEC position

2.2 Deregulation of energy markets

Deregulation of the domestic energy markets was introduced in the 1990s, causing profound structural changes in the entire energy sector. The initial policy initiatives were made in the late 1980s by unbundling the numerous roles (e.g. ownership of hydroelectric plants and dams, the national grid, local utility infrastructures, etc) tied to the previous monopolies. Simultaneously, the national grids the Nordic countries were interconnected and a unified Nordic market for trade in electricity was established. In this, futures contracts on electricity supply are auctioned. The underlying, fundamental idea of this is that competition in the market will create an efficient system that will also promote innovation and development of energy supply in response to real market demand – and not by technocratic, electric games played by engineers and politicians. The impacts of the deregulation were fundamental in a number of other ways. One immediate impact was that the government, in particular the Ministry of Petroleum and Energy and its agencies, had to find a new role in terms of providing leadership in the development of new energy sources. This is still an unresolved challenge because of structural factors: Whereas the Norwegian state's large ownership of electric utility companies (such as Statkraft) is managed by the Minsitry of Trade and Industy as a shareholder, the responsibility of rules and regulations rests on the Ministry of Petroleum and Energy and to some extent also the Ministry of Environment. The role of ownership or responsibility for promotion of national innovations in new, renewable energy sources is not clearly defined. In this post-deregulation situation, the new roles of actors have not yet been crystallized, in particular there seems to be a lack of leadership and initiative in terms of promoting innovations in new, renewable energy sources.

2.3 Norway's gas "problem"

This is a convenient label for the fact that Norway is a substantial producer of natural gas from offshore reservoirs, yet has not been able to develop this natural fortune in Norway. Most of the gas (93%) is exported; it is fed into various pipeline systems that transport the gas to Europe. Little of this is used or consumed by households or the public in Norway – one important reason for this is that most of Norway's electricity is produced in hydroelectric plants, as explained above. For more than twenty years, there has been a debate in Norway that the gas to a larger extent should be used and developed in Norway – for industrial purposes and a number of other, potentially more value-adding applications.

In the recent debates, focus has been set on production of hydrogen from natural gas as an interesting potential that should be developed.

Apart from a few petrochemical plants using liquid gas as raw material, there has so far not been any real demand for gas as an energy source in the domestic energy markets. Although most of the larger towns in Norway had gasworks and networks of pipelines for distribution of gas to public buildings and residential areas, these were gradually closed down after WWII, as electricity gained hegemony and now holds a dominant position. At present, 1/5 of Europe's supply of gas is Norwegian; less than 1% of the Norwegian gas is consumed in Norway. Building a pipeline to the larger urban areas along the Oslo Fjord and branching further to Sweden, Denmark and Finland has been one vision (of many), however, this has not materialized because of uncertainties related to the ownership and profitability of these projects. The question of constructing power plants fed by offshore gas on the western coast of Norway has been intertwined with the pipeline plans; however, these plans have created much political controversy related to the question of emission of carbon dioxide[14].

Responding to political pressure that "something has to be done" for developing industry and creating more value from the vast amount of Norwegian natural gas on the mainland, the government has recently taken some initiatives. In July 2003, after a debate in the Storting (Norwegian Parliament) on the future strategy and management of Norway's natural gas resources[15], the Ministry of Petroleum and Energy, together with the Ministry of Transportation established a commission of experts that were given as terms of reference to suggest plans for a large-scale national hydrogen program based on natural gas. Several of the points in the commission's terms of reference deal with production of hydrogen as an energy source and the use of fuel cells, for stationary electricity generation and for purposes related to transportation.

2.4 Environmental movement and commitments

In spite of the claim in the introduction that the interest for new, renewable energy sources has never gained momentum, there are nevertheless diverse groups, organizations and visions that in sum represent a strong advocacy. This is mainly for environmental reasons – justified in what they often term as creating an environmentally sustainable social development of society. During the past years, these forces have gained more attention in

14 The first cabinet of PM Kjell Magne Bondevik was forced to resign on 9 March 2000 because of a majority vote of non-confidence in the Storting (Norwegian Parliament) related to a carbon dioxide emission permit for a planned gas power plant. In 2003, plans for constructing three large-scale gas power plants have been mothballed because the companies claim that without government subsidies, the anticipated profitability will be too low, or absent, cf. article "Gasskraftverk blir ulønnsomme" ["Gas power plants will become unprofitable"] in the daily newspaper *Aftenposten,* 10 November 2003, written by Alf Ole Ask.

15 The debate was based on the governments presentation of a White Paper on the domestic use of natural gas, cf. St. meld. nr. 9 (2002-2003) "Om innenlands bruk av naturgass m.v."

political debates. In particular, activists from environmental NGOs have been vocal in promoting the development and use of non-fossil and non-nuclear fuels for energy production. In this, fuel cells and use of hydrogen have a central role.

Although it is difficult to give a precise measurement of how influential or to what extent these groups have created an impact, they have achieved to set promotion of new, renewable energies on the agenda in public debates, and by this make visible a case for the environmental justification and legitimacy of developing new, renewable energy sources. The Kyoto protocol and the International Panel on Climate Change are invoked as authorities. The most influential and visible NGO is the *Bellona Foundation*, a private, non-profit organization based in Oslo. In addition, there are a number of other organizations, some NGOs, others public or semi-public, that advocate and promote the idea for "sustainable, future hydrogen society". Among these, *The Norwegian Hydrogen Forum* (NHF), has a unique position. This is a "not-for-profit organization to promote the environmental benefits of using hydrogen as an energy carrier". However, the organization differs from the others because most of the members are engineers and scientist who work with fuel cells development and hydrogen technology and they are often employed as professionals and experts in industry, R&D and academia. For this reason, NHF resembles a professional, technological society, making them different from the activists and environmental zealots in the other organizations. Still, in having a common vision of the future potential of hydrogen and fuel cells, this organization represents an interesting and influential network within the industry – and a bridge to the environmental movement.

2.5 Growing interest in the industry

Although exact figures are almost absent, observers of the industry claim that the interest for hydrogen and fuel cells has oscillated for a long period, but it has gradually increased during the past decade. To support this claim, they point to the resources allocated to various activities and projects related to fuel cells and hydrogen technology, which seem to have increased during the last years in Norway, although the picture is unclear. This topic will be explored and explained in full detail in the next chapter. Obviously, industry is attracted to this because of the future, potential business opportunities if hydrogen and fuel cells should become an emerging market. This is probably reinforced by the changing strategic "mind-set" of the top management in the energy industry – the deregulation of the former monopolies has simultaneously been liberalization in terms of the technological orthodoxies – the hydroelectric power plant paradigm described earlier has lost its grip for a number of reasons. In addition, one should not underestimate the influence of their peers in the international business community: The signals that business leaders of automotive manufacturing giants such as Chrystler/Daimler or oil companies such as Shell give when they become interested in hydrogen and fuel cells have made an impression on to their peers in Norway and other small countries. In addition, the debates on environment, pollution, climate change, emission of green house gases, sustainable development of future society, etc. have become issues that they are also concerned with. Thus, industries will attempt to build images of themselves as responsible corporate citizens – by promoting "clean technologies" they may also create goodwill that is important for doing business in the energy sector.

2.6 Growing concern for the vulnerability of modern society

In Norway, as in many other industrialized nations, the vulnerability of a society that has made itself dependent on large centralized electricity networks and ICT-systems has become an issue. The recent black-outs in USA, Copenhagen and Italy – and the energy crisis of California a few years ago, has given support and realism to the claims that modern society's dependence on a reliable supply of electricity and non-interruption of telecommunications is so vital that there is a definite need for rethinking these systems – one has to rethink the structure in terms of standards for robustness, reliability and quality of service. The deregulation has also introduced the question of stability and predictability of energy prices – the market driven volatility of energy prices may be contrary to important strategic, social and economic goals. Decentralization of energy production and a higher degree of redundancy may incur increased costs, i.e. decrease the efficiency of a market, but ignoring the dangers of vulnerability may be risky. The prospects of developing new, renewable energy sources and technologies have grown because of these issues. During the cold winter months of 2002/2003 the question of reliability of supply became an issue in Norway because of high prices of electricity: Due to an abnormally dry summer and autumn in 2002, the large water reservoirs of the hydroelectric power plants in Norway were nearly empty, forcing the utilities to provide electricity imported from neighboring countries and reselling it at prices that the Norwegian public felt were outrageous. Deregulation and political impotence of the authorities were blamed; simultaneously, the question of developing a more robust energy strategy became an issue.

2.7 Norway’s non-OPEC position

Although Norway is a substantial oil and gas-producing nation, it is not a member of OPEC, but it benefits from the price strategy that OPEC pursues. The political reasons for non-membership in OPEC are complex – and not an issue for this report. However, Norway is a member of the OECD-affiliated organization IEA – the International Energy Agency; in addition Norway maintains a number of relationships to “Western” organizations and nations for the purpose of securing and developing future energy supply. The latter is seen in Norway’s participation in energy focused R&D projects within EU’s 5th Framework Programme, which has been extended into its successor, the 6th Framework Programme. Increasingly, these organizations and relationships have set hydrogen and fuel cells on their agenda, as evident in the Norwegian support for US President Bush’s initiative for an international partnership designed to develop a “hydrogen economy” by year 2020[16], i.e. the *International Partnership for the Hydrogen Society*, or IPHE[17]. As these organizations and relationships increasingly have set hydrogen and fuel cells on their agendas, they provide legitimacy and justification for national innovation policies designed to promote these goals, as explained earlier in this chapter.

16 These plans were first announced under a meeting for ministers of energy at IEA in Paris, April 2003, in which the Norwegian minister of petroleum and energy, Mr. E. Steensnæs, gave full support to the US initiative and simultaneously invited his US colleague Mr. Spencer Abraham to visit Norway.

17 Cf. press release from the US Department of Energy, of 25 November 2004, explaining this: http://www.state.gov/g/oes/rls/fs/2003/25983.htm. Although initially not invited, Norway became a member of this partnership after putting considerable diplomatic pressure on USA.

3 Innovation system in the Norwegian energy sector – knowledge creation, diffusion and exploitation in fuel cells and related hydrogen technology

3.1 Introduction – Scale, scope and context

Although Norway produces an abundance of energy and is a substantial exporter of oil and gas, Norway is small in terms of its population, making a number of dimensions small-scale compared with other nations. One of these is RD&D and related innovation activities, as evident in the funding of these types of activities in the area of focus in this study. Norway's *public funding* of RD&D was approximately US$ 12 per capita (year 2000 figures) in the energy sector. By comparison, Japan's funding in this sector was US$ 34, the world's highest, followed by Switzerland with US$ 25. Even if Norway's figure is the third highest in the world, this is still only 1/3 of the amount spent in Japan, per capita. Multiplying US$ 12 with 4,5 millions (Norway's present population size) makes a grand total of US$ 56 millions. Using the same equation for USA with a population of 250 millions, USA's spending is US$ 2.25 billions, i.e. the ratio of USA/Norway is 40:1; the ratio of Japan/Norway is 73:1, etc. Thus, small size is a salient feature of Norway in terms of RD&D and related innovation activities.

In 2001, Norway's total spending on R&D[18] was NOK 24.4 billions (approximately US$ 3.4 billions[19]), i.e. this total included all sectors (public and private) of society and all sources of funding (table 3.1). It is within this economic framework that most of the innovation activities related to fuel cells and hydrogen technology is carried out in Norway, i.e. within the boundaries defined as "sum energy&offshore R&D" in table 3.1. This includes a number of research fields, with a total funding of NOK 2.6 billions in 2001, equivalent of approximately US$ 360 millions. This figure is much larger than the figure quoted above, mainly because it includes the industry and institute sectors, i.e. the non-public funding of energy and oil and gas (offshore technology) RD&D.

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18 Source: *Science and Technology Indicators – 2003 Norway*, NIFU, June 2003, table 1.

19 This figure is estimated based on the currency exchange rate as of 10th November 2003, i.e. US$ 1 = NOK 7.17. Because the rate of exchange is volatile, the accuracy of the US$ equivalents has to be interpreted with caution.

