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Learning to innovate

- A comparative study on the role of learning in innovation processes within the emerging hydrogen technological systems in Denmark and Norway

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Abstract

The thesis is a comparative study on the role of learning in innovation processes within the emerging hydrogen technological systems in Denmark and Norway. The systemic perspective on innovation has been utilized as an analytical framework in order to be able to deconstruct the concept of learning and develop a better understanding of the role of learning and innovation in its social, institutional and cultural context. This context is path dependent, and therefore country-specific. The comparative approach highlights differences and identifies strengths and weaknesses of the emerging hydrogen technological systems.

Differing scenarios of the hydrogen economy, cognitive schemes and innovation modes characterized either by learning by doing, using or interacting (DUI-mode) or science and technology innovation (STI-mode) were identified as powerful steering mechanisms, shaping learning and innovation efforts. These were largely path dependent; therefore it is argued that it is imperative for actors to develop a conscious learning and innovation strategy that is informed by, and aware of, the institutional context. The ability to mindfully deviate from path dependent factors was identified as promoting path creation and avoiding premature technological lock-in.

The technological specificity of the challenges confronting the emerging hydrogen technological systems motivates both the DUI- and STI-modes of innovation and learning. However, the STI-mode needs to be connected proactively to cooperative and interactive learning processes at an early stage in order to be confronted with the multiple requirements of users, producers, regulators and evaluators. This insight motivated the construction of a new model for innovation within fuel cells and related hydrogen technology and is based on the find that the composition of learning strategies is a very significant factor explaining the success of innovative efforts within the emerging hydrogen technological systems in Denmark and Norway.

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1. INTRODUCTION

This thesis is an effort to contribute positively to the generation and quality of knowledge in two ways. First, it aims to provide a better understanding of the role of learning in innovation processes. Second, this knowledge is meant to be of some use to the participants of the emerging hydrogen technological systems in Denmark and Norway.

The master thesis is part of a degree in *Society, Science and Technology in Europe* (ESST) at the University of Oslo and Aalborg University. Travelling costs in connection with interviews have been sponsored by the HYTREC[1] project.

My personal motivation in choosing this particular topic is two-folded.

First, it is seated in a fascination of the theories and insights of the literature on innovation. Historically, this field owes a large debt to Schumpeter. He was one of the first scholars to recognize the importance of innovation and technological progress to economic growth and development. Scholars inspired by Schumpeter include Nelson & Winter, Freeman, Lundvall and Carlsson. Nelson & Winter published their work *An Evolutionary Theory of Economic Change* in 1982. This was an influential work, and terms like *Evolutionary Economics* or *Schumpeterian* have since been associated with scholars working on issues related to innovation theory and economic development. Freeman and Lundvall are credited with the term national system of innovation, which will be used as an analytical framework, combined with Carlsson's technological systems.

[1] HYTREC is short for **HY**drogen **T**echnology and **RE**search **C**enter, a Norwegian joint research effort of Det Norske Veritas, Statkraft and Statoil.

Second, this thesis is inspired by the social, philosophical and cultural meaning of the term sustainable development. It is my belief that achieving sustainable societies will require innovation on a broad scale. Fuel cells and related hydrogen technologies (FC&RHT) have been proposed as solutions to reduce the harmful political and environmental effects of a global energy economy dominated by fossil fuels and nuclear energy. Hydrogen is the most abundant element in the biosphere, but does not appear naturally; it has to be extracted, either from hydrocarbons such as coal, natural gas or oil, or from water in a process called electrolysis, or in a variety of other ways. It is an *energy carrier*, not an *energy source*. If hydrogen is used in fuel cell engines, the emission is basically water-steam. Fuel cells can be used in a wide variety of applications, such as cars, computers, cell phones, or stationary applications. The versatility of hydrogen has inspired its proponents to hail it as the ultimate future energy carrier, inspiring such visions as *the hydrogen society*.

There are a broad range of problems that need to be confronted and solved, if this optimistic vision shall come true. The most basic problem is the considerable energy losses associated with the conversion, distribution, and storage of hydrogen (Bossel, 2005). This will be elaborated in more detail in chapter 3. Other important problems include the poor reliability and high cost of fuel cells, the substantial and necessary investments in new energy infrastructure and consumer acceptance. A related problem is the incorporation of hydrogen as an energy carrier into the society and economy. The institutional set-up of countries differs, therefore new technologies are confronted with specific national problems, and this is especially true for FC&RHT, because the energy sector is a basic prerequisite for other sectors, and this sector differs considerably between countries. Powerful economic and national security interests are setting the agenda in most countries, and Denmark and Norway are no exceptions in this respect.

Despite these problems, there is a broad and growing interest in hydrogen. This is reflected by the fact that research, development and demonstration (RD&D) focusing on FC&RHT has grown rapidly the last twenty years. Several industrialised countries, such as Denmark and Norway, have recently adopted hydrogen strategies to facilitate technology development efforts and ease the transfer into the envisioned hydrogen society/economy. Car manufacturers, energy companies and research institutes of the industrialised countries, notably USA, Canada, Japan and Germany, have intensified efforts to commercialize these complimentary and interrelated technologies.

There is no strong correlation, however, between the amount of national investments in new energy technologies and changes in the trajectory of a country's energy system. If the *size* of the research and development budget is not an explanatory factor, the *composition of knowledge and learning strategies* should be investigated closely. Sagar & van der Zwaan has therefore suggested that there is an urgent need to *deconstruct learning* in order to better understand innovation processes in new energy technologies (Sagar & van der Zwaan, 2006).

The research question intended to direct the thesis is therefore the following:

What role does learning play during innovation processes in the emerging hydrogen technological systems in Denmark and Norway?

Fuel cells and related hydrogen technologies are examples of potential radical innovations that are confronted with a broad range of problems related to *technological, institutional and economic* uncertainties in order to develop into successful innovations. By studying the innovation processes of the different actors within the *emerging hydrogen technological* *system*, this thesis hopes to shed light on the *role of learning* in reducing technological, institutional and economic uncertainties of the innovation process, thus enabling innovation to take place.

But what is *innovation*? Dosi suggested that “innovation concerns the search for, and the discovery, experimentation, development, imitation, and adoption of new products, new production processes and new organizational set-ups” (Dosi, 1988, p. 222). FC&RHT should be understood as a set of complimentary and potentially radical innovations, which may alter the character of the energy system if a *number of criteria* are fulfilled.

First, the usage of the *energy carrier* hydrogen must be based on *clean primary energy sources*, primarily renewables like wind-, solar-, bio-, wave- or hydroelectric energy. CO2-sequestrated fossil fuels like natural gas, coal or oil shale and tar sands could also be utilized, even though these are not renewable, but finite natural resources. A discussion on the different scenarios for the *hydrogen economy* follows in subchapter 3.5.

Second, since FC&RHT are complimentary and interdependent technologies, it means that improvements in one of these technologies will affect the others. This can be exemplified by the major barriers to commercialization; the high cost and poor reliability of fuel cells or the limited access of renewable or clean energy for hydrogen production purposes. If one of these barriers to innovation is successfully bypassed, the other related or complimentary technologies will face a different set of options. If, for example, fuel cells prices dropped dramatically, this might have important implications for car manufacturers, who would be more inclined to try to commercialize fuel cell cars.

Third, innovations within FC&RHT are potentially radical, because they might change the current energy system gradually by easing the transition into a renewable and sustainable energy economy by decreasing energy dependency on fossil fuels and nuclear energy (even though this is a contested claim). Successful innovations within this area would be radical, because they might replace the current energy technologies in a process of *creative destruction*, which entails how the creation of new modes of productive transformation destroys existing modes that are themselves results of innovative enterprise in the past (Lazonick, 2005). Successful innovations within FC&RHT are discussed and understood according to these three criteria in this thesis.

Achieving all these feats at once is, however, not very realistic. In an *evolutionary perspective*, it is rather the *accumulated incremental and radical innovative developments over a period of time* that set the stage for the introduction of a new *technological system*, which could either compete with or disrupt existing technological regimes. A well-known and relevant example of a disruptive technological system is the electrification of Western societies, which made electricity the dominant energy carrier during the period 1880-1930 (Hughes, 1993). In this thesis I will use the term *technological system* as understood by Carlsson & Stankiewicz (1995).

> A *technological system* may be defined as a network of agents interacting in a specific *economic/industrial* area under a particular *institutional infrastructure* or set of infrastructures and involved in the generation, diffusion, and utilization of technology. Technological systems are defined in terms of knowledge/competence flows rather than flows of ordinary goods and services. They consist of dynamic knowledge and competence networks. In the presence of an entrepreneur and sufficient critical mass, such networks can be transformed into development blocs, i.e. synergistic clusters of firms and

> technologies within an industry or group of industries (Carlsson & Stankiewicz, 1995, p. 49).

Considering this definition, I will refer to the network of actors involved in FC&RHT (firms, knowledge institutes, universities, industry associations, research councils and grassroots technology organizations, environmental organizations and independent inventors) as *the emerging hydrogen technological system*. The thesis is intended to be a comparative study of the emerging hydrogen technological systems in Denmark and Norway.

This choice is grounded in a conception of that the *differing institutional set-ups, power-relations and other path-dependent factors* create unique and context-dependent barriers and opportunities for *learning and path creation*, by defining and delimiting the available *learning spaces*.

By learning, I mean *learning to innovate* within the boundaries of the institutional and cultural context one is part of, while simultaneously learning to change this context, by constantly challenging the existing boundaries. This is therefore an attempt to *apply* the evolutionary and systems of innovation perspective in an on-going technological process of innovation and transformation. I am interested in how the actors of the emerging hydrogen technological system learn, how they interact, how they characterize and utilize available learning spaces and how they present and manifest their interests politically and institutionally in an effort to ease the introduction of their own technological system.

An underlying goal of this thesis is therefore to identify which factors contribute to successful innovation and learning processes, enabling the path creation of a sustainable technological system to take place. In order to answer the research question and achieve this underlying goal, a set of interviews of actors within the emerging hydrogen technological system in Denmark and Norway have been conducted. This methodological approach is inspired by the following statement by Lundvall “It is assumed that learning is predominantly an interactive and, therefore, a socially embedded process which cannot be understood without taking into consideration its institutional and cultural context” (Lundvall, 1992, p.1). The decision to conduct face-to-face interviews was taken in the belief that such interviews would allow for an in-depth understanding of learning to develop.

The research question points towards the role learning plays in a field characterized by a high level of uncertainty. The uncertainty is multidimensional, i.e. there are a number of unresolved issues, related to potential technical, institutional and economic problems, which constitute barriers for successful innovation. Uncertainty is a salient feature of all innovation processes, but even more so when they involve interrelated and complimentary radical innovations, such as FC&RHT. Overcoming these complex and multifaceted barriers requires developing a set of *highly differentiated learning abilities* operating simultaneously on a broad level (Dosi et. al, 1988).

This means that I consider social, organizational and institutional learning and innovation to be as important as technical innovation, because without diffusion and utilization of technological innovations in the economy, the economical value and overall impact of an innovation is negligible. In the case of FC&RHT, it means that the emerging hydrogen technological system will need to develop political support, develop efficient learning organizations and networks, develop fruitful linkages to knowledgeable and relevant actors, and commercialize competitive products that have obvious advantages in comparison with existing ones, in terms of price, environmental effects, usefulness, quality and reliability.

1.1 Structure of the thesis

The introduction has so far presented the goals of the thesis, the research question, essential parts of the theoretical framework and a short overview of the empirical focus.

Chapter 2 presents the methodology of the thesis.

Chapter 3 provides a historical account and a technological overview of FC&RHT. The complex process of incorporating hydrogen as an energy carrier within the larger energy system is discussed. The scenarios of the hydrogen economy are presented and discussed in conjunction with a related theme connected to visualizing the future structure of the energy system; the distinction between centralized or decentralized solutions.

Chapter 4 deliberates the theories of the systemic perspective on innovation; national systems of innovation, technological systems and the related theories of the learning economy. The concept of the institutional set-up is explained, followed by a discussion on the interrelated concepts path dependency and path creation. Two taxonomies are presented and explained; a knowledge taxonomy and an innovation and learning taxonomy. Chapter 4 forms the backbone of the theoretical understanding that influenced the interviews and the construction of the interview guide (see appendix A). In light of the theoretical framework, innovation and learning strategies are related to the technological specificity of the problems facing FC&RHT, which implications are described and discussed. The last two sub-chapters present the empirical details of the institutional set-ups in Denmark and Norway, and relate this to innovation and learning strategies, path dependency and policy.

Chapter 5 presents and discusses the empirical findings of the interviews, utilizing the analytical tools specified in the two presented taxonomies. The comparative approach informs the structure of the chapter, and this pattern is continued in the next chapter.

Chapter 6 analyzes the research question and the underlying aims of the thesis, contrasting the Danish and Norwegian hydrogen technological systems when it is relevant. Emphasis is on the role of learning, path dependency and opportunities for path creation. The analysis also focuses on what policy implications can be derived from the identification of strengths and weaknesses. On the basis of the insights derived from the analysis, a new model for innovation within FC&RHT is proposed and explained.

Chapter 7 summarizes the main points of the thesis, and discusses what conclusions should be drawn, while also identifying areas where more theoretical and empirical research should be done.

2. METHODOLOGY

This thesis is an effort to develop a better understanding of the role of learning during the innovation processes of the emerging hydrogen technological systems in Denmark and Norway. The method chosen for this task is to conduct a qualitative cross-country comparative interview study, combined with textual analysis of central documents and observation and personal participation in two hydrogen conferences[2]. The knowledge of the role of learning in this particular setting is limited; therefore the decision to conduct open-ended, face-to-face qualitative interviews was taken. The thesis is an *exploratory* effort,

[2] HyNor 2005 "Hydrogen for Transport in Norway" & Danish Hydrogen Association yearly conference 2006: "Network & Competencies"

hoping to generate questions relevant both to the actors of the emerging hydrogen technological system and to the construction of new theory.

The first challenge in order follow this particular approach was to make a connection to some of the actors of the emerging hydrogen technological system. With that in mind, I went to the HyNor[3] conference in Stavanger in December 2005. I brought a preliminary project outline, which I distributed to some of the people attending the conference. A week later I was contacted by Carl Erik Hillesund of Statkraft, who is project manager for the HYTREC-project. I was later introduced to a contact person at HYTREC; Eirik Nyhus of Det Norske Veritas. He gave me a list of persons, explained their role in the hydrogen network, and agreed to cover travelling expenses during the course of the project. This allowed me to conduct interviews in various locations in Norway and Denmark.

2.1 Selecting the informants & the conditions of participation

Since the subject of the thesis concerns innovation processes in a field where some of the actors are on the verge of presenting their first commercial products, I decided to offer the commercial actors anonymity in order to let them speak freely, so that they would not run the risk of giving away sensitive commercial information accidentally. I interviewed two central commercial actors in each country. In addition to these, I interviewed two named actors that have central positions within the emerging hydrogen technological system in their respective countries. The unnamed informants are indicated by the abbreviation of their titles, while the other two are named. They are presented in Box 5, chapter 5.