Table 3.1: *R&D expenditures in Norway 2001 - Energy related R&D and offshore technology (oil&gas) R&D*[20]
Figures in NOK millions

R&D field	Industry	Institute sector	Higher education	Total
Total R&D in Norway	12 614	5 582	6 274	24 469
Energy related R&D (electricity)	373	231	72	676
Offshore technology (oil&gas)	1 394	424	106	1 924
Sum energy&offshore R&D	1 767	655	178	2 600
Share (%) energy&offshore of total R&D	12,1	18,2	2,8	10,6

In the country study of Norway, data was collected in order to map characteristics and size of the innovation activities related to fuel cells and hydrogen technology. The current national portfolio has approximately[21] 100 projects and activities, all of these could be classified as RD&D. As most of these extend over many years with variable budgets reflecting the intensity of activities and adjustment of plans as the projects progress, it was difficult to split the economic figures in annual entities. However, in summing up all the budgets of this current (multi-annual) national portfolio, the following figures emerged:

- total: NOK 570 millions (approximately US$ 80 millions)
- private sector funding: NOK 440 millions (approximately US$ 61 millions)
- public funding: NOK 130 millions (approximately US$ 18 millions) – most of these are funded by the Norwegian Research Council.

The ratio of public funding to private sector funding is 1:3.4, or, private sector's share of the portfolio is 77% in terms of funding. In the figures above, the institute sector is absent because research institutes do not fund R&D: Most of the institutions in this sector are contract research organizations depending on external funding, i.e. funding from either private sector or public agencies.

As will be explained further in the next section, the project portfolio is heterogeneous in terms of types, aims and activities. However, most of the projects are comparatively small, i.e. typically funding 1-2 man/years of R&D and expenses related to equipment and facilities. It also funds a number of PhD- and post-doc scholarships at the universities. This explains the high number of projects.

20 Source: *Science and Technology Indicators – 2003 Norway*, NIFU, June 2003, figure 7 and table 1.

21 The term "approximate" is used because we encountered some projects that, for various legitimate reasons had two different labels. For this reason we may have counted some projects twice. In total, 112 project titles were registered.

Considering the economic magnitude and the revenues generated from the sectors that these fields of RD&D represent, the size of RD&D activities may be considered low. In 2002, the turnover from the Norwegian oil and gas sector and electricity sector was NOK 445 billions (approximately US$ 62 billions). Compared with this figure of one year only, the portfolio of RD&D in fuel cells and related hydrogen technology (multi-annual budget) is 0.12%. Generally, the oil and gas sector and the energy sector have low R&D intensities compared to sectors such as ICT and pharmaceutics.

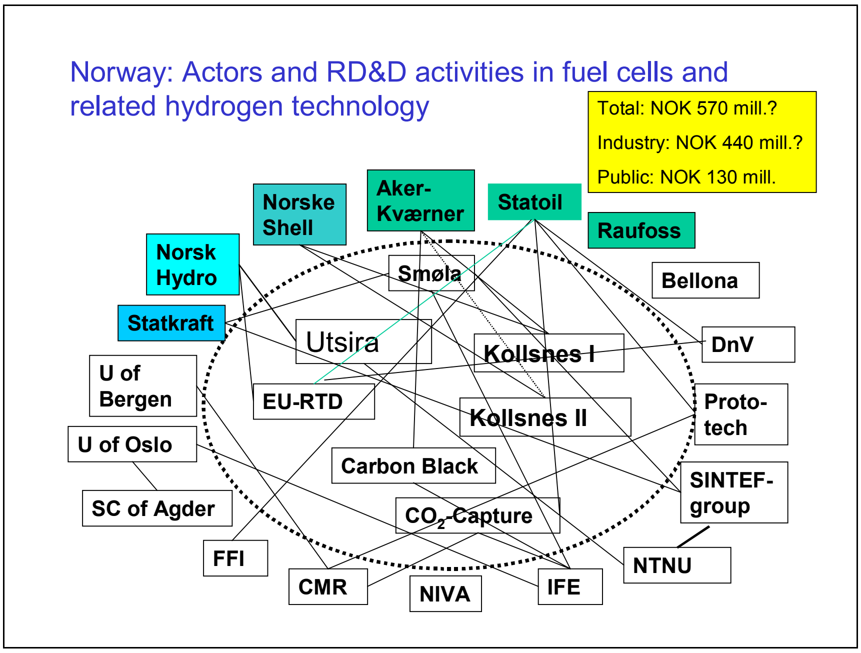
3.2 The innovation landscape and RD&D in fuel cells and related hydrogen technology

3.2.1 The actors

A number of organizations and institutions in Norway are involved in doing RD&D and related innovation activities in fuel cells and hydrogen technology. For statistical and classificatory purposes, the following categories designate these:

- *Higher education sector*, which includes universities, university colleges and colleges,
- *Institute sector*, which includes autonomous, semi-public R&D institutes, most of these do contract research for private sector clients,
- *Industry sector*, which corresponds to OECD's classification of the "business enterprise sector", or the more generic term "private (industry) sector".

In addition to these, a few NGOs in the environmental movement, such as Bellona, have RD&D projects, but these are small.



Industry sector

A characteristic of the RD&D activities in fuel cells and related hydrogen technologies undertaken by the industry sector is that the field is dominated by a few, large industrial companies (oil and gas and energy companies) and that they fund and participate in a few, large projects, as will be explained below. However, even if these projects are comparatively large and account for a major portion of the resources spent on RD&D in fuel cells and related hydrogen technology in Norway, they do not represent large investments or strong commitments in innovation activities in this field, considering the size, technological focus and financial strength of the companies. This observation, i.e. the relative modesty of these projects and the way they are focused, may be interpreted as a strategy which will allow the companies to keep themselves well informed of the technological development in the field – and by this, be able to leverage rapidly new technological or business opportunities, should these arise. This strategy is commonly known as a *second mover strategy*[22]; it avoids or minimizes the risks involved with heavy investments into risky technological development, however, it gives the companies the option to act rapidly, should opportunities emerge(Gilbertand & Bormbaum-More, 1996). Superficially, one may claim that this is a type of free-rider strategy, however, this is too simplistic, because most companies do in fact make some investments in RD&D; being a second mover requires capabilities and competencies, i.e. it requires firms to have its own R&D activities. This aspect will be elaborated further below and in the next chapters. First, a description of the activities in the industry sector in Norway, in fuel cells and related hydrogen technology RD&D:

- *Norsk Hydro* (or just *Hydro*), the largest Norwegian manufacturing company, stands out among these. Hydro has long traditions in production of hydrogen for industrial fertilizers, and is a world leader in electrolysis of water. Since the early 1970s, this firms has also invested heavily in the oil and natural gas industry, and has strong strategic interests within fuel cells and related hydrogen technology. In the beginning of 2003, Hydro established a business unit, ”Renewables and Hydrogen”, in order to focus its efforts on this business area. Hydro has been an active partner in several EU-funded projects on hydrogen distribution and has among other things established hydrogen fill station for buses in Reykjavik, Iceland.

- *Norske Shell* (or *Shell Technology)* is another large private actor in Norway. Although this company is a subsidiary of the multinational corporation Shell, it participates strongly to the Norwegian national innovation system and performs RD&D in Norway. This company is investing strongly in energy systems based on SOFC (Solid Oxyde Fuel Cells), mainly for use on offshore oil & gas platforms.

22 Cf. Joseph T. Gilbertand and Philip H. Bormbaum-More, “Innovation timing advantages: From economic theory to strategic application”, *Journal of Engineering and Technology Management*, vol. 12 (1996), p. 245-266.

- *Statkraft* is another large actor in this field. Statkraft is the largest electricity utility company of Norway and is in the process of expanding into other markets in the Nordic countries and Germany. Statkraft has currently a portfolio of around 10 projects on fuel cells and related hydrogen technology, many of these are carried out in co-operation with other industrial partners. A large part of the technology development is outsourced to contract research organizations in Norway – of these the SINTEF-Group is significant.

- *Aker/Kværner* and its sister company *Aker Elektro* have invested heavily in this R&D technology area, but due to recent financial constraints, the activity level seems to be somewhat lower than what was expected only few years ago. Still, *Aker/Kværner* wants to participate in this technology field, and, among other things, has contributed since long to the production of hydrogen from natural gas (through the so-called "carbon black"-procedure) and to energy-systems based on fuel cells.

- *Statoil* is Norway's largest oil and gas company, and was previously also very active in RD&D on fuel cells and related hydrogen technology. During some years in the 1990s it spent around 150 million NOK on fuel cell research in almost complete secrecy, with meagre commercial results. Subsequently, Statoil withdrew from this technology field for a period, but it is now about to re-strengthen its involvement here. Currently, it is engaged in technology monitoring and is working on a RD&D strategy directed at developing an dual cycle energy production system using fuel cells.

- *Prototech* is the only small- and medium-sized company which seems to be active and successful in RD&D in fuel cells and related hydrogen technology. It specializes in SOFC-development. This activity is a spin-off from Christian Michelsen Research (a research institute) in Bergen, from a research contract they had with Statoil in the early 1990s.

- *Det norske Veritas (DnV)* is also undertaking RD&D in the fuel cells and related hydrogen technology area, with security assessment, certification of pressure tanks for hydrogen storage. In addition, DnV has the project leadership of a potentially large project aimed at implementing fuel cells for ships in the merchant marine.

Other firms and business organizations that have some RD&D activities in this area are *Raufoss Technology* (development of high pressure hydrogen storage tanks for automobiles), SL Lokaltrafikk (the mass transit transportation company for the Oslo metropolitan area – a trail for using hydrogen powered buses), EBL, ABB, Elkem, and Energy Development, but their current involvement is not very strong.

Institute sector

- *The SINTEF Group* and its subsidiary research institute *SINTEF Energy Research* are the largest in terms of RD&D in fuel cells and related hydrogen technology. The

SINTEF-Group has a dominant position as a contract research organization in Norway, which explains their longstanding involvement in numerous industrially motivated research projects in the energy sector. In fuel cells and related hydrogen technology, SINTEF is highly recognized for its contributions to materials technology.

- *IFE (Institute for Energy Technology)* is another major research organization undertaking R&D on fuel cells and related hydrogen technology in Norway, and is perhaps the most visible and active actor on the international scene. IFE is active in EU-funded projects, particularly on hydrogen storage (in metal hydrides), but it also spends considerable resources on basic research on particle physics relevant for fuel cells and related hydrogen technology. Design, simulation and assistance to implementation of fuel cell energy-systems represents another area of IFE's expertice.

- *FFI (Norwegian Defence Research Establishment)* has carried out research on fuel cells for power generation in submarines. In one project, HUGIN, it successfully developed and implemented fuel cells using seawater. This technology has now, in collaboration with Statoil, been commercialised in non-military submarines, by the Kongsberg Group.

Other institutes with activities in the fuel cells and related hydrogen technology area include *CMR (Christian Michelsen Research), Rogalandsforskning and NIVA (Norwegian Institute for Water Research)*, but these have relatively modest (albeit interesting) research activity in this field.

Higher education sector

As shown in Table 3.1, only 10% of the RD&D in the oil, gas and energy fields is undertaken by the higher education sector. In spite of their modest size, they are important for at least two reasons: Education of experts, professionals and researchers, and, secondly, because of their knowledge and close collaboration with the institute sector in RD&D, as explained above. In mapping the landscape of fuel cells and related hydrogen technology RD&D in Norway, the following institutions were identified as interesting:

- The *Norwegian University of Science and Technology (NTNU)* in Trondheim is by far the university that is most involved with RD&D in fuel cells and related hydrogen technology. It has close ties to the SINTEF Group; numerous SINTEF-researchers participate in NTNU's projects, and, vise versa, professors, ph.d.-students and post.docs from NTNU participate in SINTEF's projects. This pattern is also observed in projects related to fuel cells and related hydrogen technology.

- The *University of Oslo* collaborates with IFE on RD&D in fuel cells and related hydrogen technology, in particular in material technology projects. Similar to the relationship between NTNU and SINTEF, there is an exchange of personnel between the University of Oslo and IFE.

- The *University of Bergen* is at present not much involved with FC/RHT, however, some of the personnel of the university have relationships with CMR and ProtoTech.

- The *State College of Agder* (HiA) is small, but has established a fuel cell demonstration laboratory and is currently working to establish a centre of excellence in energy research.

3.2.2 Main activities

Whereas the number of projects registered in Norway's current project portfolio were approximately 100, the distribution of resources – hence the intensity of activities – in the various projects is highly uneven: As explained, the majority of projects are small, however, there are some large projects or activities – all of these are run by the industry. Below, some of the larger projects will be described briefly.

- The *Utsira project,* under the leadership of Norsk Hydro, is a demonstration project that combines windmills with fuel cells for electricity power generation. Utsira is a sparsely populated, remote island approximately 15 km off the coast of western Norway, in the windy North Sea. The project consists of an energy system that utilizes energy from the windmill to produce hydrogen, which is fed into fuel cells for generation of electricity.