[3] HyNor is a Norwegian development project, promoting the use of hydrogen within the Norwegian transport sector by building a hydrogen infrastructure connecting Oslo and Stavanger.

2.2 The qualitative comparative interview study approach

By conducting in-depth interviews with selected persons, the goal has been to illuminate the connection between the micro and macro level of analysis. The systemic perspective on innovation suggests that it is essential to understand the institutional set-up of innovation systems. But in order to understand the dynamics of technological systems and the national system of innovation, it is arguably necessary to go down to the micro level, to meet and speak to the actual people that make up the systems. Perceived differences between Denmark and Norway were presented to Eirik Nyhus, who agreed that the presented characteristics (see Box 4) provided a useful point of departure for the design of an interview guide (see appendix A).

The interviews aimed to illuminate the role of learning. The literature on case study and interview methods suggests that studying micro processes qualitatively might be a suitable methodological choice in areas where the amount of knowledge is limited (Stake, 2000). This strategy can be labelled *exploratory and theory generating*, in contrast to quantitative methods that are more suited to confirm existing theories by revealing regularities and patterns in areas that are well known a priori. In the article *The Corporate Interview as a Research Method in Economic Geography* (1991) Erica Schoenberger notes:

> While the method does not lend itself to formal hypothesis testing, it can provide fertile ground for the generation of hypotheses about business behaviour. Indeed, the value of its qualitative and inductive aspects may be highest in periods of great economic and social change that pose new challenges to the analytical categories and theoretical perspectives underlying much quantitative research (Schoenberger, 1991, p. 181).

This thesis is informed by the fact that new and sustainable technologies reflect a period of economic and social change, hence justifying the qualitative, exploratory and theory generating approach.

2.3 Conducting the interviews

I contacted the informants by e-mail, where I explained the general focus of my research. If they agreed to be interviewed, I sent them the interview guide a week in advance in order to give them a hint on the character of the interviews, while also letting them prepare themselves if they wanted to. The interview guide provided a structure on the interviews, but the interviews were meant to be an exchange of views, not just a mechanical session of Question & Answer. This strategy proved to be successful, since many things of interest appeared as a consequence of letting the actors reflect and elaborate on their own perceptions, for example by explaining their own role within the system or by questioning the pretext of a question. Many questions were formulated at the spur of the moment in response to an answer I found intriguing or puzzling. This open-ended approach allowed them to elaborate their own views in detail, while I felt that they also got a progressively better understanding of the focus of my research during the course of the interviews. All direct quotes that appear in the interview based chapter 5 have been approved of by the informants.

2.4 Generalizability, reliability and validity

A positivistic understanding of science emphasizes the importance of methodological stringency, if the claims of a scientific report are to be taken seriously. The terms generalizability, reliability and validity have been described by Kvale (2001) as a positivistic trinity, used by its proponents to discredit the explanatory power of qualitative research. Kvale suggests another understanding, resulting in a different set of criteria, to judge the generalizability, reliability and validity of qualitative studies.

Generalizability is used to question if the claims made can be made general. The interpretations of interviews, theories and analytical frameworks used in this thesis are definitely subjective, but this need not be problematic. Kvale suggests the term *analytical generalization* to describe the use of an assertive logic, reminiscent of the kind of logic a lawyer would use in court of law. By specifying the evidence and making the arguments explicit, the researcher allows the reader to judge the generalizability as he or she sees fit (Kvale, 2001). The thesis should therefore be understood to be the outcome of my theoretical perspective, which is one out of many possible perspectives on the subject matter. This thesis is not an effort to present *the* definitive representative and general analysis of the emerging hydrogen technological systems in Denmark and Norway; it is rather an effort to better understand the role of learning in differing institutional set-ups.

The chronological account of the research process that initiated this chapter is an attempt to let the reader retrace the steps of the research process. This is related to the concept of *reliability*, which is used to question the consistency of a report. Again, the reader is allowed to judge in this matter. In a court case, the question of guilt is supposed to be illuminated by looking at as many possible sides of the case as possible. This has been institutionalized in the courtroom setting; the lawyer and the prosecutor present evidence to support their case. This study has a similar logic. I assert a number of things and suggest that theories and realities are interrelated in the sense that by studying the processes or parts of a system, and by interviewing the actors of the larger system; I can illuminate important parts of the whole.

The question of validity concerns to what degree observations actually reflect the phenomena that were intended to be investigated. Kvale suggests that validation should not be understood as an inspection at the end of a research project, it should rather be understood by the researcher as a continuous process of quality control guiding the entire process. Furthermore, validation should be understood as a skill, the quality of which is dependent upon if the researcher controls the strength of arguments, playing the role of the devil's advocate towards his own interpretations, to counteract the possibility of presenting a biased or skewed perspective. This self-questioning attitude should ideally be used throughout the whole process. To use the courtroom metaphor again; one should always be prepared to say: *I rest my case*, if the empirical findings do not match the theories and analytical frameworks that have been used to formulate the theme and general focus of the thesis. Resting one's case does not amount to giving up, but it means that one should be open to the possibility of a necessary reformulation of the case (Kvale, 2001).

Throughout the research process, interaction with the people of the emerging hydrogen technological system, in the form of interviews, meetings, seminars, conferences or informal conversations has lead me to several times reconsider the focus and outline of my research.

3. FUEL CELL AND RELATED HYDROGEN TECHNOLOGY

This chapter gives an overview of FC&RHT in order to explain the general principles and features of the technology in order to conduct a serious discussion about the pros and cons of this technology. Such a discussion should not be limited to the circles of experts or specialists. A brief introduction into the origins of FC&RHT will therefore be given and the technological properties and principles of fuel cells and fuel cell systems will be explained. Additionally, the hydrogen energy chain is an important matter to consider, since hydrogen is an energy carrier in gas form, not an energy source in itself. Any serious discussion about FC&RHT must consider costs and energy losses associated with the energy conversion processes that are necessary in order to produce, store, distribute and use hydrogen. This leads to the related discussions of the different scenarios of the hydrogen economy and the discussion on the important distinction between centralized or decentralized solutions.

3.1 Origins of the fuel cell

The first fuel cell was invented in 1839 by William R Grove, a Welsh judge and inventor. The principle was discovered by accident during an electrolysis experiment. Fuel cell technology was then mostly neglected for almost a hundred years, until Francis Bacon, a chemical engineer at Cambridge University, England, produced the first practical fuel cell in the 1950s, an Alkaline Fuel Cell (AFC). This type was later used during the first space flights by NASA, for the Apollo spacecraft. The fuel cell provided electricity, while the waste product H2O supplied drinking water for the astronauts on their journey to the moon.[4]

3.2 The fuel cell

A fuel cell is an electrochemical device that converts chemical energy directly into electrical energy without combustion and without moving parts:

> A fuel cell basically consists of two electrodes and one electrolyte. The operating principle is known from the electrolysis of water and a fuel cell is fundamentally the opposite of electrolysis. Utilizing electrolysis, water is split

[4] http://inventors.about.com/od/fstartinventions/a/Fuel_Cells.htm (25.9.06)

> into oxygen at the anode and hydrogen at the cathode. In a fuel cell the reaction is opposite and hydrogen is oxidized at the anode and reduced at the cathode and from that process heat, electricity and pure water are released.[5]

The energy products produced are heat and electricity, while the waste product is water. This is the attraction of FC&RHT; hydrogen is an extremely versatile energy carrier that can convert other energy sources into heat or electricity without emitting any harmful substances, such as CO2 into the atmosphere. The fundamental question is therefore how and from which primary energy sources the hydrogen is produced since that determines the environmental impact of hydrogen use. There are six types[6] of fuel cells undergoing RD&D aiming at eventual commercialization[7].

3.3 Fuel cell systems and applications

Fuel cell systems generally have three main components; the fuel cells stack, the fuel processor, and power electronics. In addition, there might be some kind of heat recovery system converting excess heat into usable steam, hot water or electricity. The three main applications of fuel cells are stationary installations, portable uses, and transportation.

Box 1: Overview of applications of fuel cell systems (Source: Massachusetts Technology Collaborative)[8]

Application	**Fuel cell types**	**Example of usage**
Stationary	PEMFC, PAFC, MCFC, SOFC, AFC	Combined Heat and Power (CHP) for private, commercial, and industrial buildings
Portable	PEMFC, AFC, DMFC	Power backup, wireless energy for laptops and mobile phones, spacecrafts
Transportation	PEMFC, PAFC, DMFC	Cars, trucks, buses, indoor trucks, motorbikes

[5] http://www.danishtechnology.dk/energy/14257 (17.7.06)
[6] Alkaline Fuel Cell (AFC), Molten Carbonate Fuel Cell (MCFC), Phosphoric Acid Fuel Cell (PAFC) Proton Exchange Membrane Fuel Cell (PEMFC) Solid Oxide Fuel Cell (SOFC), Direct Methanol Fuel Cell (DMFC)
[7] http://www.nfcrc.uci.edu/fcresources/FCexplained/FC_Types.htm (17.7.06)
[8] http://www.mtpc.org/cleanenergy/fuelcell/technology.htm (18.7.06)

3.4 The hydrogen energy chain

It could be foolish to consider a large-scale shift to hydrogen without thinking about which primary energy sources should be used to produce the energy carrier hydrogen. There are two reasons for this. Firstly, one must be assured that it is possible to achieve a significant positive environmental effect. The second point involves the energy losses associated with the usage of hydrogen as an energy carrier in the energy chain. Ulf Bossel, a sceptic of the hydrogen economy, asks:

> How much energy is really consumed to make, package, distribute and transfer hydrogen? Where does the energy come from? How efficient is the distribution of the lightest, thus most impractical of all energy gases? How much energy is needed to run a hydrogen economy? Can we afford such a wasteful hydrogen economy at all? These questions need to be answered before investments are made in a hydrogen future. It will cost trillions of dollars to convert the entire energy system to hydrogen. Thus, it is simply due diligence to question the optimistic claims of the hydrogen promoters before tax money is spent on research, development and hardware. Any new energy technology must be based on a sound platform of physics, engineering and economics (Bossel, 2004, p. 55).

The extreme versatility of hydrogen as an energy carrier comes at a cost, because the necessary energy conversions entail a significant loss of energy; it can therefore be said that its attraction also constitutes its most serious disadvantage. Bossel points out five easily understandable facts that to him prove the wastefulness of a hydrogen economy.

> 1) Put at its simplest, one can say that a customer receives only 50% of the original renewable electricity with hydrogen gas, and that losses rise to 75% or higher when this hydrogen is converted back to electricity.

> 2) At filling stations, hydrogen will cost at least twice as much as electrical energy from the grid.
> 3) Electricity from hydrogen fuel cells will cost about four times as much as electricity from the grid.
> 4) The 'battery-to-wheel' efficiency of electric cars is about 80%, while the 'tank-to-wheel' efficiency of fuel cell cars can barely reach 40%.
> 5) The daily drive to work in a hydrogen fuel cell car will cost four times more than in an electric or hybrid vehicle (Bossel, 2004, p. 58). (Author's numbering)

This is based on the energy losses associated with hydrogen production from renewable sources. Another option is to use CO2-sequestrated fossil fuels to produce hydrogen, but this could be even more wasteful, considering the amount of primary energy needed to extract, produce, CO2-sequestrate and distribute hydrogen from centralized fossil fuel sources. The challenge for innovators of FC&RHT is therefore to show that they can make products and processes that are both cost- and energy-efficient. They also need to commercialize these products and processes, comply with safety and industrial standards that for the most part do not even exist, and most importantly, they need to find customers that are interested in buying solutions based on a new and largely unknown technology.

Overcoming such an overwhelming challenge will require large amounts of resources, innovativeness, persistence, learning, and far-reaching infrastructural changes. There is as of yet no dominant technology or industry standard, no infrastructure and very few commercially available products. That is an important point to remember when considering the role of learning in innovation processes, which is the main topic of this thesis. *Learning* often means learning towards a set of more or less defined goals, it is therefore important to consider the pros and cons of various scenarios of the hydrogen economy before one makes any judgments about which goals to steer one's innovative activities towards. Otherwise one might risk that learning towards futile goals leads to innovation failure, ensuring the continuation of current unsustainable energy technologies (Dosi, 1988).

3.5 Scenarios of the hydrogen economy

There are basically three different scenarios of the hydrogen economy that people within FC&RHT envision.

First, there is the completely renewable scenario. In this scenario, the electricity required in the electrolysis process to produce the hydrogen is produced by renewable energy sources, such as wind, solar, wave, bio-mass or hydroelectric dams. Considering the low share of renewable energy worldwide, this is a long-term option, considered by sceptics to be slightly utopian. But Denmark and Norway already have large amounts of renewable energy installed in their energy systems in the shape of hydropower in Norway, and wind power in Denmark. The potential for a massive increase of renewable energy, especially wind power, is deemed to be promising in these two countries.[9] This means that Danish and Norwegian actors face a unique set of opportunities when it comes to innovating and commercializing products and processes that combine hydrogen with renewable energy technologies. This might be considered a competitive advantage, which should be compared with the majority of countries that constitute the forefront in FC&RHT, notably Japan, USA, Canada, and Germany. All of these countries remain heavily dependent on infrastructures dominated by fossil fuel or nuclear energy, even though Germany has experienced a strong increase of installed renewable energy during the last fifteen years (Jacobsson & Lauber, 2006). Nevertheless, the

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[9] http://www.forskningsradet.no/servlet/Satellite?c=GenerellArtikkel&cid=1148232850628&pagename=hydrogen%2FGenerellArtikkel%2FVis_i_dette_menypunkt&rendermode=preview (18.7.06)

energy losses associated with production of hydrogen by electrolysis using renewable electricity from primary energy sources must be accounted for by proponents of this scenario.

The second scenario is to use CO2-sequestration technologies to produce hydrogen out of hydrocarbons such as oil, natural gas, coal or the as of yet unexploited reserves of tar sands and oil shale[10]. This option is by many considered to be the most realistic, since it would mean that the dominant players of the current energy economy would place its waste products inside the Earth instead of inside the Earth's atmosphere, by utilizing CO2-sequestration technologies. This option would allow the current energy structure to reproduce itself, acting like a bridge to the hydrogen economy envisioned by its advocates. This bridge would then provide the necessary hydrogen infrastructure until renewable energy sources would have expanded their capacity sufficiently to provide the needed energy amounts to power the world's heating, electricity and transportation needs. Using fossil fuels in this manner would do little to change the ever accelerating exhaustion of fossil fuels, but it would prolong the structure of the current energy economy, by developing it in a more environmentally friendly direction. The CO2- sequestration scenario is particularly popular in Norway[11], since it holds the promise of increased oil and gas production, while also opening up for the development of refined and value-added energy products such as hydrogen, thus strengthening the position of the established fossil fuel dependent companies. But the energy losses associated with conversion described in the previous subchapter means that proponents of this scenario must account for expected cost and energy efficiency ratios, before one decides to go for the CO2-sequestrated fossil fuel scenario. Ultimately, the increased need for energy to produce, store and distribute hydrogen might mean that this scenario could accelerate the pace of fossil fuel

[10] http://darwin.nap.edu/books/0309091632/html/84.html (17.7.06)
[11] http://www.zero.no/fossil/co2/politikk/co2-injisering-er-bedriftsokonomisk-lonnsomt/ (18.7.06)

exhaustion, especially when one considers that a side-effect of CO2-sequestration entails increased possibilities to extract the full potential of oil and gas fields.

A third scenario involves using nuclear energy to produce hydrogen for the transportation sector[12]. This solution would allow for a zero-emission transportation sector but the problems of nuclear energy would remain, such as the unresolved issue of end storage and the risks of accidents. The energy losses that apply for renewable electricity are also valid for this scenario since electrolysis derived from nuclear produced electricity would be utilized to produce hydrogen. Widespread usage of hydrogen powered fuel cell cars would therefore necessitate a massive increase in nuclear reactors further accelerating the exhaustion of uranium, which like fossil fuels is a finite natural resource, making nuclear a poor long-term option[13].

3.6 Centralized versus decentralized solutions

A fuel cell car running on hydrogen would have the following energy chain when based on renewable energy sources: primary energy source>electricity>hydrogen>on board conversion to electricity>conversion to mechanical energy to start rolling. If natural gas is reformed, the energy chain looks like this: primary energy source>electricity> primary energy source> hydrogen>on board conversion to electricity>conversion to mechanical energy to start rolling. This places tough demands on the technology to minimize the energy losses associated with conversion. It also means that the *centralized* nature of the current fossil fuel/nuclear energy economy might be unsuited to supply large amounts of hydrogen to the transportation and

[12] http://www.dagsavisen.no/bil/article2126045.ece (17.7.06)
[13] http://www.greatchange.org/bb-thermochemical-nuclear_sustainability_rev.pdf (17.7.06)

heating sector, because of the energy required for distribution and storage of hydrogen, thus making the idea of the bridge function suggested in the second scenario above problematic.

One option could be to cut the length of the distribution chain needed to produce the hydrogen drastically, by creating *decentralized* hydrogen production from locally available renewable energy sources. If taken to the extreme, this approach could entail hydrogen production on the household level; from solar energy[14], small windmills or biomass. Such an approach would require a new type of holistic low-energy architecture, where the energy solutions would be integrated into the design of the house, making energy efficiency and energy conservation a primary concern. This would cut the distribution costs of hydrogen drastically, enabling each household to produce its own renewable hydrogen and electricity, by utilizing surplus electricity to produce hydrogen to power a fuel cell car, laptop, lawnmower or mobile phone. Such a solution could make the individual consumer an independent producer and distributor of energy products. If solar energy, the most obviously decentralized energy source, increases energy production capacity and continues to cut costs, it might release a massive *creative destructive* potential of decentralized solar-based hydrogen solutions. Such technological solutions could become *disruptive technologies or innovations*, i.e. making the existing, competing technologies outmoded. The reason for this is that developers and *producers* of decentralized renewable energy solutions, combining elements like solar, fuel cells, and hydrogen technology, enter a market where they have nothing to lose, but everything to win. The established energy *suppliers,* which have invested huge amounts in an infrastructure dominated by oil, gas, nuclear, and electricity grids, have a lot to lose, and much less to win (Scheer, 2002).

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[14] Such a solar/hydrogen home solution is scheduled for completion during the autumn of 2006 in New Jersey, USA, see link: http://www.fuelcellstoday.com/FuelCellToday/IndustryInformation/IndustryInformationExternal/NewsDisplayArticle/0,1602,8055,00.html (16.8.06)

The costs of storage and distribution in such large and centralized networks will always be paid for by the individual customer, who will be dependent upon the large energy producers and power-utilities for energy supplies. The cost and space requirements of producing, storing and distributing hydrogen have to be considered before any investments into a large-scale, centralized hydrogen infrastructure are made. It is important to keep in mind that hydrogen is not the only option available, it will for many years have to compete with the energy carrier electricity, but also primary energy sources like oil, coal, bio-energy, nuclear and natural gas and transportation technologies such as hybrid or bio-fuel vehicles. The energy carrier electricity already has a well-functioning grid that is non-polluting if the energy comes from renewable energy sources. The main disadvantage of electricity is that surplus energy cannot be stored efficiently, when energy production supersedes consumption, i.e. one cannot save up surplus energy for a cloudy day when the wind is not blowing, as is the case today for solar or wind energy plants. The problem of storing energy in batteries efficiently has also been the major barrier for successful innovation and commercialization of electric cars.

All of this does not mean that further innovation activities into FC&RHT are a waste of time, but it means that anyone interested in innovating should seriously consider which way to steer his or her learning activities before jumping on the hydrogen bandwagon. A sound assessment of where the *potential for creative destruction* lies should be considered by all actors.

The shape of the future energy system is at present impossible to predict, it is therefore important to question the basic pretexts of the energy economy experts, regardless if they are pro-renewable, pro-hydrogen, pro-nuclear or pro-fossil fuels or any combination thereof. The evolution of energy technologies is not solely decided by a few powerful countries or companies; it is also shaped by global societal concerns like climate change and diminishing fossil resources. New innovative technologies promoted by emerging technological systems may release creative destructive capabilities, aiming to disrupt dominant energy systems.

4. THE SYSTEMIC PERSPECTIVE ON INNOVATION

This chapter aims to provide a deeper understanding of the systemic perspective on innovation by presenting an analytical framework that regards the emerging hydrogen technological system, the national system of innovation and the institutional set-up to be interrelated; shaped by and shaping each other. The role of institutions in influencing learning processes is investigated. Johnson claims that institutions fundamentally influence learning processes and innovation, and since the institutional set-up of countries differ because of different cultural roots, the national dimension is important to consider (Johnson, 1992). The evolution and renewal of the institutional set-up is discussed, using the interrelated terms *path dependency* and *path creation*.

The notion of the *learning economy* suggests that social and interactive learning is a fundamental factor in innovation. This is discussed, along with a discussion on *forms of knowledge*, where Lundvall's *knowledge taxonomy is* presented and discussed. Two stylized innovation modes are presented and they are subsequently related to the technological specificity of FC&RHT.

The chapter is divided into two parts; the first theoretical, while the second part is an empirical description of the differing institutional set-ups in Denmark and Norway. The first part aims to explain and justify the usage of the technological systems and national systems of innovation as analytical frameworks, focusing on the importance of deconstructing learning and knowledge, using the taxonomies as analytical tools. The latter part makes use of these frameworks and tools, by filling them with the particular empirical realities on the ground.

4.1 Technological systems and national systems of innovation

The research question guiding the thesis is:

What role does learning play during innovation processes in the emerging hydrogen technological systems in Denmark and Norway?

Processes of knowledge flows can hardly take place without learning. Learning can therefore be understood as the dynamic factor, simultaneously embodying and releasing knowledge flows in the interaction between the actors of the emerging hydrogen technological system. These actors operate in an environment that can be characterized as the national system of innovation. Both technological systems and national systems of innovation shape and are shaped by the institutional set-up of the sector or nation that they are sprung out of. This means that learning opportunities and learning spaces can be constrained or promoted by conditions present in the institutional set-up of these systems. Therefore, the perceived institutional set-ups of Norway and Denmark are described in the last part of this chapter.

The systemic perspective on innovation is an analytical framework. A variety of frameworks, such as regional, national, sectoral systems of innovation or technological systems, are used by scholars. There seems to be a general agreement that the chosen framework depends on the object of study combined with the spatial circumstances and general context that surrounds it. Furthermore, different frameworks can be complimentary; i.e. it can be meaningful to use more than one framework if empirical realities suggest so (Carlsson et al, 2002). The cross-country comparative focus in conjunction with the subject matter of the present thesis justifies the utilization of two analytical frameworks, national systems of innovation and technological systems.

National systems of innovation have been defined by Lundvall in the following manner:

> The national system of innovation is a *social* system. A central activity in the system of innovation is learning, and learning is a social activity, which involves interaction between people. It is also a *dynamic* system, characterized both by positive feedback and by reproduction. Often, the elements of the system of innovation either reinforce each other in promoting processes of learning and innovation or, conversely, combine into constellations blocking such processes (Lundvall, 1992, p. 2).

The last sentence is especially important to consider. There is nothing to suggest that a national system of innovation somehow constitutes an optimal state, where knowledge flows freely and unhindered, promoting learning and innovation. Neither is a national system of innovation politically neutral; rather it reflects established power relationships, economic interests, the established paths and the overall structure of the economy. Therefore, it is useful to develop an awareness of the particular institutional set-up of the national system of innovation one operates in. This is particularly important for actors of the emerging hydrogen technological system, because without a well-developed sense of the surrounding institutional environment, the risk of pursuing futile innovation attempts increases. This is a theme in the next sub-chapter, where the meaning and importance of the institutional set-up is elaborated upon.

The national system of innovation approach is often used to describe and analyze broader tendencies within a national economy. In the context of this thesis, the emerging hydrogen technological system is regarded as one of many sub-systems, which make up the broader national system of innovation in their respective countries. This technological system has many linkages to other technological systems, locally, regionally, nationally and globally. The national environment is nevertheless very important when it comes to defining and delimiting the shape and scope of the technological system.

The hydrogen technological systems in Denmark and Norway are immature, emerging technological systems, developing within the national systems of innovation of each country. The national system of innovation clearly shapes the emerging technological system in various ways. National elements like government funding, research council guidelines and the general aspects of the judicial, political, economical and educational system influencing the existing industrial structure and the current energy infrastructure guide and delimit the scope and intensity of the emerging technological systems to a certain extent. These broad and overarching societal structures can be described as *institutions*. The importance of institutions for learning and innovation is discussed in the next section. This is grounded in a perception of the institutional set-up as essential for how national systems of innovation and technological systems either reinforce each other, to promote processes of innovation and learning, or on the other hand, block such processes. It is therefore a question of the role of learning in achieving institutional change in a desirable direction, i.e. the development of sustainable FC&RHT.

4.2 The institutional set-up

What is the meaning of the term institutions and why is the institutional set-up an important matter to consider?

In the context of this thesis *institutions* are understood with the *broader sociological meaning* of the term in mind. Johnson defines institutions as:

> sets of habits, routines, rules, norms and laws, which regulate the relations between people and shape human interaction. By reducing uncertainty and, thus, the amount of information needed for individual and collective action, institutions are fundamental building blocks in all societies" (Johnson, p.26, 1992).

Distinctions can be made between the softer, relatively informal and implicit nature of habits and routines, and the harder and more formal and explicit nature of rules, norms and laws. Institutions function as informational signposts, thereby reducing uncertainty. Without institutions, innovation and learning would be difficult to pursue, since one would have to navigate following an empty map.

Second; the reason why the institutional set-up is an important matter to consider is that interactive learning processes take place between actors or organizations within the national system of innovation, and within technological systems. In order to explain why this is important in a simple way, a distinction between institutions and organizations/actors can be made. This distinction can be expressed simplistically: Institutions are the rules of the game and organizations/actors are the players of the game. The national system of innovation, with the emerging hydrogen technological system as a subsystem, constitutes the playing field.

As in any game, the players can influence or interpret the rules in different manners. But the rules are also maintained and embodied by the organizations. The established way of playing the game, the rules, constitutes the heaviest influence on the organizations. There is a constant interplay between organizations and institutions in a country's institutional set-up and this is a major reason why concepts like national systems of innovation has been developed. Specific national contexts or institutional set-ups therefore effectively constitute the rules of the game.

This means that emerging technological systems face unique sets of barriers and opportunities for learning and innovation, because of the different institutions that shape the national system of innovation in a country. The emerging hydrogen technological system, a subsystem of the national system of innovation, is subject to a combination of rigidities and uncertainties. This means that the overall set of rules for the national system of innovation has been established, but that the rules of the emerging hydrogen technological system are more unstable and uncertain, therefore more susceptible to dynamic institutional change.

This is due to the *emerging* nature of the system, i.e. the uncertainty exists because the system is still relatively new to the world; to the economy and the society. There are, however, clear links to other institutions characterized by less institutional uncertainty. The most obvious example is the fact that a majority of the people involved in the emerging hydrogen technological system have an educational background either in engineering or in the natural sciences, or both. The actors, organizations and firms of the hydrogen technological systems in Denmark and Norway are found mostly within the energy sector, the machinery sector, the university and research institute sector, and to a lesser degree within the grassroots or environmental branches of the NGO-sector.

It can therefore be said that the established habits and routines of the people and organizations in the emerging hydrogen technological system constitute an important influence when it comes to shaping the emerging institutional set-up. Shared cognitive schemes create a certain perception of how things are done, or how they should be done, which influence organizational learning patterns. This means that a certain degree of institutional cohesion exists a priori, but that many uncertainties regarding how FC&RHT should be introduced into the wider society and economy remain.

The role of governments when incorporating new technologies has traditionally been one of coordination and sponsoring if the technologies in question are deemed to be desirable, as is the case with FC&RHT in Denmark and Norway. Both countries have hydrogen strategies on the state level, in addition to research programs distributing resources to FC&RHT innovation related activities.

There is a degree of *system openness*, which allows the actors of the organizations to influence the rules of the game, or the institutional set-up. A very specific example of this can be seen in the establishment of hydrogen strategies on the national level in Denmark and Norway. In both countries, the strategies have been written by representatives from government ministries[15], research councils and relevant industrial actors. These actors represent organizations that have from the outset been allowed to shape the institutional framework that their future activities within FC&RHT might be a part of.

There is substantial evidence of differing focuses, tendencies and drivers of change influencing FC&RHT learning and innovation in Denmark and Norway. This is related to the

[15] In Denmark: the Danish Energy Authority, the Ministry of Transport and Energy. In Norway: the Ministry of Petroleum and Energy & Ministry of Transport and Communications.

differing institutional set-ups and is of utmost importance if one wants to understand the related processes of *path dependency* and *path creation*.

4.3 Path dependency and path creation

Path dependency and path creation are interrelated processes, which function as selection mechanisms in the economy. The given path of an economy narrows the scope of available options, thus creating a dependency on earlier path choices. The term should be understood in an evolutionary context, where the term *path* equals development over time, while *dependency* creates limits for the creation of *variety*, which in turn influences *selection* processes. Dominant paths reflect the developments of the institutional set-up over time. Path dependency should be understood as a neutral term, describing the contingent nature of the past for the future. As Wicken points out:

> New paths interacts with old paths, and the interaction creates dynamic processes that may both transform old paths and sectors, as well as shape the new path in its emergence. This should be seen as an important element of long term transformation of the older paths that may result both in the disappearance of older sectors and paths, as well as revitalization of the older paths (Wicken, 2005, p. 2).