- The *Kollsnes project*: Statkraft, Norske Shell and Aker Kværner constituted a consortium to undertake a feasibility project in 2002-2003 in order to plan a demonstration plant at Kollsnes based on SOFC. Kollsnes, close to Bergen, has its name from the location of a gas terminal that is fed by a pipeline from the North Sea, from the Troll gas field. This project is an energy systems project, much like the Utsira described above, but its primary energy source is natural gas from the Troll field. The partners are currently deciding as to whether they should continue the project. Although the feasibility project was considered a success, the financial burden of the follow-up, *Kollsnes I* (150 million NOK) may threaten the continuation. Norske Shell and Aker Kværner are already planning a "*Kollsnes II*"-plant in a more distant future. This will be a continuation of Kollsnes I, but neither the location of the plant, nor its technical specifications are known. The idea of this is construction of fuel cell power plant with 6 MW output. This is ambitious and the project depends on, and awaits, several technical break-thoroughs.

- Although Statkraft seems reluctant to participate in Kollsnes I, the company nevertheless demonstrates considerable ambitions in the field by signing a 50 million NOK contract with SINTEF Energy Research in 2002. This will engage the two parties in collaborative research during 5 years and many of the projects covered under this contract will be in the fuel cells and related hydrogen technology field.

- Another important project is the *CO_2-Capture project* of IFE/Statoil/CMR/ProtoTech. This project has a cost of 30 million NOK and aims at improving our knowledge of capturing CO_2 in the process of producing energy from fossil fuels. The significance of developing technology in this area is reduction of CO_2-emission from next generation of gas power plants. The idea is that by using fuel cells in conjunction with gas turbines, energy efficiency will simultaneously increase while CO_2 is captured and reinjected in this process, with substantial positive environmental effects as a result.

4 Public policy for innovation in fuel cells and related hydrogen technologies

4.1 Public R&D policy

In 2003, the Norwegian government took high-level initiatives intended to increase innovation activities in fuel cells and hydrogen technology. As yet, these have not materialized in specific plans or policy measures because the government will wait for the recommendations from the commission of experts[23]. The commission is expected to make its recommendations early in 2004.

On a more general level, the government, represented by the Ministry of Petroleum and Energy, follows the policy guidelines and priorities set in a White Paper on research policy, which was sanctioned by the Storting (Norwegian parliament) in 1999.[24] In this document, the government recommended giving high priority to R&D at the "intersection" between environment (nature) and energy. Reference was made to the Kyoto protocol and to the need of promoting sustainable development. Development of technologies that will enable efficient and economic carbon sequestration has been given high priority. However, emphasis was also put on development of new, renewable energy technologies. This has justified public funding of R&D in these areas.

In Norway, public funding of R&D is channelled through the Research Council of Norway. Technically, the funding of energy research is made on the budgets of the Ministry of Petroleum and Energy, however, the Research Council of Norway acts as the funding agency. A substantial part of the funding of public R&D in energy, such as the NOK 130 millions that constitute the public funding of the RD&D in fuel cells and hydrogen technology (cf. chapter 3.1), are outcomes of these R&D policy measures.

There are as yet no targeted, specific tax incentives for R&D in new, renewable energy sources. However, the government introduced a general, horizontal tax incentive program for private sector R&D in 2002. In this, companies that perform R&D are eligible to deduct, within defined limits, some of the expenses from their ordinarily taxable profits.

4.2 Market development

In terms of public policy for market development to encourage the demand for technologies that utilize "clean" and efficient technologies, the most significant public

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23 Cf. Press release from the Ministry of Petroleum and Energy, 20th June 2003, "Regjeringen oppretter nasjonalt hydrogenutvalg" ["The government establishes a national hydrogen commission"], http://odin.dep.no/oed/norsk/aktuelt/pressem/026031-070207/index-dok000-b-n-a.html

24 Cf. St. meld. Nr. 39 (1998-99), *Forskning ved et tidsskille*, specifically pages 93-95

policy measure has been the establishment in 2001, of an organization dedicated to this: *Enova*[25]. Enova's main mission is to give subsidies to investments in clean and efficient energy technologies. It receives its funding from an Energy Fund, with a total funding of NOK 5 billions. Enova provides subsidies for investments made in clean and efficient energy technologies, in the range of 10% to 15% of the investment. Investments in windmills are eligible for a subsidy of 10%. The criteria for eligibility of subsidies are technological, in terms of energy efficiency and cleanliness – there are no national industrial policy criteria are set for eligibility. This is reflected in how the Ministry of Petroleum and Energy explains the role of Enova, in an English press release from 8th October 2003[26]:

"Our efforts in transforming energy production and consumption consist of different measures in order to stimulate alternative and new business. Enova is the operator of several programmes pursuing the goals of transforming the energy market. Competition between different solutions is of vital importance in order to provide for cost reductions and extend market access for new energy solutions. Our goal is to make these solutions profitable without public support in the long run."

As evident in the press release, the underlying belief is that markets will provide society with the solutions that are most efficient and clean – and that there is a need for subsidies for this. Enova does not fund RD&D activities, nor does it play a role in making RD&D recommendations or promoting innovation activities related to development of new, renewable energy sources. According to Enova, this policy is in accordance with the terms of reference for Enova, which were decided by the Storting (Norwegian parliament) when they approved establishment of the Energy Fund. However rational, this is also an aspect which contributes to the decoupling and fragmentation of NIS, which will be discussed further in the conclusion, in chapter 6.

In addition to Enova, some targeted policy measures have been introduced during the recent years, in order to encourage demand for automobiles that are "clean", such as:

- Exemption or reduction of taxes for vehicles using electric motors,
- Electric cars are given privileged access to special fast lanes on highways reserved for public transport (buses and taxis),
- Free parking of electric cars on municipal parking lots in Oslo.

25 For more information, consult: www.enova.no

26 Cf. Press release from the Ministry of Petroleum and Energy, 10th October 2003, announcing a proposal for increasing the funding of Enova in the 2004 budget with NOK 130 millions, to a total of NOK 600 millions. http://odin.dep.no/oed/engelsk/aktuelt/pressem/026021-070101/index-dok000-b-f-a.html

4.3 The impact of deregulation on public innovation policy for development of new, renewable energy

As pointed out earlier, the deregulation of the energy markets in the 1990s apparently caused public authorities to become more market oriented in terms of a national innovation policy for the energy sector. Even if this seems to be changing now because some policy initiatives are expected in the spring of 2004, compared to other OECD-member countries such as Canada, Korea or Japan, Norway does not have a specific public innovation policy or strategy for development of new, renewable energy sources. There is no Norwegian "roadmap" counterpart to the Canadian of how Norway should create a hydrogen society. The reason for this is not economic – the Norwegian state is wealthy – but political, as evident with the establishment of Enova, described above. Furthermore, existing policy measures and instruments that could promote innovation activities are not used, such as public procurement schemes and special public R&D contracts that may be coupled with public procurements. The government of Norway, as a major shareholder in the largest energy and oil & gas companies in Norway, does not provide these companies with any guidelines or encourage these to undertake R&D or invest in innovation activities related to new, renewable energy sources and innovations. The government perceives itself as a quiet shareholder in these companies and rarely intervenes in the internal affairs of these companies. This non-interventionist role as a shareholder may explain why government would never intervene in the rivalries that cause some of these companies not to cooperate in the development of innovations in new, renewable energy sources.

The UK approach of coupling future greenhouse gas emission requirements with innovation policy encouraging development of new, renewable energy sources does not have its counterpart in Norwegian energy policy. The attractiveness of the UK approach is that it assumes that the market (as in Norwegian policy) will drive forward the required innovations, thus it is compatible with market liberalistic energy policies, however, public policy sets the criteria only in terms of environmental standards.

Although little is known of what kind of policy initiatives that the Norwegian government will announce in 2004, one may reasonably expect that it will propose a higher degree of national cooperation among key stakeholders (chiefly, the industry, but also academia, research institutes and various funding agencies related to energy technology development, such as Enova). This may be proposal of a few large-scale national development programs that the government will provide funding to. The realism of this is based on the fact that the Storting (Norwegian parliament) has expressed clear expectations of some highly visible initiatives that will address the Norwegian gas "problem" – one year prior to the next general elections (2005).

4.4 The future public R&D agenda according to the R&D community

According to a study sponsored by the Norwegian Research Council and published in 2000[27], in which the future prospects for using hydrogen as an energy source was analysed, the industrial development potentials are claimed to be good (Kvamsdal & Ulleberg, 2000). The study even claims that Norway, as a substantial gas producing nation, has a unique potential. The potential is well suited to existing competencies in producing hydrogen by means of electrolysis. The report, which was based on the results of a large workshop with participation of representatives from industry, academia and research institutes, made a number of recommendations for R&D with a commercial and technological potential. These recommendations were organized in three categories of priority according to urgency and two categories in terms of future temporal horizon (within and beyond the next 10 years), in sum yielding six areas of recommendations. Within the next ten years, the study recommended intensified R&D (i.e. highest priority, increased funding) in areas related to production of hydrogen from natural gas with carbon dioxide separation, and system solutions based on PEMFC. Similarly, the study recommended high priority for long-term R&D (next 30 years) in hydrogen production from hydro electrolysis, storage of hydrogen in solids, and materials research relevant for hydrogen. In the intermediate category ("moderate R&D"-priority), the study identified and recommended a larger number of R&D-areas as relevant for the next ten years: Integrated systems, liquid hydrogen storage, combustion technology for composite hydrogen, systems solutions and demonstrators. The long-term areas (next 30 years) in this category were identified as: biophotolysis of hydrogen and SOFC. In the third category of priority, which the study recommended as "technology surveillance", storage of compressed gas was identified as an R&D-area for the next ten years. The long-term areas requiring technology surveillance were: Photo electrolysis of hydrogen and gasification of biomaterial.

In terms of a national R&D agenda, the study is interesting because it probably gives an accurate depiction of what the R&D-community perceives as important subjects and goals. Experts representing the industry participated in the workshops and the writing of the study. Thus one may assume that the study also articulates the interests of the industrial stakeholders, an impression that is reinforced by analysing some of the appendices to the study. One of these (Appendix E) lists the activities and competencies of Norsk Hydro and Statoil. These seem to match the top priority listed above. Still, in terms of an innovation perspective, the agenda probably only gives an approximate indication, because one may assume that the priorities listed are of a pre-competitive and pre-normative type, i.e. not the proprietary type of R&D that industrial firms undertake for their own product or process development.

27 H.M. Kvamsdal and Ø. Ulleberg, Hydrogensamfunnet – en nasjonal mulighetsstudie, SINTEF, Trondheim, 2000, A5107.

The contrast between these recommendations as to what should be done and the absence of a public innovation policy and strategy that responds to this is striking.

5 Innovation performance and its assessment

5.1 Knowledge profiles and networks

5.1.1 An empirical approach to knowledge profiles and networks

In the Norwegian country study on innovations in fuel cells and related hydrogen technology, analyses of bibliometrics and patents were carried out. The purpose was to characterize the knowledge profile of Norway. The results of these will be presented in the next sections, which is based on an extensive report written in the course of the country study of Norway[28]. As a method and empirical approach, bibliometric analysis and analysis of patents have limitations; they do not measure innovations or aspects related to innovation systems in a country. Still, these analyses provide insights that may supplement other approaches because they provide comparatively exact measurements of the output and profile of the science and technology knowledge base of a country. The underlying assumption is this: The science and technology knowledge base of the country is reflected in the output activities of the communities involved in innovations related RD&D such as scientific publications and obtained patents. Thus, these analyses provide an indication of characteristics and quality of the knowledge base, which is important in the field of fuel cells and related hydrogen technology development.

The OECD secretariat has also made a bibliometric study, *Mapping the knowledge base of a technological field: the case of fuel cells technology*, (Hassan, 2003). The main advantage of this study is the international comparison. In this report, worldwide data on patents and scientific articles were used to develop internationally comparable indicators. The focus of the Norwegian bibliometric analysis was limited to the Norwegian fuel cells and hydrogen technology related innovation system. For this reason, a broader methodological approach was chosen. The table below shows how OECD study differs from NIFU's bibliometric study of Norway.