Wicken uses the term in a historical and evolutionary context, describing and analyzing the economic history of Norway.

In the text *Path Creation as a Process of Mindful Deviation*, (2001) Garud and Karnøe, consider the cognitive aspects of path creation, characterizing it as an intentional process, initiated by entrepreneurs:

> In our view, entrepreneurs meaningfully navigate a flow of events even as they constitute them. Rather than exist as passive observers within a stream of events we see entrepreneurs as knowledgeable agents with a capacity to reflect and act in ways other than those prescribed by existing social rules and taken-for-granted technological artifacts… entrepreneurs are embedded in structures that they jointly create and from which they mindfully depart (Garud & Karnøe, p.2, 2001).

This perspective attempts to simultaneously account for the dependency of path creation on past choices, i.e. path dependency, while also emphasizing the dynamics of intentional entrepreneurship. Garud & Karnøe aim to understand path creation in real-time from the viewpoint of the involved actors, the entrepreneurs. The terms path *dependency* and path *creation* reflect that scholars inspired by evolutionary economics put different emphasis on the importance of dependency versus creation, what unites them is them is the insight that these are interrelated processes that are heavily influenced by differing institutional set-ups.

Wicken argues that path creation only can be observed ex post, because it is dependent on a successful path dependency process (Wicken, 2005). Garud & Karnøe's understanding of path creation opens up the possibility that tendencies observable in the present point towards path creation. Identifying such tendencies should be a core focus for applied evolutionary economics, which aim to contribute to policy-making, both on the level of technological systems and on the level of the national system of innovation. An underlying goal of the present thesis is to identify such factors, and the cross-country comparative perspective is therefore used in order to detect tendencies and factors favourable to innovation, learning and, ultimately, path creation. This is therefore an effort of *applied evolutionary economics*, aiming to contribute positively to the generation of knowledge on the role of learning in innovation processes in general, while also facilitating the utilization of this knowledge to the involved actors in Denmark and Norway.

The discussion on path dependency and path creation is continued in the sub-chapters 4.7 and 4.8, focusing on the differing Danish and Norwegian institutional set-ups, and the possible implications these differences might have on the role of learning and innovation of the emerging hydrogen technological systems. But in order to conduct a meaningful analysis on knowledge and learning, knowledge has to be conceptualized, distinguishing between different kinds of knowledge.

4.4 The learning economy & forms of knowledge

Lundvall proposed that the current economy is a learning economy. In order to understand what he means by that statement, Lundvall's knowledge taxonomy is presented and defined, because of its usefulness as an analytical tool.

It is important to recognize the distinct meanings of the terms information and knowledge. Information is knowledge that can be made explicit in a codified form. This type of knowledge can be transmitted in various ways; through books, papers or computer networks. Other parts of knowledge can only be attained through learning processes characterized by active, personal participation, often in a social setting. This type of knowledge is tacit rather than explicit, meaning that one might know how to do something without being able to explain how to do it. It has to be learnt either by doing, using or interacting.

Lundvall gives two reasons to utilize the term learning economy:

> First, it helps us to avoid an analysis where the focus is only on the institutions aiming directly at producing and distributing knowledge (schools, universities, R&D laboratories etc.) to the exclusion of routine-based learning…Second, currently, there is a special need to focus on how economic structures and the institutional set-up affect the process of learning (Lundvall, 1995, p. 3).

The second reason sums up the rationale behind the research question, and the underlying goal of identifying factors beneficial to path creation. But in order to understand the role of learning, one must operate with some kind of knowledge taxonomy. Lundvall proposed the following:

Box 2: Knowledge taxonomy (Based on Lundvall, 1995, pp. 4-5)

Form of knowledge	**Characteristics**
Know-what – Knowledge about facts, factual information. *Know-why* – Scientific knowledge about the principles or laws of nature, of the human mind or of the society. The production and reproduction of know-why is often organized in specialized organizations, such as for example universities.	Primarily explicit or codified knowledge. Easier to transfer. STI-mode. Global knowledge
Know-how – Skills or the capability to do something. Know-how is typically a kind of knowledge developed and kept within the border of the individual firm. But as the complexity of the knowledge-base is increasing, a mix of a division of labour and cooperation between organizations tend to develop. The need for firms to be able to share and combine elements of know-how is one of the most important rationales for participating in industrial networks or initiating inter-organizational relationships. *Know-who* – Social skills involving knowledge of who knows what and who knows how to do what. The competency involved in forming special social relationships, utilizing common codes of information, can be characterized as relational knowledge or learning.	Primarily tacit knowledge rooted in practical experience. More difficult to transfer. DUI-mode. Local knowledge.

The knowledge taxonomy implies that know-what and know-why are easier to transfer, and thus they are also more accessible to a wider range of actors. Know-how and know-who are usually more internal to an organization, a firm, or an industrial network. The mix of trust, common routines and shared cognitive schemes can be termed organisational competence, which might be required if know-how and know-who are to become critical features of well-functioning innovation networks. Short social, cultural and geographical distances between the members of industrial networks might contribute to successful learning processes and innovation (Berg Jensen et al, 2005). These notions will be examined empirically in chapter 5, utilizing the knowledge taxonomy above.

4.5 Modes of innovation and learning

The distinctions between modes of innovation and learning serve, as was the case with the knowledge taxonomy, to order a complex field of knowledge production, diffusion and utilization. It is taken for granted that the forms of knowledge described above, and the modes of innovation and learning described below, rarely can be seen to operate in their pure forms. But the categories function as useful focusing devices, providing links between the theoretical parts of the thesis, to the empirical parts. They are analytical tools, illuminating the complex role of learning and innovation within the emerging hydrogen technological system in Denmark and Norway.

Box 3: Modes of innovation and learning (Based on Lundvall, 1995, p. 4-5)

Mode of innovation and learning	**Characteristics**
STI-mode of innovation and learning. (*S*cience *T*echnology *I*nnovation) Knowledge policy as science policy.	Formal R&D processes. May start with a combination of ‘local’ and ‘global’ knowledge, but will mostly result in ‘global’ knowledge. Example: Patents.
DUI-mode of innovation and learning. Learning by *D*oing, *U*sing and *I*nteracting) Knowledge policy as promoting learning organisations and networking.	Involves interaction within and between teams, may result in new shared routines. Learning by doing and using primarily result in ‘local’ knowledge. Example: Know-how

Within the context of the organizational structure of large firms, it is clear that departments might put different emphasis on the two modes of learning. The R&D department might mainly base its activities on the STI-mode, while the departments of production and marketing might be more characterized by the DUI-mode. This is also relevant in the setting of the emerging hydrogen technological system, because different actors put different emphasis on the different modes, partly because of differing technological focuses within the larger spectrum of interrelated and complimentary FC&RHT. Whatever the mix of learning and innovation-modes, it is essential to link them in an efficient manner, so that they serve to complement, rather than contradict, each other (Berg Jensen et al, 2005).

The centrality of learning is emphasized here since the matter of inquiry in the thesis is how learning manifests itself in the innovative processes of the emerging hydrogen technological system in Denmark and Norway. Background research suggests that there are significant and interesting differences in the way innovation in the emerging hydrogen technological system is focused and organized. These differences can be illustrated schematically:

Box 4: Summary of contrasting characteristics between the emerging hydrogen technological systems in Denmark and Norway

Denmark	**Norway**
Main focus: Fuel cells/Fuel cell systems	Main focus: Hydrogen production, storage and distribution
Small and medium sized companies. Core competency: System integration	Mainly large companies. Core competency: Exploitation & distribution of natural resources (Oil & Gas)
Near first commercialization attempts	Mainly pre-commercial (Except Hydro)
Market focus	Research focus
Dominant tendency: DUI-mode of innovation and learning (Learning by Doing, Using and Interacting)	Dominant tendency: STI-mode of innovation and learning (Science Technology Innovation)
Dominant cognitive scheme: Bricolage	Dominant cognitive scheme: Breakthrough

These characteristics has functioned as a *basis for inquiry*, and influenced the construction of questions in the interview guide (see appendix A). In the next part of this chapter, these contrasting empirical characteristics are described further, and linked to the overall theoretical framework described above. The terms bricolage and breakthrough, indicating cognitive schemes, are also defined and elaborated upon in the next two subchapters.

4.6 The technological specificity of learning in the case of FC&RHT

It is important to keep in mind that there are real technical difficulties that need to be overcome before FC&RHT can contribute positively and significantly to the larger energy system. For fuel cells systems, important technical problems involving reliability, energy losses in conversion processes, expensive and/or poor materials need to be addressed and solved if fuel cells shall become commercially and environmentally viable. Likewise, for hydrogen, the energy losses associated with production, conversion, storage and distribution remain; if these are not reduced, it is quiet unlikely that hydrogen will make any major impact in the energy system of the future.

Solving some of the problems confronting FC&RHT will in all probability necessitate advances in basic scientific knowledge, which partly justifies the STI-mode of innovation and learning. Solutions to other problems might benefit from what is usually termed incremental innovation; the small and gradual improvements associated with the DUI-mode. It is valid to ask if Danish and Norwegian actors can solve the multiple problems confronting FC&RHT by just pursuing stylized versions of the DUI-mode or the STI-mode single-handedly. The technology specific character FC&RHT mean that there are no ready-made answers to this question; each new technological system is confronted with a unique set of challenges and opportunities. This means that models or modes of innovation derived from successful innovation processes are *not automatically transferable* to other technologies, they have to be reconsidered and remodelled considering the unique context facing each new technology.

Solutions to problems will therefore also need to address the specific and particular nature of the institutional set-up. In addition to the technical problems, a multitude of what might be termed economic and institutional problems remain before FC&RHT can diffuse to the wider economy and society. These problems are found within the institutional set-up of each country. In order to solve these problems, there is an urgent need to understand the institutional set-up.

4.7 The institutional set-up of Denmark

When it comes to renewable energy technologies, Denmark has an outstanding position. A striking example is the leading position of the Danish wind mill manufacturing industry, which has a world market share of around 40 % for land based wind mills, and 90 % for ocean based wind mills. The Danish Ministry of Economic and Business Affairs mapped what they call the environmental cluster in Denmark. They conclude that this cluster consists of 420 companies, 46 knowledge institutions and employs around 60 000 people, making it one of Denmark's largest business clusters.[16]

These figures are presented in order to conduct a discussion on path dependency and path creation. Both of these terms should be understood in a spatial and temporal sense. The early 70s, when the world experienced the first oil crisis, signalled the start of what may be called

[16] http://www.mst.dk/default.asp?Sub=http://www.mst.dk/udgiv/publikationer/2006/87-7052-075-5/html/helepubl.htm (16.8.06)

modern renewable energy technologies. Wind, solar and bio-energy are probably the most well-known. A relevant question is how Denmark achieved a leading position.

Denmark is a small country; distances are short geographically and socially. There is a strong tradition of grassroots involvement and influence. The situation in the early 70s arose out of two concerns; the oil crisis and opposition to nuclear power. The coalition of anti-nuclear and pro-renewable grassroots organizations started a unique development path. Not content with just being anti-nuclear, a wide variety of actors started to develop alternative energy technologies. Cooperative efforts were made by independent researchers, practically minded inventors and grassroots organizations (Beuse et al, 2000).

This was a process of path creation, as understood by Garud & Karnøe. The entrepreneurs in the Danish case, however, were not typical businesspeople. The words network or movement better capture the essence of the group of Danish entrepreneurs and innovators. The variety of actors supporting and working towards a common and broadly defined goal; sustainable development, managed to develop a new path, by mindfully and intentionally deviating from the established view that the future of energy equalled nuclear energy. This suggests that:

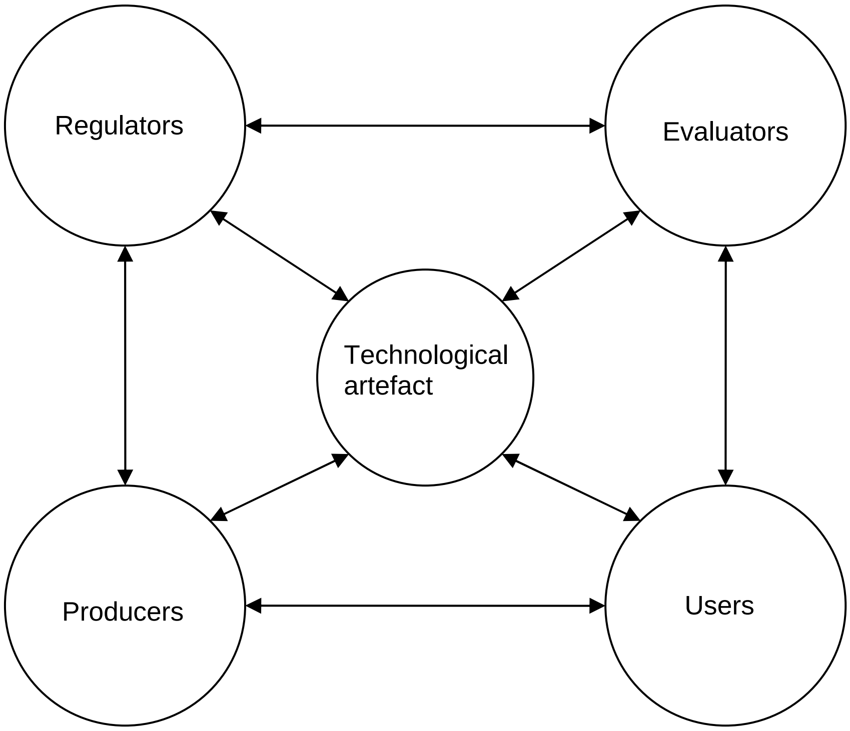
> The accumulation of inputs from multiple actors generates a momentum that can harness the inputs of distributed actors. As it gains momentum, the emerging path begins enabling and constraining the activities of involved actors (Garud & Karnøe, 2003, p. 278).

The quote above is taken from the article *Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship* (Garud & Karnøe, 2003) and describes, compares and analyzes the innovation processes that lead to the emergence and diffusion of wind turbines in Denmark and the United States. In the case of wind turbines, the innovative and pre-commercial phase took place in the period 1974-80, while the industrialization phase ensued from 1980 onwards. FC&RHT is still in the innovative and pre-commercial phase, since few products have been marketed and no dominant designs have emerged.

The term *bricolage* is used to characterize the Danish innovation processes that resulted in the development of the dominant wind turbine design.