[28] Cf. Antje Rapmund and Stian Nygaard, *Bibliometric and patent analysis of Norwegian research on fuel cells 1990-2002*, NIFU U-notat 19/2003, NIFU, Oslo, 2003

Table 5.1: *The bibliometric study of the OECD secretariat and NIFU's study - Comparison of methodological issues*

	OECD's study	NIFU's study
Databases on scientific publications	ETDE data base of the International Energy Agency and ISI's SCI Expanded. That means only references which were found in ETDE primarily and later on also in SCI are included.	SCI Expanded, ISI Proceedings, INSPEC, ETDEWEB and Norwegian experts
Databases on patents	EPO patent applications and US patents granted by the US Patent & Trademark Office	Norwegian Patent Office, Thomson Delphion and the US Patent & Trademark Office
Choice of keywords	Alkaline Fuel Cells; Direct Methanol Fuel Cells; Molten Carbonate Fuel Cells; Phosphoric Acid Fuel Cells; Proton Exchange Membrane Fuel Cells; Solid Oxide Fuel Cells and Regenerative (Reversible) Fuel Cells	Fuel cells, Alkaline Fuel Cells; Direct Methanol Fuel Cells; Molten Carbonate Fuel Cells; Phosphoric Acid Fuel Cells; Proton Exchange Membrane Fuel Cells; Solid Oxide Fuel Cells and Regenerative (Reversible) Fuel Cells, hydrogen storage, hydrogen production and metal hydride
Choice of publication types	Only scientific articles	Scientific articles, conference proceedings, theses, reports, books and book chapters and Norwegian journal articles
Choice of patents	Triadic patent families	Patents and patent families
Time period for scientific papers	1990-2000	1990-2002
Time period for patent families	1990-1996	1990-2002

5.1.2 Bibliometric analysis of Norwegian research on fuel cells and hydrogen technology 1990-2002

By using a keyword approach, the bibliometric study identified 421 relevant publications having an author with an address in Norway, for the period 1990-2002. Keywords like 'fuel cell' and the names of the various fuel cell types were used. In addition, terms related to hydrogen storage, metal hydride and hydrogen production were also used. The papers were categorized: All papers were classified in at least one subject field; of these, 162 papers were classified in two subject fields because these covered more than one subject, i.e. the subjects are sometimes interwoven. E.g.: Metal hydrides may be classified as belonging to the subject *material*, but also the subject *storage of hydrogen*. In the data set, publications about the various types of fuel cells (31 %) and about fuel cells related materials (36 %) were almost equally large. Hydrogen technology (19 %) and fuel cells related processes (14 %) were the other main subjects as shown in figure 5.1. Table 5.2 gives a further breakdown of the publication in subjects.

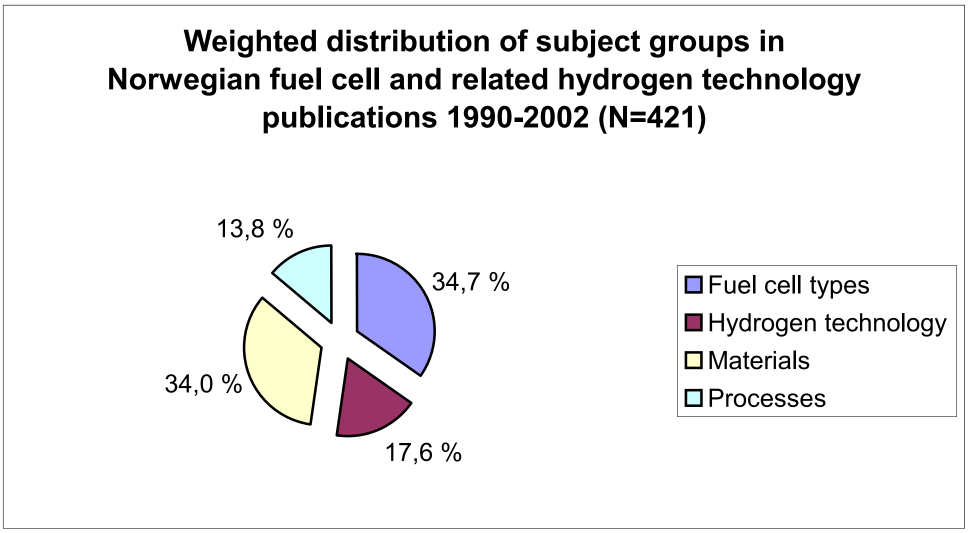

***Figure 5.1**: Weighted distribution of subject groups in Norwegian fuel cells and related hydrogen technology publications 1990-2002 (N=421)*

The bibliometric analysis indicates that Norwegian research is especially strong in solid oxide fuel cells (SOFC) and proton exchange membrane fuel cells (PEMFC). The material also indicates activities in alkaline fuel cells (AFC) and seawater primary cells. However, in the period analyzed (1990-2002), the importance of SOFC has declined since 1996. This decline reflects that two comparatively large projects for development of SOFC, NorCell II and Mjøllner, were phased out in this period, as will be explained in chapter 5.4. Subsequently, the importance of PEMFC has increased. This development is shown graphically in figure 5.2.

Table 5.2: *Main subject categories in the data set (N=421)*

Subject category	Number of papers
SOFC – Solid oxide fuel cells	127
Metal hydride	56
Perovskite	39
Membrane	36
PEM Proton exchange membrane fuel cell	32
Hydrogen production	28
Zirconium	28
Electrical conductivity	26
Hydrogen storage/transport	25
Battery	23
Hydrogen evolution	17
Hydrogen in energy supply systems	17
Oxidation	17
Ceramic	16
End use of hydrogen	14
Chromium	13
AFC Alkaline fuel cell	10
Energy efficiency	10
Palladium	10
Seawater primary cells	9
Oxide	8
Corrosion	6
Electric work method	5
MCFC Molten carbonate fuel cell	4
Hydrogen in the transport sector	3
Curved carbon surfaces	2
Regenerative fuel cell	1

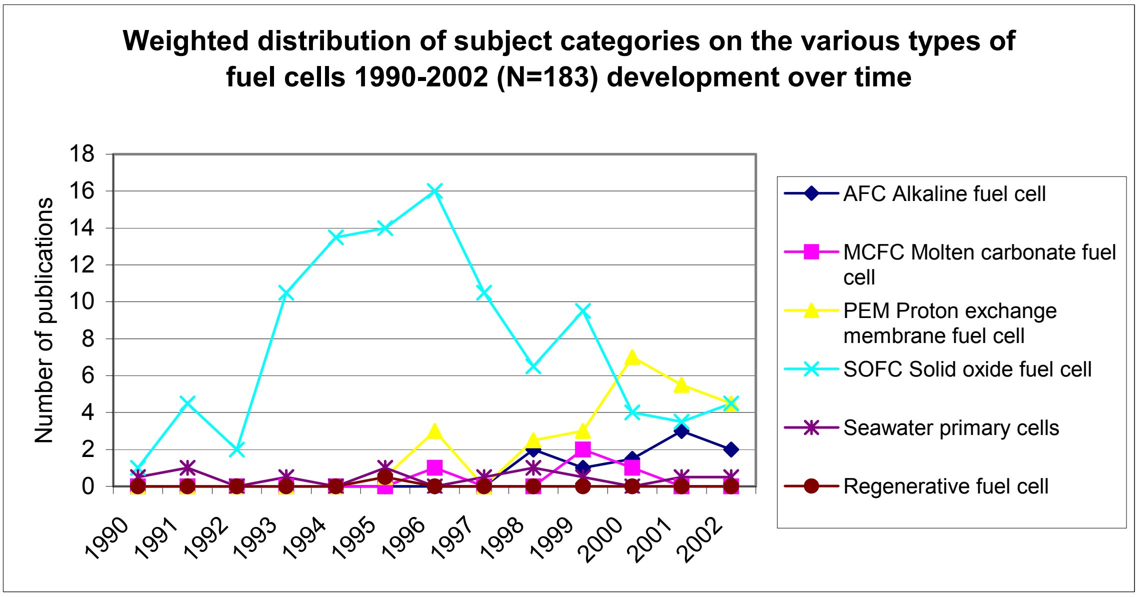

***Figure 5.2**: Weighted distribution of subject categories on the various types of fuel cells 1990-2002 (N=183) development over time*

According to the results of the bibliometric analysis, the main Norwegian research institutions in fuel cells and hydrogen technology are:

- NTNU – Norwegian University of Science and Technology,
- University of Oslo,
- SINTEF Material,
- Institute for Energy Technology,
- FFI –Norwegian Defence Research Establishment and
- University college of Agder.

In addition to these, the analysis found papers and articles published by authors employed in industrial companies, on topics related to fuel cells and hydrogen technology, such as:

- Statoil,
- Norsk Hydro,
- Prototech AS, and
- Kværner Oil&Gas.

The "map" depicted in figure 5.3 shows the bibliometric landscape of Norway: The circles represent the institutional affiliation of the authors; the size of the circle represents the number of publications of these institutions, and the lines between the circles represent co-authorship. These lines are interesting because they may be interpreted as strong indicators on networks of collaboration. In the map, the Norwegian University of Science and Technology in Trondheim (NTNU) has a dominant, central position. The NTNU is connected to the majority of the other research institutions and also to some of the business enterprises which were active in the field. The NTNU is close to the SINTEF group which is located both in Trondheim and in Oslo.

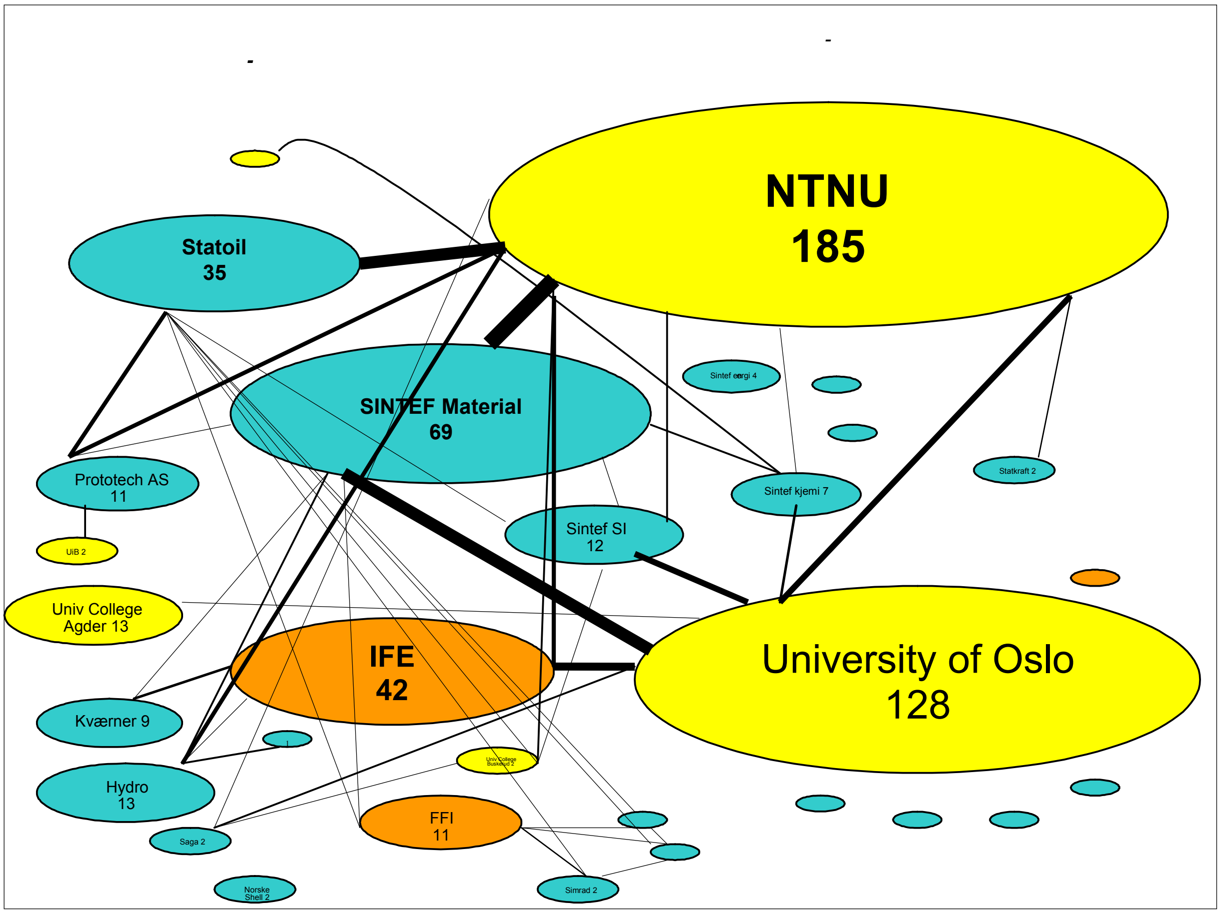

Figure 5.3: *Network map of Norwegian research institutions in fuel cell research 1990-2002 (N=421).*
Source: NIFU/INSPEC/ISI-Web of Science/ISI Proceedings

The bibliometric analysis also provides information on co-authorship between Norwegian authors and foreign colleagues: In the collected data set, 39% of the ISI-indexed papers were internationally co-authored. The main co-authoring countries were USA, Denmark, The Netherlands, Japan, Great Britain, Germany, France and Switzerland.