“Bricolage was characterized by co-shaping of the emerging technological path as actors in Denmark sought modest yet steady gains. In contrast, actors in the US pursued a path that we label as breakthrough” (Garud & Karnøe, pp.278-279, 2003). Bricolage is understood here as a cognitive scheme, as indicated in Box 4. Bricolage emphasizes adaptiveness and the small but gradual stepping stones that lead forward on the innovation journey. There are indications that similar processes of co-shaping of technology are evident in the emerging hydrogen technological system in Denmark, and this is investigated further in the next chapter, which is based on interviews. The arrows in the following figure attempts to describe the learning flows between the Danish agents involved in the emergence of the modern wind turbine:

Figure 1: Bricolage: Distributed agents involved in the emergence of a technological path
Based on: Garud & Karnøe, 2003, pp. 277–300

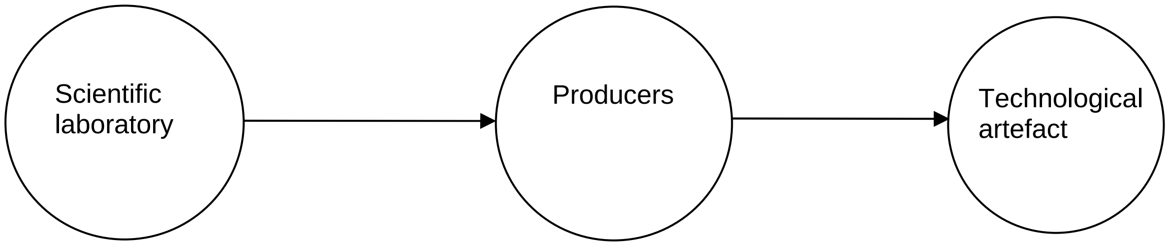


Knowledge and learning was characterized by widespread interaction. There is a notable absence of science in this figure. Wind mill technology was not an essentially novel innovation, since earlier versions of wind mills had been produced in large quantities in Denmark during the period 1860-1960. There was therefore not an urgent need to develop new basic scientific knowledge during the innovative phase of the modern wind mill. All the major ingredients were basically developed; it was a matter of improving the parts and the whole of the technology incrementally, not to utilize new scientific knowledge. This is important, because as discussed in sub-chapter 4.6, FC&RHT differs in this respect.

The cognitive scheme breakthrough (see Box 4), on the other hand, likens innovation processes to a series of sudden and major leaps, which instantly and dramatically reach the objectives of the innovators. Breakthrough resembles linear models of innovation, depicting innovation as a one-way street, where knowledge flows start with science and ends up with a marketable technological innovation. This was the approach chosen by the American wind mill innovators, who ended up with being beaten by the less scientifically sophisticated Danes. The following model visualizes breakthrough:

Figure 2: Breakthrough: Distributed agents involved in the emergence of a technological path

Based on: Garud & Karnøe, 2003, pp. 277–300



The one-way character of the learning arrows show how there was an expectation of scientific breakthroughs to function as causal mechanisms, triggering production of a marketable technological artefact, in this case wind turbines. This approach failed, probably because it adopted a strategy that failed to account for the technology specific character of wind turbines. The influence of this cognitive scheme on the Norwegian hydrogen strategy is discussed in the next subchapter. The two figures presented above are constructed versions of innovation approaches benefiting from the privilege of the historian, i.e. it is clear what happened; the Danes won and the Americans lost. In the case of FC&RHT, however, outcomes are highly uncertain since this technology is still in the pre-commercial phase, where no dominant designs have evolved. The figures are therefore stylized representations of distinctly different innovation and learning approaches that function as cognitive schemes. It is taken for granted that they rarely operate in their pure and stylized form, but the figures serve to order and visualize thought patterns underlying innovation and learning.

The existence of a renewable path is an important part of the Danish institutional set-up, influencing the emerging hydrogen technological system. This path has received considerable political support since the early 80s. A shift of this favourable attitude towards the renewable energy path coincided with the rise to power of the current Danish government in 2001. Within the first hundred days in power, Fogh Rasmussen's right-wing government cut funding of renewable energy technologies drastically. The rationale for this decision was that Denmark already had reached or superseded the projected goals of installed renewable energy, and the ideological conviction that commercial companies should stand on their own feet, without being dependent upon government subsidies.[17]

In the context of pre-commercial renewable energy technologies, this decision had a striking impact. Many actors and organizations lost their funding. A pre-commercial and emerging technological system is naturally very dependent on external funding, without which little innovative activity can be carried out. The decision to withdraw funds hit the independent knowledge institutes and smaller firms the hardest, while established industrial actors suffered a less severe drawback.

In the specific case of the emerging hydrogen technological system, which primarily consists of small or medium-sized firms, universities and knowledge institutes, it meant that other sources of funding had to be searched for. Some local government sources, in particular Ringkjøbing amt, have stepped in as an important actor supporting FC&RHT in Denmark.

[17] http://www.ft.dk/Samling/20012/spor_sv/S1087.htm (16.8.06)

Despite these rather recent setbacks, the renewable energy path is growing and remains strong in an international comparison. The absence of nuclear energy and the dwindling share of fossil fuelled energy consumption[18] in Denmark means that most actors of the emerging hydrogen technological system envision the renewable scenario of the hydrogen economy, steering their learning and innovative activities towards that scenario. This is also stated in the national hydrogen strategy:

> The overarching and long-term goal is that Denmark develops and demonstrates efficient and competitive technologies and systems, where hydrogen – primarily based on renewable energy – can be integrated as energy carrier in a clean, efficient, and reliable energy supply system and that Denmark becomes among the best internationally.[19] (Author's translation)

The importance of the national strategy should not be exaggerated, since some of the most important actors have plans of their own that remain largely unaffected, either because of their own financial strength or other sources of financing. But to many of the minor actors, like independent inventors, grassroots technology developers and smaller firms, who are much more dependent on public funding, the already formulated strategy might mean that their exclusion becomes permanent, not temporary. To counter this exclusionary mechanism, the Nordic Folkecenter for Renewable Energy, one of the most important excluded actors, has sought other forms of financing. To be able to update its hydrogen filling station and participate in the Danish hydrogen transportation network Hydrogen Link[20], the centre has

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[18] http://www.ens.dk/graphics/Energi_i_tal_og_kort/statistik/aarsstatistik/Statistik2004/Energistatistik_2004.pdf (16.8.06)

[19] http://www.ens.dk/graphics/Publikationer/Energiforskning/Brintteknologier_juni_2005/pdf/Rap_Brint_Strategirapport_V9.pdf - (16.8.06)

[20] http://www.hydrogenlink.net/dk/hydrogenlink/ (20.9.06)

received funding from the local Viborg county and the EU[21]. This shows how changing funding conditions alters the institutional set-up. Instead of applying for research money from national level agencies, regional and supra-national levels are utilized for this purpose.

The regional focus is also evident in the bustling activity of small and medium-sized hydrogen related firms that have formed a network. The nodes in this network are the Danish Hydrogen Association (DHA)[22] and HIRC[23] (Hydrogen Innovation & Research Centre), situated in Herning, Ringkjøbing county, Jutland. These two organizations were formed in 2004, but have already participated in a number of RD&D projects and assumed a position as network coordinators. They are characterized by having a very self-conscious attitude towards their own innovation effort. The annual DHA conference in 2006 was entitled *Network & Competencies* and featured the inauguration of a hydrogen demonstration area, in which associated firms and knowledge institutes present their activities in the form of technological artefacts, multimedia presentations, text posters and folders.

HIRC are also active promoters and developers of niche applications. The term *system integration* is a key to understand how a substantial amount of Danish actors see their own role in the development of fuel cell *systems*. They regard themselves as having a comparative advantage in system building and integration. They aim to design, build and commercialize fuel cell technology by integrating this technology either in existing technology, or in novel niche applications, which they consider to be immediate commercialization opportunities for Danish firms.

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[21] http://www.thisted-dagblad.dk/apps/pbcs.dll/article?AID=/20060816/THISTED/108160159/0/thisted&SearchID=73253953746653&sectioncat=thisted (6.9.06)
[22] http://www.danishhydrogen.com/ (23.8.06)
[23] http://www.hirc.dk/ (20.9.06)

Technological niches might allow for learning processes to take place. As Kemp et al. note:

> Niches are important because they facilitate processes of learning (about the technology and the market) and processes of societal embedding (capital formation, the set up of distribution, dissemination of knowledge, gaining of user acceptance, etc.) that are necessary for the further development of new technology or technology system. Niches help to create virtuous cycles that allow a new technology to escape lock-in, by helping the technology to overcome initial barriers of high costs, the non-availability of complementary technologies and the non-alignment of a new technology when it has not yet benefited from dynamic scale and learning economies (Kemp et al, 1999, p.10).

The Fuel Cell Power Shaft Pack[24] consortium represents focused niche development. It was initiated by HIRC and aims to present the first serially produced fuel cell engine within three years. This engine is meant to replace electrical, diesel and petrol-driven engines used in bikes, smaller trucks and mobile work tools. Benefits such as longer operating hours and less weight, noise and pollution has been identified as commercial reasons to exploit this niche application. The consortium consists of eight diverse machinery production firms, HIRC, Copenhagen Business School, Technological Institute and the Institute for Energy Technology at Aalborg University.

As mentioned before, the renewable energy path in Denmark is unique in an international comparison. But, an interesting aspect is that this path both originated in, and is concentrated in Jutland. This realization has inspired lobbying activities in the form of a think tank, promoting the new region Central Jutland as a renewable energy hub, focusing on FC&RHT, wind- and bio-energy technologies[25]. This is an indication of the willingness of actors to promote their activities and manifest their interests politically, in an effort to secure and

[24] http://www.fc-spp.dk/ (8.9.06)
[25] http://www.hirc.dk/Default.aspx?ID=161 (6.9.06)

increase future funding, while simultaneously increasing public awareness of the environmental and economic benefits of renewable energy technologies.

The collaborative attitude of the actors associated with HIRC and DHA reflects the term bricolage as cognitive scheme. Collaborative learning and co-shaping of technology seems to have become an institutionalized form of innovation in the Danish setting. DUI-learning and innovation has traditionally been a major characteristic of industrialization processes in Denmark, and this mode of innovation seems to be compatible with FC&RHT, an area where the STI-mode of innovation might be assumed to dominate, because of the perceived complexity of the technology. This will be further investigated in chapter 5, which is based on the interviews.

4.8 The institutional set-up of Norway

The most striking feature of the Norwegian economy is the dominance of oil and gas related income. In 2004, the petroleum related activity accounted for 47 % of the Norwegian export value, which equalled a 28 % share of the state's income.[26] Norway is the world's third largest exporter of fossil fuels, in the form of oil and gas, which explains the huge impact on the country's economy. Another striking feature is the amount of installed renewable energy, in the form of hydropower, which supplies almost all electricity in Norway.[27]

Some of the most important actors within the emerging hydrogen technological system in Norway are found within the oil and gas sector. Large companies like Norsk Hydro and Statoil are partially owned by the state. There are therefore very strong links between the state

[26] http://www.odin.no/filarkiv/243684/Miljo_05_norsk.pdf (16.8.06)
[27] http://www.odin.no/filarkiv/250119/Fakta_EV_05_kap.02.pdf (16.8.06)

and the oil sector, a relationship that developed during the second half of the 20th century. The oil related community of powerful business and political elites managed to shape research policy, energy policy and credit policy in order to strengthen and reinforce their own development, effectively designing, implementing and maintaining the institutional set-up of the fossil fuel dependent companies (Wicken, 2005).

The fossil fuel path has been hugely beneficial to Norway in financial terms. The country is considered to be an example to follow for other resource rich countries. Norway has avoided falling into the traps of fossil fuel dependency, such as heavy corruption, irresponsible public spending or devastating environmental degradation. Nevertheless, an environmental opposition emerged during the 80s[28]. This opposition initially took a confrontational stance to the fossil fuel path, but gradually developed an attitude of cooperation and therefore initiated partnerships with the fossil fuel companies. The rationale behind this strategic choice seems to be a conviction that can be summed up as *if you can't beat them, join them*; in the hope of gaining influence on the future direction of the fossil fuel sector and the larger energy system.

There are a few important examples of environmental NGO/fossil fuel alliances in the emerging hydrogen technological system. ZERO[29] and Bellona are important actors of the HyNor[30] partnership, whose principal actors are Norsk Hydro and Statoil. This project has received considerable media exposure, and might be the most visible hydrogen related demonstration project in Norway. The role of ZERO is mainly as a source of knowledge. They have a homepage where they publish their own reports and related news. In addition to

[28] The environmental NGO Bellona is the best known example. http://www.bellona.no/ (8.9.06)
[29] Zero Emission Resource Organization, an environmental NGO committed to work against climate-change, by promoting non- or low-polluting alternative technological choices. http://www.zero.no/ (8.9.06)
[30] HyNor is a Norwegian demonstration project, encompassing 40 partners from firms, NGOs, research institutes and the public sector. It promotes the use of hydrogen within the Norwegian transport sector by building a hydrogen infrastructure connecting Oslo and Stavanger.

this, they organize workshops and act as promoters of their stated goals. Like Bellona, they work as mediators of knowledge, connecting and lobbying actors, interpreting and mediating knowledge from different contexts (Kristiansen, 2001). They do not, however, contribute with any innovation efforts geared towards practical technology development.

The three most recent Norwegian governments have been supporters of renewable energy in theory, but not in practice. Public funding of fossil fuel research is growing steadily and receives 400 million kroner next year, while renewable energy funding remains at 170 million kroner. The national research council of Norway (NFR) has received criticism for not implementing the intentions of consecutive governments on this matter. The administrative director of NFR, Arvid Hallén points his finger back at the ministries when asked of NFR's priorities in July 2006. "There has been an understanding between the Research Council (NFR) and the Ministry of Petroleum and Energy that there has to be built a large, publicly controlled research effort on petroleum[31]" (Author's translation). This 'understanding', combined with available figures[32] on research on petroleum and renewable energy, indicates that the alliance between the fossil fuel sector, the Ministry of Petroleum and Energy and the NFR remains strong, thus ensuring the institutional viability of the fossil fuel path.

It might be argued that the self-reinforcing power of this path has become so strong, that a *lock-in* situation has been created, steering the fossil fuel path further into dependence of natural resources, by developing ever more sophisticated exploitation techniques, of which CO2 sequestration is one, since injection of CO2 into oil and gas reservoirs contributes to

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[31] http://www.klassekampen.no/kk/index.php/news/home/artical_categories/nyheter/2006/july/olje_for_alle_pengene (22.8.06)

[32] NFR's principal petroleum research program Petromaks has received an increase of its funding by 184 % since 2003, while the principal research program on renewable energy RENERGI, has increased it funding by 2.5 % in the same period: http://www.klassekampen.no/kk/index.php/news/home/artical_categories/nyheter/2006/august/hard_kritikk_av (8.9.06)

increased pressure, which leads to enhanced oil recovery[33]. The fact that state funding of petroleum research only constitute a minor part of the total research budget within this area, makes the poor funding of renewable energy even less comprehensible. For research efforts within renewable energy technology, funding is a question of existence. For petroleum research, the state financed 400 million of the total budget of 4.4 billion kroner, constitutes a minor share, less than 10 %[34]. The majority of financing comes from private sources. The effect is that the state, through NFR, helps actors that could do without help, while not supporting the research efforts of the renewable actors substantially. This is ironic, since they are the ones that might create a new path, providing growth opportunities today, but more importantly, in the future, when fossil resources run dry.