However, most significant: The data set shows that Norwegian fuel cell research is well recognized internationally, as the impact of Norwegian papers is higher than predicted, using an approach for measuring impact of articles by means of citation analysis. This observation is based on the citation index derived from the material. Closer analysis of this may support an interpretation that the trend of the last four years is increased recognition because the score on the index has increased, as shown in figure 5.4.

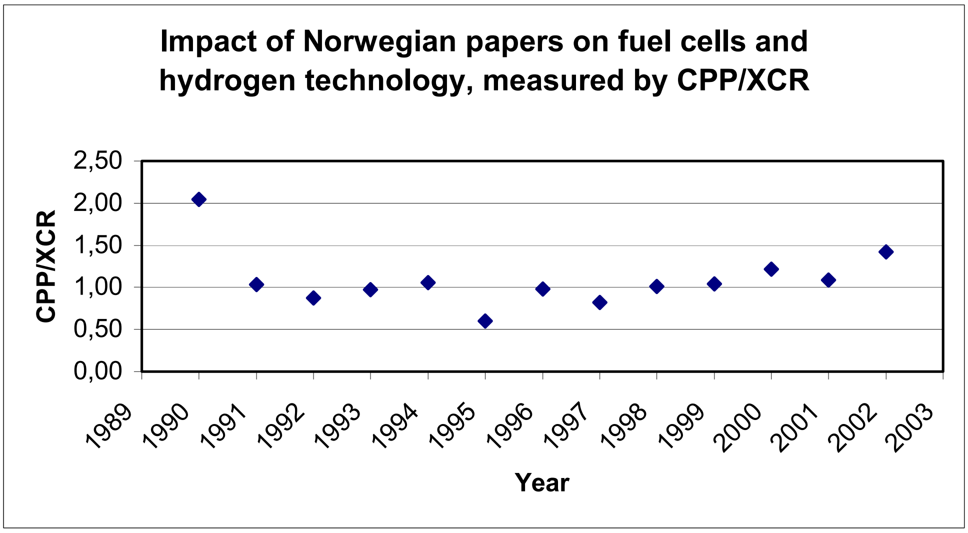

Figure 5.4: *Impact of Norwegian fuel cell papers measured by CPP/XCR over the period 1990-2002*

Source: NIFU/ISI (NCR). This includes the following types of publication: articles and proceeding papers.

In summing up, the bibliometric analysis shows that although Norway's community of science and technology in the field of fuel cells and hydrogen technology is small because of the low number of articles published in the period of 1990-2002, the quality of this appears to be high because of the high score on the citation index. Furthermore, this community is highly specialized, with a focus on a few niches and topics. During the period of analysis (1990-2002), a shift in research interest may be observed in that publications on SOFC decreased after 1996, however, publications on PEMFC increased afterwards. These observations are to some extent reflected in the analysis of patents, which is the subject of the next section.

5.1.3 Analysis of Norwegian patents on fuel cells and hydrogen technology[29]

By searching databases on patents using keyword related to fuel cells and hydrogen technology covering the period of 1990-2002, 209 patents were found with an inventor having a Norwegian address. In the analysis, the patents were classified in the following technological categories:

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

[29] This is based on Stian Nygaard: *Innovation in fuel cells and related hydrogen technology in Norway: patents and knowledge interactions in a system of innovation.* University of Oslo, 2003 (ESST MA)(Nygaard, 2003)

Only patents from the Norwegian Patent Office, the European Patent Office (EPO), the US Patent & Trademark Office (USPTO) and the Japanese Patent Office (JPO) were included. Table 5.3 gives an overview of the 209 patents, showing the assignees and class of patents obtained.

Fuel cell related patents are concentrated around Statoil and FFI: Two large projects in 1990s - *Mjøllner* (Statoil) and *Hugin* (FFI and Statoil) – were the source of many of these. The semi-fuel cells from Hugin are used in unmanned underwater vehicles in active use today; Statoil's solid oxide fuel cell was demonstrated in 1997 but has not been commercialized. Hydro and Clean Carbon Energy are the two other assignees with more than one fuel cell patent. Hydro's patents are important in the CO_2 Capture Project in Norway. Patents related to hydrogen storage were obtained by Kværner and IFE, both of these deal with storage in carbon materials. Patents related to hydrogen production belong to Kværner, Statoil, Hydro and Prototech. SINTEF (inventor: Rune Bredesen) has patented seven inventions related to membranes in fuel cells. A group from NTNU has four patents on new materials and a researcher from the University of Oslo has one patent assigned by a foreign firm.

Analysis of the patents shows that some of these came out of co-operation in joint projects (Statoil, FFI, Siemens). In some patents, personal contact between inventors (Kværner, Sintef, IFE) is evident.

Analysis of knowledge flows in patent citations show that these are mainly made to foreign patents (U.S., Japan, EU). The only exception is between Statoil and FFI (joint project) and between Kværner and IFE (IFE cites Kværners patents). Patent citations are used in about half of the patents in the data set, literature references were used only in two patents, one by IFE and one by Kværner.

The 209 Norwegian patents are concentrated in 25 patent families: "A patent family refers to a set of patents taken in various countries for a single invention" (OECD, 2002b). Of these are 11 "triadic" patent families; that are patent families which were applied for at the European Patent Office (EPO), the US Patent & Trademark Office (USPTO) and the Japanese Patent Office (JPO). 24 patents were single patents; that means not members of any patent family. Patents that are a member of patent families have generally a higher value than single patents. The eleven triadic patents are mostly filed by Kværner and they cover mainly hydrogen production and storage.

Table 5.4 gives an overview of the patent families, and table 5.5 gives an overview of triadic patent families.

Table 5.3: *Patents by assignee and class*

Assignee	**Patent classes**						**Total**
	Fuel cell	H_2 storage	H_2 production	Membrane	Material	Processes	
Kværner		36	56				*92*
Statoil	18		8				*26*
Sintef				6			*6*
IFE		7					*7*
Clean Carbon Energy	2						*2*
Prototech			4				*4*
FFI	29						*29*
Norsk Hydro	2		11	1	6		*20*
M.M.M. S.A.		1					*1*
Due miljø AS				1			*1*
Allied-Signal Inc					1		*1*
L.E. Nyfotek						4	*4*
Siemens, Norway	1						*1*
Donaldson Co Inc.	1						*1*
Private	5						*5*
Alcatel	2						*2*
Standard telefon	2						*2*
Statoil/Alcatel	4						*4*
ABB	1						*1*
Total	*67*	*44*	*79*	*8*	*7*	*4*	*209*

Table 5.4: *Patent families by assignee and class*

Assignee	**Patent classes**						**Total**
	Fuel cells	H_2 storage	H_2 production	Membrane	Processes	Material	
Kværner		4	6				*10*
Statoil	3		1				*4*
Sintef				1			*1*
IFE		1					*1*
FFI	5						*5*
Norsk Hydro AS			1			1	*2*
Prototech			1				*1*
L. E. Nyfotek					1		*1*
Total	*8*	*5*	*9*	*1*	*1*	*1*	*25*

Table 5.5: *Triadic patents by assignee and class*

Assignee	Patent classes			Total
	Fuel cells	H_2 storage	H_2 production	
Kvaerner		3	5	*8*
IFE		1		*1*
Norsk Hydro AS			1	*1*
Statoil/Alcatel	1			*1*
Total	*1*	*4*	*6*	*11*

5.2 Qualitative assessment of the Norwegian innovation system for fuel cells and related hydrogen technology

5.2.1 Almost no small and medium-sized enterprises (SME)

One of the features of the Norwegian fuel cells and related hydrogen technology field is that the structure of participating firms is characterized by relatively large companies. There are few SMEs: Apart from a couple of very small firms delivering consultancy services of negligible importance, only the company Prototech in Bergen may be classified as a SME. Prototech was founded as a spin-off from the research organization CMR – Chnristian Michelsen Research in Bergen. The paucity of SMEs and spin-offs from the research sector is probably a sign that the fuel cells and related hydrogen technology is a relatively immature technology field in Norway. This immaturity may be explained by several factors, not necessarily mutually exclusive:

- Apparently the relative long prospects of pay-back through commercialization of fuel cells (discouraging SMEs in general) are not compensated by industrial or research system demand for goods and services needed to conducting RD&D. This may possibly be interpreted as a matter of critical mass, i.e. that the Norwegian market is not large enough to support an undergrowth of SMEs, such as in Canada.
- Although most of the large companies in the field (e.g. Statoil, Statkraft, Shell, etc.) have mechanisms for investing venture capital to promising upstarts, there seems to be a paucity of public or private venture capital in Norway allowing this type of business to emerge. However, the picture is not clear, because some of the corporate venture capitalists claim that the problem is a lack of good start-ups to invest in.
- Although the weak industrial structure in Norway in fuel cells and related hydrogen technology represents a barrier for the development of the larger Norwegian companies in the field – the fragmentation and rivalry within the industry does not encourage the development of an autonomous and self-sustaining fuel cells industry in Norway.
- If a fuel cell industry can be allowed to be built up abroad, without the participation of Norwegian companies, the interest by policy makers and the Norwegian opinion will probably also be less. This may also retard the adoption of fuel cell based energy systems by Norwegian users and the implementation of a hydrogen infrastructure.

By contrast, in Canada, the industrial structure is completely different. According to "Canadian Fuel Cell Commercialization Roadmap" (2003)[30], an estimated 1,800 persons were employed directly by the Canadian fuel cell industry. This industry is constituted by 17 companies whose primary market focus is fuel cell production, and a large number of suppliers, service providers and fuelling infrastructure companies, most of which are SMEs by Canadian standards (less than 500 employees). The "roadmap" identified not less than four industrial clusters in Canada within the fuel cell industry, and found industrial and research based relations between customers, suppliers, competitors and research laboratories intertwined in rather complex formal and informal relations.

Many of the small Canadian companies involved with the fuel cells and related hydrogen technology field provide instruments, parts and machinery for production and testing of fuel cell based systems, mostly for use in demonstration projects and prototypes of all types of fuel cells and sizes. Due to the fact that R&D budgets allocated to the technology field are important, and that RD&D activities are high, it is actually possible to make sales and profits in a market exchanging production goods and services for use in production of energy systems that do not yet have commercial existence. This point may seem counterintuitive to conventional economic logic in terms of long-term sustainability, however, in a national innovation policy and strategy perspective, this is significant. Needless to say, an important factor in this is the willingness to make commitments towards common goals, as articulated in the Canadian roadmap.

5.2.2 Automotive industry lacks, and supplier industry awaits

Except from a few niche products (specialized industrial vehicles and electricity driven cars) there is no automotive industry in Norway. In recent years, however, the supply industry to the international automotive industry has gained market shares and is now growing relatively strongly. Norway's automotive supply manufacturing industry is among the most profitable and promising activities for several of the large metal manufacturers (aluminum and other light metals, e.g. Raufoss, Hydro Aluminium, Kongsberg Automotive).

At present, the car manufacturing industry is among the strongest drivers internationally to the development and implementation of fuel cell power generation. This is the case both in Germany, in the USA and in Japan. The dominant firms in the automotive industry are most often large, multinational (e.g. DaimlerChrysler, VAG, GM/Opel). They take on an active role, allocating substantial resources from their own RD&D, and encouraging R&D from potential suppliers of fuel cell systems. Both DaimlerChrysler and GM are important shareholders of Ballard in Canada, and provide considerable amount of capital to R&D to

[30] Cf.: http://strategis.ic.gc.ca/epic/internet/inmse-epe.nsf/vwGeneratedInterE/ep00027e.html. Industry Canada - the Canadian ministry of industry – has published this report. Industry Canada plays an important leadership role in the development of a fuel cell industry in Canada.

this company, which explains why this company is still in business in spite of large deficits.

As yet, there are no potential Norwegian supplier of fuel cells to the automotive industry, however, Raufoss, a major manufacturing company of automotive parts, is undertaking R&D to develop high-pressure hydrogen storage tanks for automobiles. A bottleneck in the future hydrogen society will be the need for building fuel (hydrogen) supply infrastructure. This also includes more generic knowledge of hydrogen storage and storage facilities, both stationary and mobile (in vehicles). The demand for such complementary technologies by the automotive industry is certainly clearly expressed. Although production, storage and transportation of hydrogen constitute the primary research interests of Norwegian manufacturers and research laboratories, rather few of them are directly working in collaboration with the automotive industry (except for some notable exceptions through participation in EU research projects, e.g. CUTE).