The position of the emerging hydrogen technological system is interesting in this respect. Since fossil fuel actors are heavily involved in this system, it seems that they have managed to leverage their considerable influence what regards funding. RENERGI, NFR's main program promoting clean energy, doubled hydrogen funding between 2004 and 2005. It amounts to 39.3 million kroner, or 31 % of the total RENERGI budget[35]. It is not surprising, considering the entangled nature of politics, research and the fossil fuel sector, that the Norwegian hydrogen strategy promotes the second scenario of the hydrogen economy; the use of reformed and CO2-sequestrated natural gas to produce hydrogen:

> There are especially four circumstances that justify a Norwegian effort on hydrogen:
> - Exploit Norwegian natural gas resources

[33] http://www.zero.no/fossil/co2/teknologi/lagring/typer/20040813-16 (8.9.06)

[34] http://www.klassekampen.no/kk/index.php/news/home/artical_categories/nyheter/2006/july/olje_for_alle_pengene (22.8.06)

[35] http://www.forskningsradet.no/servlet/Satellite?blobcol=urlvedleggfil&blobheader=application%2Fpdf&blobkey=id&blobtable=Vedlegg&blobwhere=1146561029905&ssbinary=true (8.9.06)

- Industrial development
- Environmental benefits, particularly within the transportation sector
- Participation in the frontline of international research[36] (Author' translation)

The connection between hydrogen, natural gas exploitation, CO2-sequestration technologies and the political goal of complying with the Kyoto protocol has been a heavy influence on the Norwegian hydrogen strategy. The hope is to achieve multiple goals simultaneously; increased value of natural gas, innovation and value creation within CO2-sequestration technologies creating a new path, and the positive environmental impact of hydrogen powered vehicles within the transportation sector, enabling Norway to reduce its emissions of CO2.

An important weakness of the strategy, however, is that there is an implicit, but not explicit presumption that hydrogen will eventually replace the current transportation infrastructure. This is a highly contested claim. In the article *The car and fuel of the future*, Romm discusses alternative fuel vehicles (AFVs):

> It is possible we may never see a durable, affordable fuel cell vehicle with an efficiency, range, and annual fuel bill that matches even the best *current* hybrid vehicle. Of all AFVs and alternative fuels, fuel cell vehicles running on hydrogen are probably the least likely to be a cost-effective solution to global warming, which is why the other pathways deserve at least equal policy attention and funding (Romm, 2005).

The objective of achieving positive environmental effects is based upon a hope that international actors will supply the needed technology in the form of commercially viable and competitive fuel cell vehicles. This is as indicated a highly uncertain presumption. Likewise, the focus on becoming a major future supplier of hydrogen and electrolysis equipment for

[36] http://odin.dep.no/filarkiv/256289/Hydrogenstrategi.pdf (22.8.06)

hydrogen gas stations rests on the hope that hydrogen powered vehicles utilizing fuel cells might achieve a *breakthrough*, and become widely used in the future. This dimension is elaborated upon in the strategy:

> Use of hydrogen in Norway is dependent upon international technology development, while Norwegian developed technology is dependent of utilization in an international hydrogen market…It is not given that, or when, a breakthrough for hydrogen as an energy carrier will come – it will in any case be far ahead in time. It demands several technological breakthroughs and considerable public support.[37] (Author's translation)

While this quote can be seen as evidence of a cautious and sober outlook, which takes global supply- and demand-chains into account, it also describes technology development as involving a series of linear breakthroughs, generating dramatic outcomes that are possible to pinpoint in time. Breakthrough as a cognitive scheme is a salient feature in innovation processes characterized by STI-innovation (see Box 4 and Figure 2). The STI-innovation mode entails a linear model of innovation, meaning that basic scientific research is thought to precede applied technology development, utilizing mainly the science-based know-what and know-why types of knowledge, resulting in a bias towards scientific research-driven innovation processes (Kline & Rosenberg, 1986).

The establishment of the national hydrogen platform is influenced by the STI-mode. "The majority of the activities within the platform will be tied to research and development. Technological breakthroughs and new knowledge of a formative character is a prerequisite for hydrogen to achieve leverage as an energy carrier"[38] There is an implicit presumption of that the decisive inputs into the 'black box' of innovation will emanate from new scientific knowledge, resulting in a focus on scientific research and development, while the elements of

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[37] http://odin.dep.no/filarkiv/256289/Hydrogenstrategi.pdf (29.8.06)
[38] http://odin.dep.no/filarkiv/256289/Hydrogenstrategi.pdf (29.8.06)

DUI-innovation are largely left out, even though demonstration projects are mentioned. This reflects the Norwegian focus on creating large infrastructural value-chains based on natural gas>hydrogen>transportation. It is correct that there is a real need for new basic scientific knowledge if such a value-chain shall become viable. Considering this, it is a worrying sign that the strategy does not mention the considerable energy losses associated with the hydrogen energy chain, since these represent fundamental challenges that need to be overcome if hydrogen shall be considered to be a cost- and energy-efficient sustainable energy carrier in the long run.

The strategy also suffers from a lack of focus on niche applications, where FC&RHT could become viable in the short term. Niches open up learning spaces, where innovations can be tested and developed. These are characterized by a high degree of DUI-innovation and learning, emphasizing know-how and know-who forms of knowledge.

Norsk Hydro's Utsira project is an example of niche development where dynamic learning processes might take place. The Utsira project consists of two windmills that are connected to an electrolyser, which produces hydrogen. The hydrogen is stored, and can be utilized during periods of windmill inactivity to supply electricity to ten households on the small island of about 200 inhabitants, thereby including user-producer interaction in the innovative process. The obvious goal has been to test a stand-alone system that can function independently of a grid connection, supplying electricity to isolated places where the costs associated with grid connection are high. The German firm Enercon built the windmills, while the Danish firm IRD built a gas engine and a fuel cell system[39].

[39] http://www.hydro.com/no/press_room/news/archive/no_news_view/hydrogen_iceland/utsira_fakta_no.html (13.9.06)

On Utsira, Norsk Hydro is testing a novel application based upon combining a mature renewable energy technology, in the form of wind power, with an emerging one: FC&RHT. The commercial niche of this project is clearly defined; decentralized wind/hydrogen solutions aimed at isolated islands or other remote places where the cost of grid connection is high. The project can therefore benefit from synergetic effects because of the linkages to the windmill sector which has experienced double-digit growth during the last fifteen years, and to fuel cell producers (Jacobsson & Lauber, 2006). These linkages intensify collaborative interaction between producers, who utilize DUI-learning to merge two technologies in order to create an innovative hybrid system. Such co-shaping of technology is characteristic of bricolage as a cognitive scheme.

The HyNor project is a demonstration project meant to create a learning space for the development of hydrogen gas station equipment, such as electrolysers producing hydrogen locally or hydrogen storage units. While there are possibilities for learning in that area to occur, important linkages to producers of fuel cell vehicles seem to be largely absent. Brage Johansen, manager of Statoil's hydrogen department was interviewed by Aftenbladet.no on the non-existence of competitive fuel-cell cars40 "We are dependent upon a breakthrough of the fuel cell. It is too expensive today, and its lifespan is too short. When a new Henry Ford appears, and that will happen in the course of five years, this will change"41 (Authors translation and italics).

The projected goal, a demonstration infrastructure for hydrogen powered vehicles, is dependent upon the willingness and capability of fuel cell car producers to introduce such vehicles. In this case it is difficult to see how the HyNor project can influence the direction throughout the whole innovation effort to reach this goal. The HyNor project might therefore

[40] The HyNor project utilizes rebuilt versions of the electric/internal combustion engine hybrid Toyota Prius, where the internal combustion engine is converted to hydrogen.
[41] http://web3.aftenbladet.no/innenriks/okonomi/article334428.ece (25.8.06)

only be capable of reaching a limited number of stepping stones or learning spaces, unless competitive fuel cell cars materialize. The lack of linkages to producers and suppliers of fuel-cell cars might prevent synergetic DUI-learning processes to occur. The cognitive scheme of breakthrough is expressed as a hope that things will change as a consequence of other innovator's potential eureka moments, even though bricolage is evident in the collaborative design of the project. The role of learning in this project might therefore be limited to hydrogen production, storage and distribution, which is not to be sneered at, but it essentially amounts to duplicating the CUTE42 and ECTOS43 projects, where Norsk Hydro has already participated. In those projects, however, there were close linkages to Daimler Benz44, a developer and producer of fuel cell buses. Duplication of an innovation effort in a new context is however an example of technology transfer, which ideally provokes DUI-learning processes, and possibly innovation in the future.

Statoil also has a focus on niche applications. The company recently initiated a joint venture with Swedish heavy truck maker Volvo to produce auxiliary power sources based on fuel cells for heavy vehicles. Auxiliary power is used to provide heat and electricity in truck driver's onboard sleeping quarters. Currently, such trucks either run idle or utilize small diesel generators for the same purpose, emitting substantial amounts of pollutants.

To sum up, the institutional set-up of Norway is dominated by the fossil fuel path. There are tendencies that this has created a lock-in situation, constraining and blocking the overall focus and funding on renewable energy. This shapes the innovative efforts within the emerging hydrogen technological system, since many of the most important actors are fossil fuel companies. While not suggesting that a small country like Norway should focus on developing all aspects of FC&RHT simultaneously, there seems to be some evidence of

[42] Clean Urban Transport for Europe
[43] Ecological City Transport System
[44] http://www.daimlerchrysler.com/dccom/0-5-7145-1-596003-1-0-0-0-0-0-9-0-0-0-0-0-0-0-0.html# (30.8.06)

breakthrough as a cognitive scheme, as seen in the national hydrogen strategy, and in the design of the HyNor project. This shapes learning and innovation activities, insofar as a number of breakthroughs for FC&RHT in the transportation sector function as an implicit prerequisite for innovation efforts. The energy loss problem is not mentioned in the strategy, even though it appears marginally in the Norwegian public exposition preceding the strategy.45 Innovation efforts are therefore vulnerable, since they are highly dependent of the breakthroughs of related technologies, in this case fuel cell cars. Vulnerability is of course almost inevitable since FC&RHT are interdependent technologies, but a critical scrutiny of the hydrogen energy chain would reduce such vulnerability and uncertainty considerably.

There are also exceptions to this trend, like the Utsira project, which demonstrates the ability of a large actor within the fossil fuel path, to design an innovation environment characterized by less uncertainty, and a high degree of overall control of project design and outcome. The same can also be said of the Statoil/Volvo joint venture. These two projects represents technological niches that are more appropriately described by the terms bricolage and DUI-learning, considering the multiple inputs of actors working and interacting to reach a common and defined goal.

5. THE INTERVIEWS

The interviews offered an opportunity to let the informants elaborate on their perception of learning and innovation processes and the institutional set-up. They also provided insights into ways of thinking and talking about FC&RHT that would have been very difficult to obtain in any other setting apart from inter-personal interviews. This specificity might be up for criticism because of its lack of generalizability. It is a valid criticism, but misses the point.

[45] Hydrogen as the energy carrier of the future. http://odin.dep.no/filarkiv/211298/NOU0404011-TS.pdf (20.9.06)

This is an exploratory effort, aiming specifically to generate questions on conflicting views and interests, different cognitive schemes, or similarities of interest. The open-ended approach was based on an interview guide (see appendix A), but the structure of the interviews was loose, more like an informal exchange of views. Quotes will be used extensively, and they will be linked with the theoretical concepts of the last chapter, in order to be able to conduct a meaningful analysis in chapter 6.

The research question focuses on the role of learning during innovation processes. It might seem obvious that learning is essential, but based on what kind of knowledge and innovation mode? And which goals guide learning processes, providing focus? What is the role of policy, strategy and the institutional set-up?

Box 5. The informants

Denmark	**Norway**
1. Business Development Manager (BDM), small firm focusing on design, development and production of hydrogen and fuel cell systems.	1. Business Development Director (BDD), large energy company, leading within FC&RHT in Norway.
2. Managing Director (MD) of a medium-sized leading international manufacturer of air handling systems.	2. Head of Energy Systems (HES), small firm focusing on mechanical engineering, product design and manufacturing services covering a broad spectrum of application areas.
3. Preben Maegaard, leader of the Nordic Folkecenter for Renewable Energy, an independent NGO, established in 1983 to pave the way for renewable energy and energy savings by developing, testing and demonstrating technologies, designed for manufacturing in small and medium scale industries.	3. Steffen Møller-Holst, Leader of the newly established (2006) Strategic Council for Hydrogen of Norway and Research Manager at the department of Energy Conversion and Materials at SINTEF, Trondheim.

5.1 The Danish interviews

All Danish informants agreed that learning is pivotal in reducing uncertainty. The following quote by BDM explains how:

> Learning is important because we are going to decrease the prices by two thirds and it means that we have a lot to learn in order to find out how to do it. It is about learning about the needs of the users but also, since we build systems; how do we change the system in order to lower the costs by decreasing the amount of components. We ask the users and get a yes or no and then we go back. It is a lot of trial and error, so to say… the cost of the fuel cell unit needs to be reduced by two thirds before we can match batteries, so there is still a long way to go, but now we know the requirements of the market and now we know which way to focus in our own development in order to satisfy these requirements, so that we can go back to the laboratory and build the next models, and let them pass through a similar process. It’s like a loop.

This describes user-producer interaction between actors. Learning process clearly involve know-who and know-how, and these forms of knowledge are portrayed as interacting continually, in a loop-like fashion. This is clearly DUI-innovation, but built on, and combined with, the existing know-what and know-why of the engineers in the laboratory. These forms of knowledge are associated with the STI-mode, but the point is that, while they form the basis for learning, they do not form the starting point of the innovation process. User requirements are referred to as providing focus in the innovation process. Focus entails choosing among a set of available options, and therefore contributes to reducing uncertainty.

A similar description of the learning process was given by MD:

> There is nothing that compares to starting up a project; implementing it and making it work, if one wants to build know-how. It's there one learns from all the small faults you might have done on the way, and it's those that need to be solved in order to make it commercial.

This emphasizes the importance of DUI-learning in order to build know-how. The importance of learning by doing mistakes is accentuated, and innovation is clearly seen as a gradual process, not a dramatic event.

Preben Maegaard's characterization of innovation is strikingly similar to Schumpeterian and evolutionary definitions:

> It is just a question of combination of a certain competency and some resources and some visions. There are some combinational capabilities that one needs to have there, there has to be some invention qualities in the people that do it, and then they need to interact and inspire each other.

Maegaard emphasizes the interaction between people with different competencies.

The perceived dominancy of DUI-innovation is clearly confirmed by the quotes above – in the first quote, learning by using is emphasized, in the second, learning by doing, and in the third learning by interacting.

The following statement by BDM gives an indication of the perceived market stage:

> It is interesting to see that Danish businesses are among the first to commercialize…We are making the things work while pushing the prices further down, it has developed beyond that prototype stage… the demonstration market is big and difficult to define; we are looking to find our niche.

BDM regards the present situation as the late pre-commercial phase, and therefore target the demonstration market, i.e. selling fuel cell systems to the growing number of global hydrogen demonstration projects, as a promising niche.

MD describes a niche application in the following statement:

> It has crystallized itself clearly for us that power-backup will be the first place where this can become commercially useful…The primary reason is of course that the fuel cell technology; it has not developed so far yet, so that the durability is not very long and when the durability is not long, then one needs to find some applications where it does not matter and it does not matter so much where you need to have a power-backup, which will only be used when the normal electricity supply fails…we have to make an effort because we have technology and we have business. We shall connect those two things.

This statement identifies a niche application, by taking into consideration the developmental stage of FC&RHT and the possible business area where there might be a pathway for this particular company. This shows how uncertainty is reduced by choosing a very particular technological and market niche, where the technological requirements are low, and where the competing technology, i.e. battery technology, is voluminous, expensive and suffers from poor durability and rapid output degradation.

Seen together, the two quotes on niches show how business know-how is utilized in practice. The requirements of two markets; the demonstration market and the telecom power-backup market, guide innovation efforts and focus learning strategies, thereby reducing uncertainty. BDM and MD are both involved in business development and strategy, and this is reflected in their language. The DUI-mode, utilizing mainly know-how and know-who, is evident. Business areas are identified utilizing know-who, by knowing the actors of the market. The chosen innovation and learning direction is based on business know-how, in the sense of knowing the requirements of known actors, or users. A direct consequence is the establishment of interaction between BDM and MD's firms and what might be called advanced or professional users, such as telecom companies or firms involved in hydrogen demonstration projects.

DUI-learning plays an important role in the Danish setting. Is this accounted for and understood by policy makers? BDM suggests that this is not the case:

> There is a need for the public authorities to understand that there is a long distance between the laboratory and the market and that there are many phases in-between… The reason that we have been able to pull our project ahead is that we have had local authorities, which have given us the possibility to do so. This would not have happened nationally.

The messy and uncertain nature of innovation processes are summed up as the many phases in-between. National policy is described as being too focused on the STI-mode, which is a recurring feature of BDM's criticism of Danish policy in the interview.

A similar criticism is sharply formulated by Maegaard:

> We should rather create support programs for people with promising ideas and solutions from the informal as well as the formal sector that have the possibility working not only theoretically but also practically in full or near full-scale with the concrete technologies. They should be given proper opportunities, and should not have to go through a hearing nor necessarily be assessed or evaluated by the scientists with whom they often compete; that will delay the development towards implementation as the formal decision makers and evaluators often lack the practical background. It is a prerequisite one has from

> the present liberal government that only high level research leads to results. This represents the conventional research and development strategy based on the linear or straight-lined way of thinking. However, experiences from the past 25 years of progress within implementation and commercialization of renewable energy is highly based on learning-by-doing principles with a broad approach involving not a single but a variety of actors. With a careful non-biased selection based on the most promising solutions, some countries have been able to take leadership and have created new strong industries within renewable energy technologies whereas other countries have missed similar opportunities. Choice of research and development strategy has proved more important than the funding available. One example of this is the Danish wind energy sector that emerged in the 1980s having access to considerably less resources than the same sector in the UK. Denmark subsequently captured 40% of the world's wind turbine industry whereas the UK has to import its needs for wind turbines. It is my assumption that the UK government allocated funding for wind energy research with the expectation of having a professional industry in that field; that failed, however, due to the selected research and development strategies. That is something that is not understood in Denmark today and therefore Denmark will loose the promising industrial opportunities that R & D within several other renewable energy technologies represent in the ongoing transition from the fossil fuels to the renewable energy forms.

This is a clearly formulated critique of linear models of innovation, characterized by the STI-mode. Maegaard even phrases this in evolutionary terms, utilizing the term selection to describe what would happen if a broad (variety) effort is appropriately funded by the government. He puts great emphasis on the knowledge gained by practical experience, i.e. learning-by-doing. There is an explicit critique of the priorities of the current government. This should be seen in light of that funding has been cut for the centre that Maegaard leads, but the critique is nevertheless relevant, and based on long experience and knowledge of innovation processes within renewable energy technology.

5.1 The Norwegian interviews

As in Denmark, the Norwegian informants all agreed upon the importance of learning in innovation processes. The following quote from BDD differentiates between forms of knowledge:

> Yes, learning is very important, especially the kind of learning which can not be attained through reading books and articles. It is essential to learn from people by actually meeting them in social setting, be it formal or informal. One has to hear the arguments put forth and understand how the analysis is constructed in real life.

BDD makes a clear distinction between know-what and know-why on one hand, and know-how and know-who on the other, which is described as essential. Know-how is not delimited to technological know-how; BDD is talking about this in a context of business development, where understanding *how* an analysis is constructed in real life, in a social setting (know-who), is understood to contribute to improved business know-how.

Know-how refers to largely tacit skills or capabilities. The following quote from HES shows how know-how can be built through learning by doing:

> The most important learning is the tangible, that you yourself get a feeling about the things. It is one thing to read all theories and all the books; but to have the opportunity to think through and design the experiments, analyze the experiments and touch the material afterwards and to see what happens and get a feeling on that…it is at that point you see how the things really work.

This illustrates how learning-by-doing in a laboratory setting is perceived as a very important part of the learning process. To be able to benefit from such learning; one has to have a scientific educational background encompassing know-what and know-why. STI- and DUI-learning are therefore necessary to combine in order to build know-how.

The active search for niches seemed important for Danish actors. Møller-Holst elaborates on this "The Danes are more professional when it comes to business. They are tradesmen (kremmere), like we say in Norwegian. They find a niche and put all their resources on that, and they perform very well, but they cultivate a role and they are often better at that."

This confirms the highly developed business know-how of Danish actors, while suggesting that an understanding of roles is important, which is described as a Norwegian weakness. Møller-Holst made frequent comments of the inability of Norwegian actors to benefit from synergetic effects, because of the poorly developed understanding of roles within the technological system. One's role is understood to shape focus in the innovation process, thereby reducing uncertainty. Poor understanding of roles can therefore be seen an example of poor institutional understanding, hampering innovation processes.

All Norwegian informants commented upon the presence of highly qualified people with scientific and engineering competencies within the emerging hydrogen technological system in Norway. But the disjointed nature of activities and the lack of linkages was a general point of frustration. This suggests that STI-innovation knowledge forms like know-what and know-why are well developed, while DUI-innovation knowledge forms like business know-how and know-who, are less developed.

The Norwegian informants also suggested that cooperative activities in Norway often bypassed the national level; collaboration projects were mostly initiated with international actors, mainly European. The actors of the Norwegian emerging hydrogen technological system were described as reluctant to cooperate with each other.

The role of policy and strategy should be to favour an institutional set-up conducive to innovation and learning, and ultimately path creation. Policy was commented in the following manner by BDD:

> The most important policy measure is predictability in a long perspective. This has been difficult in Norway, because governments change frequently, resulting in a loss of continuity. The bio-energy program in Sweden is an example that one should learn from. This program got guarantees for financial support for five years and they managed to reach the objectives set up at the outset.

Stability of the regulatory framework is seen to contribute to predictability for commercial actors. This is seen as a particular problem in Norway, possibly because of the frequent change of governments, resulting in poor predictability. Predictability is portrayed as contributing to efficient learning processes, because it allows actors to set and reach pre-defined goals. This suggests that the role of policy should be to create protected learning spaces for pre-commercial technologies, in order to stimulate path creation at a latter stage.

HES made this remark on the path-dependent nature of Norwegian policy:

> Yes, in Norway, there are clear guidelines for what the money is supposed to be used for, so that is very significant for us. It is about that we shall use mainly natural gas in an environmentally friendly manner. Secondarily renewable energy, but primarily, primarily in Norway as we understand it on our part, it is environmentally friendly usage of natural gas. It lies in…where we are at…if you read the texts to the research programs, it reveals itself.

This shows how the forces of path dependency are very influential in Norway, in that activities are steered in a certain direction, which ultimately is defined by the government, in a top-down manner. This can be interpreted as reducing uncertainty, because it creates a focus on innovative efforts within the fossil-fuel scenario of the hydrogen economy, in an effort to connect FC&RHT to the fossil fuel path. But it can also be seen as a problem, in that it hampers innovative activities focusing on the renewable scenario, thus reducing variety and therefore also influencing selection.

As the leader of the Strategic Council for Hydrogen, Møller-Holst holds an influential position in shaping policy and strategy. I asked him the following question: If you could select and rank the three most important public policy measures needed to implement a national learning and innovation strategy within fuel cells and related hydrogen technology in Norway, which would they be?

> I noted more than three but…I would say that the national action plan, which the Strategic Council will launch by the end of 2006 in itself is one of them. Then you have predictability. I have also noted the establishment of what we call a national virtual hydrogen laboratory; if you look at hydrogen technology, it includes many different aspects; that is why we need a national hydrogen laboratory infrastructure, which would mean that if you have prototype or something, you can get it tested… a network of different laboratories, but which have dedicated missions, so that if you are testing reformers you'll do that in Trondheim, and if you are going to test a storage unit, you would typically do that at Kjeller[46]… Lastly, when it comes to commercialization, it is about support structures for demonstration projects.

This answer is interesting, because it mentions all the integral parts of figure 1 (see p.41):

[46] Institute for Energy Technology (IFE)

the role of *regulators* providing predictability, the establishment a collaborative test infrastructure for technology *evaluators,* and support structures for demonstration purposes, involving *users* and *producers*.

The action plan is meant to function as the implementation of the recommendations of the strategy. Møller-Holst regards it as imperative that this plan receives support from actors, as there are no elements of coercion involved. It seems that some of the frustration of the informants is addressed by Møller-Holst. Predictability is emphasized and systematic collaborative efforts, creating linkages, are promoted in the form of a national virtual hydrogen laboratory, catering to the needs of the emerging hydrogen technological system. Support structures for demonstration projects are also recommended. The comments made by BDM and HES suggests that this is wise, since learning processes were described in terms of know-how and know-who, reflecting DUI-innovation and learning.

6. ANALYSIS

To analyze transformation processes in energy technologies is a complex task. In this thesis, technological systems have been combined with national systems of innovation as theoretical frameworks. This is grounded in the belief that socially defined networks and the institutional set-up play a large part in promoting or blocking various phases of the innovation process. These various phases include searching, creation, utilization and diffusion of a technology or set of interrelated technologies, such as FC&RHT.

It has been therefore been argued that there is a need to develop an understanding of how knowledge is generated and diffused, i.e. *learnt,* within the emerging hydrogen technological systems of Denmark and Norway. Lundvall's knowledge taxonomy and innovation modes have been used as methodological tools, in order to achieve a better understanding of learning processes in these systems.

Learning does not take place in a vacuum. The various scenarios of the hydrogen economy function as powerful steering devices of actor's perceptions and expectations of FC&RHT, therefore influencing both search processes and the creation of novel innovations. In addition to the technology specific character of scenarios, the terms bricolage and breakthrough have been used to describe cognitive schemes that shape actor's expectations on their own and other's role in the emergence of the hydrogen technological path.
Path-dependency and path creation are interrelated processes shaping technological transformation processes. They are related to the particular national institutional set-up and the role of the emerging hydrogen technological system in shaping and influencing this set-up. A relevant question is therefore to what extent actors manage to "navigate a flow of events even as they constitute them" (Garud & Karnøe, 2001, p.2). Their capability to do so will affect the utilization and diffusion of FC&RHT.

Scenarios, cognitive schemes, and innovation modes employing a variety of knowledge forms have been identified as the primary socially defined factors influencing the capability of the actors of the emerging hydrogen technological system to learn and create knowledge. Learning and innovation take place within a given path-dependent institutional set-up. The relative strength of the emerging hydrogen technological system is measured by its ability to change the institutional set-up in a beneficial direction, by securing political and financial support. The availability of funding and hard resources, which is a prerequisite for the creation and maintenance of learning spaces within organizations, is affected by the political efforts of the emerging hydrogen technological system. This entails things like network or industry association creation, direct lobbying, development of media strategies and public awareness campaigns.

As an effort to apply evolutionary economics in an on-going process of technological change, a central aim of the analysis will be to identify the potential capabilities of the emerging hydrogen technological systems of Denmark and Norway to mindfully deviate from path-dependent relevance structures by mobilizing a collective learning and innovation effort aiming at eventual path creation.

To do so, system managers, such as innovation team leaders and policy makers need to keep an eye on *system openness*. This term is employed to describe the absorptive capacity of an innovation system.

> The more open a system is for impulses from the outside, the less the chance of being 'locked out' from promising new paths of development that emerge outside the system. It is, therefore, important for 'system managers' - such as policy makers – to keep an eye on the openness of the system, to avoid the possibility of innovation activities becoming unduly constrained by self-reinforcing path-dependency (Fagerberg, 2005, p. 13).

In the case of the emerging hydrogen technological system, maintaining system openness might require organizational innovation, rather than technical innovation. The *selection* of possible paths should not be constrained by the system itself since this might result in a negative path-dependency. It is especially important to keep a *variety* of developmental options open in the early, pre-commercial stages of technology development (Fagerberg, 2005).

Group-think, in the form of developing a system-wide consensus dominated by one scenario, cognitive scheme, and innovation mode should therefore be interpreted as a warning sign, because it might lead to system failure in the event of competition from technological systems that have chosen other technological paths. Competitiveness and system openness are therefore mutually reinforcing categories. Cantwell explained this relationship:

> …Competitiveness derives from the creation of the locally differentiated capabilities needed to sustain growth in an internationally competitive selection environment. Such capabilities are created through innovation, and because capabilities are varied and differentiated, and since the creative learning processes for generating capabilities are open-ended and generally allow for multiple potential avenues to success, a range of different actors may improve their competitiveness together (Cantwell, 2005, p. 561).

The general challenge for system managers and policymakers is therefore to create an organizational and institutional framework conducive to innovation in order to develop the capabilities needed for path creation. In the following, the challenges and opportunities ahead for Danish and Norwegian actors are analyzed.

6.1 The role of learning in Denmark

On the basis of the presented data material, it is fair to suggest that the role of learning in Denmark entails a focus on a utilization of know-how and know-who, which is characteristic of the DUI-innovation and learning mode. This does not mean that explicit forms of knowledge such as know-what and know-why are trivial forms of knowledge one can do without. The DUI-mode means that tacit forms of knowledge such as know-how and know-who are utilized as the starting point of innovative endeavours, while explicit knowledge of a more scientific character is used throughout the innovation process when, and if it is needed.

The indirect effects of employing scientifically trained personnel can be characterized as a prerequisite for innovation, but the priorities of the interviewed innovation managers were clearly biased against the STI-mode and linear models of innovation, which were described as misrepresentations of the innovative process.