Norwegian firms and research laboratories are certainly aware of the importance of RD&D in hydrogen technology, and they have excellent track records in terms of R&D achievements in this field compared to many other potentially competing research environments elsewhere. However, considering the speed by which technological change goes on within this area, a more aggressive, "hands-on" strategy and concerted action by Norwegian firms, research institutes and national research system may be justified.

5.2.3 The role of electric power utility companies

In both Norway and internationally, electricity companies are active in this field, for several reasons. First, the supply and demand for electric power fluctuates, making prices change considerably over seasons and periods of time. By generating electricity from fuel cells powered by stored energy bearers, prices can be considerably more easily controlled and more precisely anticipated by electricity suppliers. Second, this may permit more decentralized energy production and distribution, and by this, the robustness and reliability of the electric grid may increase. Energy sources based on such technologies are likely to take substantial market shares in the medium to long term. Thirdly, electric power utility companies have environmental obligations to decrease pollution and environmental hazards (e.g. nuclear energy).

In Norway, energy suppliers are predominantly producing electricity from hydro-turbines. They are able to control the speed of the turbines rather precisely by adjusting the intake of water to demand of electricity. Still, Statkraft, the largest electric power utility company in Norway (approximately 40 TWh generated in Norway) has demonstrated considerable interest in fuel cells and related hydrogen technology through several RD&D projects conducted both alone or in cooperation with Norwegian and foreign partners.

5.2.4 The establishment of research groups of complementary actors is promising

Although Norway is rich in terms of per capita income, its economic capacity is limited, which strengthens the argument of using collaboration strategies to overcome technological barriers in development of fuel cells and related hydrogen technology in electric power generation. This is important for:

- improving technical and scientific knowledge necessary to advance within this technology field,
- obstacles related to technical normalization and standardization,
- development of complementary technologies, specifically IT and integration of hydrogen based energy system in existing energy systems,
- questions pertaining to infrastructure and subsidization/taxing of different energy sources in order to create favourable economic framework conditions for industry.

Returns to investment in R&D within the fuel cells and related hydrogen technology field are very uncertain due to technical difficulties and appear to be so far into the future, that private incentives to invest in the field are weak. In addition, complementarities of technologies – i.e. that all the necessary technologies be available and efficient at the same time, or else the realization of returns to investment in either of them is prevented – impose on each investor the requirement that other investors' R&D efforts are successful. This is something which is outside of the involved organizations' abilities to affect, and which, consequently, increases the uncertainty to high levels.

This calls for a participation of public bodies in both the technical areas and to the financing of R&D efforts in the field in order to persuade private agents to commit. The large number of complementarity fields also calls for collaborative efforts and coordinating R&D performed by many different organizations. The participation and collaboration of different agents is particularly important in demonstration projects, which will be increasingly important for the progress of the field as we approach commercialisation. Norwegian industrial actors have often worked in larger collaborative projects. A very recent example, announced on the Internet October 9th 2003, which involves transnational collaboration, is a joint cooperation agreement for renewable hydrogen which involves Stuart Energy (Canada), Statkraft (Norway) and Corporacion Energia Hidroelectrica de Navarra S.A. (Spain).[31]

The Japanese roadmap ("The Fuel Cell Commercialization Conference of Japan") for fuel cell research gives an example of what complementary firms and public research efforts can achieve in a co-operative setting (Maeda, 2003). The research agenda within fuel cells and related hydrogen technology is so complex and non-trivial that the most promising strategy is to establish research groups constituted by firms of different industries, with different technical strengths and motivations, yet common goals. The Japanese initiative is

[31] http://money.iwon.com/jsp/nw/nwdt_ge.jsp?cat=PRRELEASE&src=102&feed=cmt&section=news&news_id=cmt-282b1514&date=20031009&alias=/alias/money/cm/nw

constituted by 134 member firms and individuals, chaired by one of the Chairman and CEO of Toshiba Corporations, a very influential industrialist in Japan. The Conference expands its activity into aspects such as basic technology, public infrastructures, governmental regulations, international standardizations and fundraising (Maeda, 2003). It is clear to this Conference that economically viable power production from fuel cells requires a massive, broad mobilization of all types of actors – in close collaboration with national and international organizations and authorities. In order to overcome important bottlenecks such as infrastructure for fuel supply, such widely involving initiatives may be required.

5.3 Results and/or expected outcomes of these activities

In spite of a relatively strong private involvement in this area, there is no realised net financial return on investment available to investors. Moreover, the prospects of harvesting such returns in the next years are dim. The technological challenges are considerable and non-trivial. Still, commercial firms and research institutions persist in spending money, energy and time working in this field and this demonstrates that there are other forces driving them than expectations of immediate return on investment.

We observe two types of actors in the fuel cells and related hydrogen technology field: For-profit firms and R&D organizations, and these follow different motivations for engaging in RD&D in this area. The for-profit firms engage in relatively many smaller and a few larger demonstration projects, often – but not always – in collaboration with other firms. These activities are application oriented, aimed at learning how to combine different types of existing knowledge in new applications instead of investing in radically new knowledge. Many of these firms also use relatively large resources on technology monitoring and on networking activity. This enables them to have some knowledge of many different technologies, simultaneously, they become visible among potential business partners (and competitors) and knowledge producers (from which eventual technological break-throughs can be expected to come). Their behaviour can be qualified as one of *fast second mover* (Gilbertand & Bormbaum-More, 1996). The funds they expend on these activities are not considered investments requiring economic returns. Rather these are considered sunk costs that are immediately written off and that enable them to benefit from possible future technological and commercial opportunities in the fuel cell area. Their benefits, so far, are therefore predominantly *option benefits* and *knowledge benefits*, the former being by far the most important for these industrial enterprises (Department of Energy, 2001). Thus, for the time being, there are no observable economic benefits.

For R&D organizations like universities and research institutes, the rationale for engaging in RD&D in this area is different, and so are the benefits they receive. These organizations are not depending directly upon a technological and commercial success of a totally new energy source to be able to maintain their engagement in this topic area. Most of their

RD&D activity is funded by their clients or by public research funds. When these organizations take own initiatives and perform RD&D with own funds, it is in order to apply for patents, to publish in scientific journals, or as the result of internal strategic decisions of building up a competence base they can draw on to get projects in the future. As long as there are commercially driven customers that are motivated by the strategy of *fast second mover*, R&D organizations will be able to receive returns on their investments in knowledge in fuel cells and related hydrogen technology. When succeeding in moving the knowledge frontier forwards, these organizations will also have *knowledge benefits* and *option benefits*. Clearly, the success of these organizations is also closely related to the industrial prospects of for-profit firms, due to the fact that their willingness and interest in purchasing R&D-services from R&D organizations depends on their distance from commercially viable products and services. But it is more important for R&D organizations to obtain a reputation of excellence among its potential customers, so that they have a valuable lead time and a scientific quality that put them in a favourable position to be chosen as partners to large and long-lasting R&D projects that can be expected to be more and more frequent as the fuel cells and related hydrogen technology field approaches the market.

Based on the considerations discussed above on outcomes and results, these may be systematized using a framework developed by the National Academy of Sciences (NAS) for making assessment of energy research (Department of Energy, 2001)[32], as shown in table 5.6. NAS' framework is for public investment and programmes established by public agencies. It is an assessment of costs and returns from such projects, i.e. based on an ex-post perspective, most of the projects were oriented towards creating incremental innovations. In RD&D on fuel cells and hydrogen technology, the uncertainties, time horizons and potential implications are different – if successful, fuel cells and hydrogen technology may become radical innovations creating large economic impacts. So far, most of the benefits are related to knowledge and the options these provide.

[32] Cf. National Academy of Sciences, *Energy Reseaerch at DOE: Was it Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000(2001)*, National Academy of Sciences, Washington 2001, Appendix D

***Table 5.6**: Benefits and cost of RD&D undertaken in Norway on fuel cells and related hydrogen technology*

	Realised benefits and costs	**Options benefits and costs**	**Knowledge benefits and costs**
Economic benefits and costs	▪ RD&D funding as "sunken costs" ▪ Negligible economic benefits so far	Important because RD&D provides industry with knowledge and insights to support their strategies and future investments	▪ Production of hydrogen from natural gas ▪ Know-how related to transportation of gas (hydrogen) in pipelines and in ships ▪ Know-how related to use of fuel cells in merchant marine ships and offshore platforms ▪ Electrolysis of water for producing hydrogen ▪ Production of hydrogen using micro algae ▪ Components and testing fascilities for PEM fuel cells ▪ Materials for storage and transportation of hydrogen ▪ Systems analysis – future energy systems based on new, renewable energy technologies
Environ-mental benefits and costs	None so far	Significant potential in terms of reducing emission of greenhouse gases	High potential because of the knowledge produced in RD&D
Security benefits and costs	Not applicable	High potential	▪ Contribution to standards setting, risk analysis and assessment related to hydrogen. ▪ Energy systems analysis for future systems with increased reliability and robustness

5.4 Competition, rivalry and dynamics in NIS

5.4.1 Introduction: The NorCell, NorCell II and Mjøllner projects

Spanning over a decade, from approximately 1988 to 1998, development of SOFC using natural gas as feedstock was the goal of three separate, comparatively large R&D projects in Norway. Initially, there was just one, single 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 funders of the project, the state-owned oil & gas company Statoil, split out and established its own SOFC-project, *Mjøllner*.[33] Simultaneously, the original NorCell-project evolved into a new project called *NorCell II*. This project was terminated at the end of 1994. Statoil kept its Mjøllner-project alive until 1998. Possibly because initial expectations were high, a number of informants characterized the outcome of these projects as meager, some attributing this to non-technological factors such as “politics” and “rivalry”. The details of these projects will be elaborated first, followed by an analysis and discussion of innovation policy aspects.

5.4.2 Initial push: A visionary professor and Norway’s gas “problem”

According to informants, the initial NorCell project was inspired and motivated by Per Kofstad (1929-1998), a research scientist and professor of inorganic chemistry and material science at the University of Oslo. Having obtained his university education in USA (a Ph. D. from University of California, Berkley in 1953), he is described as an unconventional and influential academic who believed that basic and applied research are two sides of the same coin – this attitude being attributed to his formative years in USA. One of his research interests was in solid state ionics, i.e. ionic conductivity and oxidation/corrosion, which led him to undertake research on the effects of carbons and hydrogen during oxidation. In the course of his work, he became interested in fuel cells development because this would provide an interesting application of his fundamental interest in solid state ionics based on using natural gas as feedstock. In the mid-1980s, he was instrumental in creating enthusiasm and obtaining financial support for what became known as NorCell, a project aimed at development of a SOFC using natural gas as feedstock. The main funding champion was Dr. Inge Johansen, at the time CEO of the public research funding agency NTNF[34], however, the project proposal also received favorable support from a politician in the ruling Labour Party, Mr. Arne Øien, who was cabinet minister of the Ministry of Petroleum and Energy, from May 1986 to October 1989. Needless to say, one reason for this interest was the potential of developing a technology (SOFC) that would provide much higher energy efficiency than conventional gas turbine power plants, a topic closely related to Norway’s gas “problem” (cf. section 2.3). Gaining access to, and subsequently obtaining support from these high-level sources was essential for a flying start-up of NorCell.

[33] 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).

[34] Norwegian acronym for the official English name: *The Royal Norwegian Council for Scientific and Industrial Research*. This agency was merged with a number of other research funding agencies when the present Research Council of Norway was established in 1993.

5.4.3 NorCell I

The R&D in the NorCell-project was carried out mainly in the laboratories of SI[35] – a semi-public research institute in Oslo, but also at professor Kofstad's laboratory at the University of Oslo. Starting up in May 1988, the objective was to develop and demonstrate planar solid oxide fuel cell (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. Initially, NorCell was planned as a five years project with a total budget of NOK 25 millions (approximately US$ 3.5 millions), of which 50% was funded by NTNF and the rest by the industrial partners mentioned above.

The project leadership was given to the above-mentioned R&D organization SI in Oslo, in a project organization consisting of scientists and engineers from several organizations and disciplines. This included researchers working in the Centre for Material Science at the University of Oslo (Per Kofstad's lab), who contributed to the project with their knowledge both on the fundamental issues relevant for fuel cells, such as materials under high temperatures and corrosion, but also on aspects related to conductivity. 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. In this, some patents by Westinghouse labeled as "classics" were analyzed closely. In addition, informants claim that their "bible" in terms of information consisted of four books[36], all from the USA. These books presented information on tests and measurements of different fuel cells types, this being crucial for the R&D in NorCell.

5.4.4 NorCell II

NorCell II started in September 1991, two 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: First, Statoil had left the project and begun its own planar

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[35] This (SI) is an acronym for *Sentralinstituttet for Industriell forskning*, which translates into English as the *Central Institute for Industrial Research*. SI is now part of the lager SINTEF-group, Norway's largest contract research organization.

[36] The most important sources were:

- S.S.Penner (ed.), *Assessment of Research Needs for Advanced Fuel Cells*, Pergamon Press, New York, 1986
- Office of Technology Assessment (US Congress), *Marine Applications for Fuel Cell Technology*, 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.

SOFC R&D project, Mjøllner. Second, Statkraft left the project for reasons that are not known. Third, the metal manufacturing company Elkem joined the project, bringing with them its US-based subsidiary Ceramatec. According to the final report from NorCell II, Elkem-Ceramatec's entry into the project came after two years of "..informal contact between the [first] NorCell-project and Elkem, in order to discuss possible co-operation between the two project teams."[37] It was stated that there were many similarities in the R&D carried out by both NorCell and Elkem-Ceramatec in USA. 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[38] in USA, this vouching for their high quality. NorCell II was planned as a three years project with a total budget of NOK 50 millions (approximately US$ 7 millions) of which NTNF would fund 50%, the rest by the industrial partners. The R&D was done by two teams, one team in Norway based on the first NorCell project team and one team at Ceramatec in USA.

The final project report from 1995 states that the NorCell II project had been terminated at the end of 1994, even if some of the goals of the project had not been achieved. The project reports also states that for the time being there are no funds available for further development towards a commercial product. The report explains that the reason for not achieving the goals of the project was due to unrealistic assumptions as to the initial status of the R&D – and the capability of achieving the goals that were set initially. Accordingly, the project underestimated the need for fundamental research – that planning the project as a straight-forward technology development project was a misconception. 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[39] that can be labeled as SOFC patents. Two are related to an interconnect[40], a field in which the NorCell project had some success. The knowledge gained from the NorCell project was indirectly transmitted to NorECS and SI. NorECs (an acronym for Norwegian Electro Ceramics AS) is a company that was started by researchers from Centre for Material Science at the University of Oslo. Using the trademark *Probostat*, NorECs has

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37 Report filed in the Norwegian Research Council, "Sluttrapportert", prosjekt 28632/212, Norcell II, 29th March 1995, p. 2.

38 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.

39 The four patents were:

- Semi-internally manifolded interconnect stack design (filed 1993-10-06) patent number US5376472
- Dual column fuel cell module (filed 1994-02-04)
- Thermally integrated heat exchange system for SOFCs (filed 27.12.1994) US5366819
- Pin-fin interconnect for planar ceramic electrochemical cells.

40 The interconnect is connecting anode and cathode and is a critical area for degradation of the fuel cells.

developed and commercialized a "measurement cell for electrical properties and permeability studies at high temperatures and in controlled atmospheres"[41]. Probostat may be used for testing and building of cells for studies, characterization and testing of electro-ceramics, fuel cell components, membrane materials etc. In addition, the NorCell II project developed gas-permeable membranes that can be used in carbon sequestration. According to informants, knowledge from NorCell was transmitted to Mjøllner because people who had worked on NorCell moved to Mjøllner after NorCell was finished.

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. In 1998, Ceramatec's owner Elkem sold the company to the management of Ceramatec, and by this exited from fuel cells technology development. Subsequently, Ceramatec established a subsidiary company, *SOFCo*, dedicated to development of fuel cells in the partnership with Babcock & Wilcox. Some Norwegian informants claim that the outcome of NorCell II was a hard blow to Norwegian R&D fuel cells community – and that because of lack of funds, it was unable to recuperate afterwards, whereas Ceramatec of USA, through its subsidiary SOFCo, reaped substantial benefits[42].

5.4.5 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. Apparently, Statoil had started the Mjøllner project on a small scale in 1988, i.e. approximately simultaneously with the first NorCell project, as evident in a number of publications.[43] 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

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41 Cf.: http://www.norecs.com/NORECS_CELL_1.html

42 Cf.: http://www.netl.doe.gov/publications/proceedings/99/99fuelcell/fc6-4.pdf, presenting a paper, *Status of SOFCo's Planar SOFC Development*, on p.3, under the section "Acknowledgement", gives credit to DARPA, US Army Research Office, EPRI and GRI – no metion of its former Norwegian partners and funding.

43 The following publications provide an indication of this:

- O. Melhus, Ø. Johannesen, R. Tunold, R. Ødegård, A. Godahl og P. Sundal : "Verifikasjon av ABB's fastoksyd brenselcelle (SOFC) teknologi." SINTEF-rapport STF34 F89041, NTH, 1989.
- O. Melhus, Ø. Johannesen, R. Tunold, R. Ødegård, A. Godal og P. Sundal : "Konseptstudie, MJØLLNER fase 1." Prototech / SINTEF-rapport, strengt fortrolig, Bergen/Trondheim, 16.november 1989.
- O. Melhus : "Forskningsbehov ved direkte bruk av naturgass. Brenselceller." Rapport utarbeidet for Norsk Energi i forb. med SPUNG-programmet, NTH, 1989.

faster than in a cooperative R&D consortium. The R&D in the Mjøllner project was done by approximately 25 engineers and scientists, organized in three teams; one at the R&D department of Statoil in Trondheim, one at Prototech, a subsidiary firm of Christian Michelsen Research in Bergen, and the third at NTNU/SINTEF[44], also in Trondheim. Formally, Prototech was Statoil's contractor for the fuel cells system development, while the development of components, such as electrolytes, membranes and interconnect, was carried out in Trondheim. When the project was finished in 1998, Statoil was able to successfully demonstrate a pilot plant generating 10 kW and test-run this for 200 hours, based on natural gas as feedstock.

Six patent applications can be directly linked to the Mjøllner project, and all of them are assigned for by Statoil: Statoil has the patent rights from Mjøllner, but Prototech has the right to develop the technology. Parts of the laboratory equipment used in Mjøllner were also taken over by Prototech. Statoil's R&D on fuel cells is at present (2003) scaled down, but the company participates in an EU project on methanol fuel cells and a few other activities. Several of the employees in Prototech were inventors on Statoil's patents and had leading roles in the innovation process. Prototech is now using the knowledge from Mjøllner to further develop a SOFC. Prototech has developed the SOFC technology based on own R&D and has now made agreements with several energy producers of delivery for a SOFC to be used in combined heat and power production (CHP) plants. They obtained a contract for manufacturing of a SOFC unit to be used in a CHP, commissioned by BKK, an electric utility company serving the western part of Norway. This contract was originally given to Norske Shell, and the company even won an innovation award in 2002 for this fuel cell. However, when Norske Shell failed to construct the heat exchanger for this fuel cell, Prototech was given the task of completing the contract.

The cost of the Mjøllner project was close to NOK 150 millions (approximately US$ 20 millions) as it ended in 1998. At this point, 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, such as with Siemens: Initially, Siemens showed great interest because they themselves were undertaking R&D on planar SOFC, for purposes of developing commercial, stationary power plants. However, as Siemens merged with Westinghouse in 1998, it decided to drop its own approach in favour of Westinghouse's tubular geometry[45] in SOFC, moving its fuel cells R&D unit to USA.

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44 NTNU is a Norwegian acronym for "Norwegian University of Science and Technology", and SINTEF official name in English is "The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology (NTH)". NTH was the former acronym of NTNU. Both NTNU and SINTEF are located in Trondheim, however, in 1992, SINTEF merged with SI in Oslo.

45 http://www.dwv-info.de/wss/wse985.htm#Siemens for more information on this.

Some informants claim that Statoil's decision to exit NorCell and run its own project (Mjøllner) reflects a traditional corporate rivalry between Statoil and Norsk Hydro, in so far as these companies are competitors in a number of market segments, for obtaining exploration licenses offshore, etc. As Statoil and Norsk Hydro are known for their inability to cooperate in a number of other cases, a split could be explained as "natural", in spite of the Norwegian state being a major shareholder in both companies. Others point to Statoil's corporate culture in the 1990s, which encouraged entrepreneurial activity, granting autonomy to employees with ambitious projects and providing these with funding. Informants inside Statoil emphasize that Mjøllner had a strong rationale related to Statoil's corporate business and technology strategy in the 1990s. Considering the size of Mjøllner and its duration, the latter explanation seems most plausible. Most informants, however, point to cultural differences between NorCell and Mjøllner. Whereas the first, NorCell, was dominated by academically oriented scientists with close ties to the conservative University of Oslo, Mjøllner was dominated by technologists with engineering backgrounds and close ties to NTNU, i.e. two different mind-sets in terms of creating and developing technology. However, there are significant policy issues that will now be the next topic.

5.4.6 Innovation policy aspects

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, paucity of results). Possibly as a result of this, R&D in fuel cells was scaled down dramatically as priorities were shifted towards hydrogen and carbon sequestration after 1999 in public research funding. At present, the Norwegian R&D in fuel cells is minuscule compared to the early 1990s. By this, Norwegian NIS has gradually lost the expertise and knowledge that was obtained earlier.

Some innovation theorists such as Porter (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 NIS 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 represent a system failure or did they constitute a climate of normal (healthy) competition that a country should have?

These two competing projects resulted in a situation where Norway, as a small country, had two technologically ambitious and expensive, large projects working on development of almost identical SOFC. Because NFR cancelled all the support to R&D on fuel cells after NorCell II and Statoil scaled down its fuel cell program, knowledge built up over several years has gradually vanished or become obsolete. At the same time, part of the competence base and the patent rights were lost to USA. One informant said that, “the problem with NorCell was that, first there was all this effort and competence building, but then there was no support and the knowledge disappeared. This is not good use of invested money on knowledge”. Several informants stated that the outcome of NorCell and Mjøllner was a great disaster for an ambition of sustaining a large Norwegian fuel cell program.

In development of potentially radical innovations such as fuel cells, building a capability to operate with a broad perspective is important when doing R&D. Accordingly, some claim (with hindsight) that the SOFC projects not only duplicated each other, but were too narrow in scope and for this reason became vulnerable. From a national policy perspective, this may be interpreted as a lack of robustness in the R&D strategy design. Accordingly, having two projects doing R&D on the same technological alternative fostered homogeneity, rather than heterogeneity. Thus, the strategic options became narrow and vulnerable. Fostering heterogeneity could mean a strategy or policy capable of directing one project at developing SOFC and another at developing PEM fuel cells. If this had been the case, Norway would have possessed a broader knowledge in fuel cells technology. However, this did not happen, which raises the question of why such strategic leadership was absent.

In making investments in knowledge having a potential for creating 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 down-scaling of Norwegian R&D in fuel cells technology development after the projects were finished was unfortunate and premature in a NIS-perspective 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. With hindsight, it seems evident that the decision to down-scale R&D in fuel cells was unwise, in so far as the knowledge base that was established has not be developed and has gradually become obsolete. In the meantime, other nations have surged forward, making a substantial progress towards developing commercially viable fuel cells.

6 Conclusions and issues for improving the innovation system

6.1 Fuel cells and hydrogen technology as innovations

Norway produces an abundance of energy; most of this is exported, either directly as electricity, gas or oil, or indirectly, embedded in products that have been manufactured in energy intensive processes. This abundance of energy provides the nation with a considerable income and is of vital importance for its present status as a wealthy nation. Norway has a potential for increasing its energy production even more by developing innovations, both in fossil fuels and in new, renewable energy sources. Innovation activities in fuel cells, in particular development of related hydrogen technologies, are perceived as offering opportunities that are promising for Norway because this may provide solutions for Norway's "gas problem", i.e. create more value from its vast reservoirs of natural gas: Innovations in these technologies and related energy systems represent potentials for economic development in the future. If they materialize, these will also contribute to a sustainable development trajectory for society because these are considered clean and use renewable energy sources.

However, in spite of these potentials, creating innovations in fuel cells and related hydrogen technologies will require a considerable, prolonged effort, mainly in terms of RD&D, in order to become commercially viable technologies and energy systems. Although substantial progress has been made towards these goals during the last decades, there is still much uncertainty related to numerous non-trivial technological challenges and barriers that have to be overcome in order to succeed, i.e. become competitive with other energy sources. This makes the concept of *reverse salient* relevant. Coined by Thomas Hughes (Hughes, 1987) for explaining the emergence and evolution of large technological systems, such as electric power systems, he explains this:
"Reverse salients are components in the system that have fallen behind or are out of phase with others./…/ In an electrical system engineers may change the characteristics of a generator to improve its efficiency. Then another component in the system, such as the motor, may need to have its characteristics – resistance, voltage, or amperage – altered so that it will function optimally with the generator. Until that is done, the motor remains a reverse salient." (p.73).

According to Hughes, when a reverse salient "..cannot be corrected within the context of an existing system, the problem becomes a radical one, the solution of which may bring a new and competing system" (p. 75). Following this, one may reasonably classify innovation activities in fuel cells and related hydrogen activities as directed towards creating radical solutions, or radical innovations. Emergence of radical innovations is usually the result of prolonged efforts, high costs and risks, involving many people and organizations. This complexity is particularly evident in development of new, large technological systems and infrastructure. In terms of innovation policy and strategy, this is significant because creation of radical innovations pose challenges that markets are not well equipped to solve, i.e. what is commonly recognized as constituting market failure. Although contested, innovation studies have shown that in order to succeed in creating radical innovations, there is a need for strategy, or more specifically, a strategy that gives direction and coordination for working towards the goal, i.e. a strategy for creation of radical innovations (Chesbrough & Teece, 1996; Godoe, 2000). This implies *leadership*. Innovation studies have shown that there are a number of modes of leadership; leadership may be embodied in a policy goal (e.g. "roadmap") or a person, in a government or a company, or alliances of various institutions such as governments, companies and NGOs. International organizations such as standards setting bodies have at times proved capable of this type of leadership, as seen in the development of the GSM mobile communication system in Europe in the 1980s (Godoe, 2000), or in DARPA's leadership role in the development of the Internet (Hafner & Lyon, 1996). This leadership, combined with a commitment from all the parties and stakeholders involved, may be termed an *innovation regime*; the degree of cohesion and capability of cooperation gives an indication of its strength. Thus, some sectors have weak innovation regimes – others strong. On a national level, one may claim that the existing innovation regime in Norway in fuel cells and related hydrogen technology is weak, for a number of reasons that will be analyzed and discussed in the next sections. Creating a strong innovation regime increases the likelihood of succeeding with innovation oriented activities and ambitions. In this, policy matters.

6.2 Some characteristics of the Norwegian innovation system in fuel cells and related hydrogen technology

The current national portfolio of innovation activities related to fuel cells and hydrogen technology consists of approximately 100 RD&D projects and activities. Although most of these projects are comparatively small research projects, there are a few large demonstration projects run by the industry, i.e. oil & gas companies and electric utility companies. As most of the projects extend over many years with variable budgets reflecting the intensity of activities and adjustment of plans as the projects progress, it was difficult to split the economic figures in annual entities. However, in summing up all the budgets of this current (multi-annual) national portfolio, the following facts emerged:

- total: NOK 570 millions (approximately US$ 80 millions)
- private sector funding: NOK 440 millions (approximately US$ 61 millions)
- public funding: NOK 130 millions (approximately US$ 18 millions) – most of these are funded by the Norwegian Research Council.

According to these figures (which are approximate), the ratio of public funding to private sector funding is 1:3.4, or, private sector's share of the portfolio is 77% in terms of funding. The high share of private sector is due to their financing of a few, large demonstration projects. Considered as a share of the revenues generated by the Norwegian energy sector (in 2002: US$ 62 billions), the size of funding of RD&D in fuel cells and hydrogen technology is small, possibly an indication of underinvestment. Still, for demographical and industrial reasons, one may claim that Norway lacks capacity to increase this level of investment; although lack of funding may appear as a problem, policy, strategy and implementation of strategy may represent the real challenges.

In summing up, one may observe that Norwegian innovation activities in fuel cells and related hydrogen technology consist of three domains or segments:

- *Industry*, mainly large oil and gas companies and electrical utility companies, that invest in RD&D related to innovation oriented activities in fuel cells and related hydrogen technology, however, apparently following what may be characterized as a "fast second mover"-strategy,
- *R&D and scientific community*, which pursue agendas set by the development and technology itself, i.e. highly specialized in a few niche areas, driven by a knowledge agenda,
- *Government,* specifically the ministries having responsibility for sectors such as energy, industry and transportation, but also various agencies affiliated with the government, such as research funding agencies, which has given fuel cells and related hydrogen technology some priority and attention. However, after the deregulation of the energy markets in the 1990s, there has been a policy shift towards greater reliance on market mechanism for promotion of innovations in energy technologies.

As elaborated earlier, a salient feature of the Norwegian energy sector in terms of a national innovation strategy for fuel cells and related hydrogen technology is *decoupling,* i.e. lack of a coherent, unified national strategy that all actors may relate to. In innovation policy debates related to the energy sector, two recurrent themes now seem to contribute towards the emergence of a more proactive innovation policy:

- First, because most of the proven oil fields (not gas) probably will be depleted during the next decade, many argue that now is the time to invest in energy technology innovations that will substitute this.
- Second, that "something should be done" with Norway's abundant supply of gas, i.e. increasing national utilization and value creation of the gas that Norway produces because the reservoirs of gas are large and expected to produce for many decades in the future.

Responding to the issues raised in these debates, the Norwegian government has, as explained earlier, announced that in 2004, it will take some policy initiatives to promote innovation activities in fuel cells and, in particular, hydrogen technology. This coincides with similar initiatives taken in other countries during recent years; of these, the recent US initiative for IPHE – International Partnership for the Hydrogen Society - has been important, as explained in chapter 2.6.

In the decoupling which at present seems to be a characteristic of Norway in an innovation perspective, each segment of the energy sector pursues strategies and interests that in themselves are rational or reasonable:

- *Government:* One may claim that after the deregulation of the energy markets in the 1990s, the government has made a tacit transfer of innovation leadership to the markets and the industry. Although new policy initiatives are expected in 2004 that will

promote innovation activities in fuel cells and related hydrogen technology, government policy has put emphasis on two areas:
    - *Market stimulation measures* by providing subsidies for investments in clean and efficient technologies, through establishment of Enova (cf. chapter 4.2) – the intention of this is to create a market demand and competition for efficient new energy technologies,
    - *Funding of public R&D,* aimed at developing technologies and solutions in the "intersection" between environment (nature) and energy, in particular development of carbon sequestration technology for gas fired power plants. Policy initiatives aimed at promotion of RD&D in new, renewable energy technologies have received some, but not much, funding as evident in the budgets of the Research Council of Norway.
- *Industry:* Does not want to take commercial or technological risks that they rightly perceive as high in fuel cells and related hydrogen technology. However, they want to be in a position to act or respond immediately if a profitable opportunity or market emerges, i.e. their strategy may be termed as a "fast second mover"-strategy. At times companies are rivals, at others times they are partners in joint projects, a behavioural characteristic (opportunistic) which is rational. The combined resources of the Norwegian companies in the oil & gas and energy industry are large, even by international comparison. Although their demonstration and technology development projects in Norway represent a substantial part of the national innovation activities, these do not represent large scale commitments for the companies. Simultaneously, as "fast second movers", they should be capable of escalating their innovation activities rapidly, should they decide to do this.
- *R&D and scientific community:* They are interested in pursuing their own, knowledge-driven agendas. The bibliometric analysis showed that the quality of R&D is generally high. The agendas are also relevant insofar as these are aimed at solving important, non-trivial issues, such as how to increase hydrogen storage capacity in tanks by means of metal hydrides, etc. Reflecting the small size of Norway, this community is not large, however, this may explain its cohesion and shared view of direction, as explained in chapter 4.4, in the proposed R&D agenda. As most of the R&D institutes are contract research organizations, they depend on funding from industry and public funding agencies. After the large fuel cells development projects in the 1990s ended (cf. chapter 5.4), funding of fuel cells R&D has decreased; the research community has made adjustment accordingly. The national knowledge base that these efforts created is rapidly deteriorating and becoming obsolete.

In sum, these strategies are not coordinated as each segment pursues its own strategy or non-strategy, i.e. they are decoupled or only weakly linked to each other. The latter is evident to the extent that one may observe areas of overlapping, common interests, e.g. government provide some (not much) funding to R&D in renewable energy sources in the R&D and scientific community, which also may receive some additional funding from the industry because they are interested in these technologies or want to maintain expertise for future contingencies. Or, companies may invest in RD&D for political, good-will reasons, in addition to more instrumental purposes. Simultaneously, there is a community of professionals, mostly people who are engineers or scientists, who populate all the segments and maintain close relationships based on a common sense of mission, i.e. the promotion of a future hydrogen society. In this landscape, the almost absence of Norwegian SMEs may be interpreted as an indication of a national climate that does not foster innovations.

Being fragmented and decoupled, one may characterize the innovation system as weak on a national level; this weakness has many attributes of a systemic imperfection in which the role of the government and public policy possibly constitutes the main, initial challenge.

6.3 Improving innovation systemic efficiency

The conceptual framework of national systems of innovations (NSI) rests on observations that some nations and regions differ significantly in their innovation capability and capacity, i.e. what may broadly be termed efficiency. This explains why some nations, regions and industrial sectors are more efficient than others, and why these are able to maintain their innovation leadership:

"Innovation patterns are highly country- and even, to a large extent, cluster specific, depending on the individual country's economic specialization and institutional set-up. The implication is that individual countries must find their own way in the innovation-driven economy, and that innovation policy needs to be based on national capabilities for learning". (OECD, 2002a)

Thus the idea of a *system* implies that there are interacting, active elements that are conductive to the promotion of innovations – and that, by comparison, one may be able to identify, specify and explain *why* nations or sectors differ in terms of innovation efficiency. This difference may then justify characterizations, e.g. that some systems are more efficient that others – possibly provide justifications for policy measures and initiatives designed to enhance innovation system efficiency.

In discussing what an efficient innovation system consists of, the OECD booklet *Dynamising National Innovation Systems* points out that increasing efficiency is not equivalent to increasing support for basic R&D or other measures designed to reduce market failure in technology development. Nor does this imply construction of a "grand design" – although such a design may serve as a useful vehicle or heuristic device in some cases, e.g. "roadmaps". What OECD may be attempting articulate as "the need for a coherent and comprehensive policy-making" (OECD, 2002a), may be labelled as *3rd Generation Innovation Policy*[46]. In this conceptual model, 3rd Generation Innovation Policy is seen as the latest, contemporary stage in a trajectory of innovation policy models. In the *1st Generation Innovation Policy,* the underlying belief was the linear innovation model, which had a paradigmatic status for a long period after WWII, until the late 1970s and early 1980s. In this, the idea was that innovations stem from a flow of knowledge starting up with "basic research" as the primordial source. During the 1980s, a policy shift

46 Mr. Svend Otto Remøe, one of the authors of the OECD booklet (OECD, 2002a), used this term during a presentation at OECD's International Conference on Innovation in Energy Technologies, in Washington, 30 September 2003, for explaining the ideas of this booklet.

occurred, based on tenets that innovations are market driven; the best innovation policy is one that is general: Policy should be neutral in terms of technology and industry. Subsequently, deregulation and liberalization became important items on innovation policy agendas. This, which may be labelled as the *2nd Generation Innovation Policy*, has not met expectations, for a number of different reasons. As numerous innovation studies have shown, successful innovation processes and countries that have a high rate of innovations (e.g. Japan) do so for a complexity of reasons; the market, although important, is only one of many factors that contribute to success (David C. Movery, 1982; Etzkowitz & Leydesdorff, 1997; Rosenberg, 1994; Rycroft & Kash, 1994). The inadequacies of the 2nd Generation Innovation Policy has led to a search for a new, alternative type of innovation policy, or the 3rd Generation Innovation Policy, i.e. an innovations system oriented policy that would respond to the complexities of innovation processes. This is ambitious, because it requires inclusion of all the interacting, active elements that are conductive to the promotion of innovations, i.e. a policy that recognizes and relates itself to the complexity of innovation processes and systems that create innovations.

With some caution, the data and analyses of this country study supports an interpretation that there are aspects in Norway's current energy innovation policy that resembles the tenets of a 2nd Generation Innovation Policy. The most visible aspect of this is perhaps that large sums are given as subsidies, through the Enova, for promoting diffusion of energy technologies that are defined as "clean and efficient". The government claims that these subsidies, as a market development strategy, in the long run will promote competition and innovations. The evident decoupling of the different segments in Norwegian RD&D is more complex and less visible; however, there seems to be few, if any, policy measures that are designed to create cohesion and direction in the RD&D activities, or providing these with innovation goals. Earlier in this chapter, Norway was characterized as having a weak innovation regime, in spite of many assets in terms of an advanced competence and knowledge base and resources. Using OECD-terminology, one may claim that the national innovation system at present has a potential for greater efficiency – greater efficiency may provide the nation with considerable future benefits, more so than the present policy.

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