The renewable scenario holds clear precedence over the fossil fuel scenario. Learning and innovation activities are therefore directed towards that scenario, reflecting expectations of continued growth in the share of renewable energy, in Denmark, but also globally. Additionally, synergetic effects are expected to develop. This involves suppliers of renewable energy like electric utility companies, but more importantly, also producers of renewable energy technologies, primarily windmill producers. Producers of innovative renewable energy technologies target not only Denmark, but the global market, and this is seen by all informants as a tremendous opportunity.

Bricolage as a cognitive scheme seems to be an apt description of the group of producers associated with HIRC and DHA. The negative characterization of national regulators implies that the Danish hydrogen strategy seem to be somewhat disconnected from innovation activities of the informants, who all belong in Jutland. Two informants attributed this to regional tensions. On the national level, there are tensions between the STI-mode inspired national laboratory Risø[47], located on Sjælland, which receives a very large share of total FC&RHT funding, and the DUI-mode informants, residing in Jutland. Bricolage as a cognitive scheme may not appropriately describe the national system of innovation, but it may well be an appropriate term to describe the emerging hydrogen technological system of *Jutland*. Innovation activities are characterized by cooperation and utilization of accumulated

[47] http://www.risoe.dk/risoe2.htm (6.9.06) Risø is a national laboratory under the Ministry of **S**cience, **T**echnology and **I**nnovation (**STI**).

learning, which is diffused, resulting in improved system level knowledge. Organizations might therefore be able to benefit from lower technology development costs and improved diffusion of knowledge simultaneously, thus creating a virtuous cycle, stimulating learning and reinforcing innovation efforts.

Niche applications are clearly targeted, partly for hard financial reasons, but also because of the perceived learning spaces that these open, since they offer opportunities for user-producer interaction. Such interaction in the early and pre-commercial phase should be considered to be rare and precious learning opportunities for innovation teams, as it contributes to improved knowledge of the market, the users, the technology and the institutional set-up. In addition to this, firms can utilize perceived pioneer status to promote a positive public image of the emerging hydrogen technological system.

6.1.1 Path dependency and opportunities for path creation in Denmark

The recent developments of a less supportive attitude towards renewable energy on the national level seem to have affected independent and grassroots innovators the most, but there are signs that some dynamic actors have found ways of by-passing the state in financing matters, since all informants either had received, or planned to apply for, EU and regional funding. This suggests that supra-national and regional regulators might come to play a more important role in facilitating and financing learning spaces in Denmark, as long as the current government's priorities remain unchanged. National regulators are however in the process of implementing the hydrogen strategy, and this might contribute to a strengthening of the emerging hydrogen technological system, but this remains to be seen.

There are signs of alliance building between a range of renewable actors that are aiming to gain political influence regionally in order to convince politicians that the new region Central Jutland should officially promote the formation of a FC&RHT cluster. If such efforts succeed, it might mean that the self-reinforcing dynamics of the renewable energy path in Denmark has grown sufficiently strong as to be able to handle exterior shocks, such as national funding cuts.

The existence of a strong and expanding renewable energy path in Denmark constitutes the most important comparative advantage for the emerging hydrogen technological system. If linkages develop, since there are obvious common interests for wind power firms and the emerging hydrogen technological system when it comes to producing hybrid systems that use hydrogen as energy storage for the surplus electricity production of windmills, the emerging hydrogen technological system might be able to connect itself to the renewable energy path, in a process of successful path dependency, resulting in path creation.

The potential for creative destruction is the greatest for producers of energy technology systems that bypass the structures of the current energy system, since they have no financial interests in its vast infrastructure. Innovative and strategic wind/hydrogen alliances promoting decentralized solutions could make inroads into the production, supply and distribution of renewable energy simultaneously, if they manage to commercialize viable energy systems aimed directly at decentralized users, instead of the established actors of the centralized energy infrastructure.

6.1.2 Implications for innovation managers and policy makers in Denmark

The characteristics of the emerging hydrogen technological system presented in Box 4 were largely confirmed by informants and other obtained data. To say that there is a focus on fuel cells and system integration, DUI-learning and innovation, and early commercialization through niche applications seems correct. It is important to remember that this is based on three interviews and extensive reading and interpretation of articles, homepages and participation in the annual DHA conference. Important questions regarding the policy implications for innovation and system managers can nevertheless be asked on the basis of this empirical material.

All informants had negative comments on the role played by *regulators* on the national level. Regulation and funding was seen as favouring STI-innovation. Two informants explicitly attributed this to the poor understanding of regulators of how innovation processes proceed, which in their view entailed mainly DUI-innovation. There might therefore be a need for policy makers to reconsider their policies, since there obviously are actors who are in the process of commercializing FC&RHT products. This is not to suggest that indirect subsidies should be awarded for commercialization attempts, but that the system wide advantages associated with DUI-learning and innovation should be recognized, and supported financially, since this might be an efficient way of accelerating learning processes. The reservation of a large share of funding to develop an improved scientific understanding of FC&RHT partly reflects the belief that such an understanding eventually leads to STI-innovation, but it must be said that such priorities also reflect the very real scientific challenges FC&RHT is confronted with, especially when it comes to minimizing the energy losses of the hydrogen energy chain.

The informants were all involved in innovation in different contexts and at different levels. Nevertheless, they shared the view that successful innovation entails cooperative learning processes, consistent with bricolage as a cognitive scheme and the DUI-innovation mode. Cooperation at a pre-commercial stage was seen as beneficial for future competitiveness, because of the benefits associated with improving and diffusing the knowledge and capabilities of the emerging hydrogen technological system, to reach the innovation related objectives of the individual organizations and firms. This might be the most important lesson for policy makers, considering the positive correlation between system openness and competitiveness.

It is important to remember that the DUI-learning and bricolage tendencies reflect strategies of informants exploiting early niches, where the relatively low technological level of FC&RHT can justify such an approach. The innovation strategy of combining and improving ready-made ingredients consisting of fuel cell stacks, electronics and mechanics constitute a clear parallel to the development of the modern wind turbine. While this might reflect a particular strength of the Danish national innovation system, it also means that a one-sided DUI-mode strategy could have its limitations if the goal is to resolve the major scientific and technological hurdles necessary for the hydrogen society to be considered a feasible future scenario.

6.2 The role of learning in Norway

Conducting the interviews inspired an interesting realization: learning was described in strikingly similar ways, regardless of nationality. Socially defined forms of knowledge like know-how and know-who also held precedence in the emerging hydrogen technological system of Norway.

Box 4 was constructed as a basis for inquiry. After only having *read* about FC&RHT in Norway, I was left with the impression that this was an area where science based forms of knowledge like know-why and know-what prevailed. The STI-innovation and learning mode was therefore assumed to be dominant. But, upon *discussing* learning with the informants another picture was confirmed; DUI-learning and innovation was portrayed as essential.

How should these different images of learning be interpreted? Norwegian policy documents and the national hydrogen strategy suggest that learning to innovate within FC&RHT predominately entails improving the know-why and know-what forms of knowledge, requiring a strengthening of the scientific knowledge base and therefore an implementation of the STI-mode. This reflects the pervasiveness of linear models of innovation, especially among policy makers.

Another interesting realization was that collaboration projects clearly aimed for latter commercialization, like the Utsira project and Statoil/Volvo joint venture, are characterized by bricolage, while the less commercially focused HyNor project and the hydrogen strategy display signs of breakthrough as a cognitive scheme. How should this be explained?

It seems as if there is a correlation between bricolage and a business-inspired mindset on the one hand, and breakthrough and a science-inspired mindset on the other. An important prerequisite for bricolage to develop is that each member of an innovation team has a cross-disciplinary understanding of the most important constraints and considerations of the innovative process, or "understands the essential master blueprint of the overall innovation" (Van de Ven, 1986, p. 600). Being involved in business development, bricolage might therefore be essential, because business development entails coordinating and maintaining an overview of the numerous efforts by multiple actors towards clearly defined commercial goals. Being involved in scientific work, the mind might be set on achieving a very particular goal. To reach such a goal, STI- and DUI-learning is combined, in the sense that one utilizes a knowledge base of know-what and know-why, while skilfully testing possible combinations (know-how), i.e. engaging in learning by doing or using for a long period of time, until at last; eureka it works, thus explaining why this process is portrayed cognitively as a *breakthrough.*

The Norwegian hydrogen strategy and the HyNor project are basically promoting a future hydrogen society, which explains the prevalence of breakthrough as a cognitive scheme. Achieving a widespread hydrogen transportation infrastructure as an integral part of a future hydrogen society requires fundamental breakthroughs to be realized. It is therefore at this point in time quintessentially impossible to understand the master blueprint of these larger visions, since they contain a formidable variety of causal factors that currently are difficult enough to understand, let alone predict or plan for.

The emphasis of the commercial informants in Denmark was on commercializing existing technology by integrating it into new systems, by exploiting niches where the current state of FC&RHT do not matter so much. In Norway, the focus is on improving the technological and scientific knowledge further, before commercialization ensues. Except for Norsk Hydro, which has commercialized electrolysers, commercialization is not around the corner for Norwegian firms. This might be caused by an overemphasis on the STI-mode in Norway.

The third socially defined factor influencing learning in Norway is the prevalence of the fossil fuel scenario. The dominance of that scenario was confirmed by the informants and the strategy. While a concentrated learning effort geared towards one scenario might lead to a reduction of uncertainty in the innovation process by ruling out alternative paths, it might be considered a gamble; increasing risk, but also potential rewards.

The role of personal learning for Norwegian informants does not differ essentially from that of Danish informants. This is a sign that the DUI-mode of learning and innovation is underutilized in Norway. The impression is that scientific competence is more influential in shaping learning and innovation strategies in Norway, while economic competence is more influential in Denmark. This tendency is also reflected in the varying focus on niches of the countries' respective hydrogen strategies. The dominance of the fossil fuel scenario means that FC&RHT learning processes in Norway are mainly steered towards that scenario.

6.2.1 Path dependency and opportunities for path creation in Norway

The significant influence of the fossil fuel path on the emerging hydrogen technological system has been described. The question is how this will affect path creation in Norway. There are some positive effects. The most significant is probably that FC&RHT has friends in high places of the established fossil fuel path[48], which has eased the gathering of financial and political support. The influence of actors connected to the fossil fuel path could therefore be used to reinforce the development of natural gas>CO2-sequestration>hydrogen production and distribution value chains, and this is already happening.

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[48] The opening of the first hydrogen filling station of the HyNor project in Stavanger was attended by the minister of transport and communication and the CEO of Statoil, while the prime minister was pictured when driven to the airport in a hydrogen car. See: www.zero.no/om/vg-20060910-s6-7.pdf (22.9.06)

This path dependent potential advantage might also become a severe disadvantage, if the dominant structures of the current energy economy are upset by competing technological choices, such as decentralized and renewable hybrid systems like solar/hydrogen or wind/hydrogen, or continued acceptance of bio-fuel and electric cars in the transportation sector. The Utsira project demonstrates how this disadvantage can be overcome. Norsk Hydro has a diversified hydrogen strategy, pursuing hydrogen production with CO2-sequestration, technology supply in the form of electrolysers and filling stations and system integration of renewable energy technologies.[49] Risks are therefore spread, which takes into account the possibly multiple potential avenues to success, by steering learning activities towards the first and second scenario simultaneously.

The inability to develop linkages and cooperative learning processes has been the most important weakness of the emerging hydrogen technological system. Godø and Nygaard characterize FC&RHT in Norway during the period 1990-2002 as a case of system failure, where the overall inability of actors to benefit from synergetic processes is seen as an important explanatory factor (Godø & Nygaard, 2006). The empirical interview data supports this characterization. The inability to benefit from synergies suggests that the underutilization of economic competence as compared to scientific or engineering competencies in the emerging hydrogen technological system in Norway has become a path-dependent trait, affecting path creation negatively.

The national strategy favours the fossil fuel scenario. While this is not surprising, it is a path-dependent sign of groupthink, which should be regarded as a warning sign. It sets limits on variety and contributes to closing the innovation path of the emerging hydrogen technological

[49] http://www.hydro.com/no/our_business/oil_energy/new_energy/hydrogen/index.html (10.9.06)

system at an unnecessarily early and pre-commercial stage, therefore hampering selection, future competitiveness, and possibly path creation. It also displays the tendency of policy makers to envision the future as basically similarly structured as the present. The only difference in the future scenario proposed by the strategy seems to be that car-owners would fill up hydrogen, instead of gasoline, at the same type of filling stations, served by the same type of companies, utilizing the same distribution networks. Such scenarios conveniently skip the question of the energy losses associated with centralized distribution and decentralized use of hydrogen. This suggests that the incentive of creating a value-chain for Norwegian natural gas and hydrogen should become subject of critical scrutiny as soon as possible, otherwise Norway runs a risk of spending considerable resources on what could end up as a futile technological choice, both in terms of environmental benefits and financial rewards.

6.2.2 Implications for innovation managers and policy makers in Norway

The establishment of the hydrogen platform signals an intensification of FC&RHT efforts in Norway. Achieving a higher degree of cooperation within the emerging hydrogen technological system in Norway is seen as very important by Møller-Holst. The planned establishment of a national virtual hydrogen laboratory is a positive step in that direction, since it might contribute to improved diffusion of technological and scientific know-how and lower R&D costs for users.

The most important aspect of the role of learning in Norway is the need for improved economic and organisational competence, like business know-how and know-who, to better be able to exploit business opportunities. Godø and Nygaard largely attributed the system failure between 1990-2002 to the rivalries between the dominant actors of the fossil fuel path;

Norsk Hydro and Statoil. This relationship now seems to be improving, considering the cooperative efforts of these companies in the HyNor project. While this is positive, they share a connection to the fossil fuel scenario, which could hamper efforts to open up the system in order to exploit genuinely new opportunities of the emerging hydrogen technological system (Godø & Nygaard, 2006).

A main priority for innovation managers and policy makers should therefore be to improve system openness by intensifying efforts to create linkages to the renewable energy sector. This involves organizational competence and creativity, and is essential if patterns of path dependent learning are to be broken.

An example of a concrete search measure would be to explore the potential involved in the creation of solar/hydrogen hybrid systems[50]. The solar technological system in Norway is experiencing strong growth, and the Norwegian company REC[51] is the world's largest producer of Solar Grade Silicone, which is the required raw material in solar panels[52]. The advantages associated with intensified collaboration across mutually reinforcing technological systems suggest that solar/hydrogen alliances might be able to exploit synergetic effects, which could set processes of creative destruction in motion.

In addition to this, efforts to identify early niche applications and markets should be initiated, mainly because of the learning benefits associated with niches, but also because of the commercial and financial benefits associated with inflow of hard cash, which might contribute to reinforce on-going FC&RHT activities.

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[50] Integrated solar/hydrogen fuel stations has been developed by Honda, see link: http://world.honda.com/FuelCell/HomeEnergyStation/HomeEnergyStation2004/ (10.9.06)
[51] Renewable Energy Corporation
[52] http://www.tu.no/nyheter/energi/article54543.ece (10.9.06)

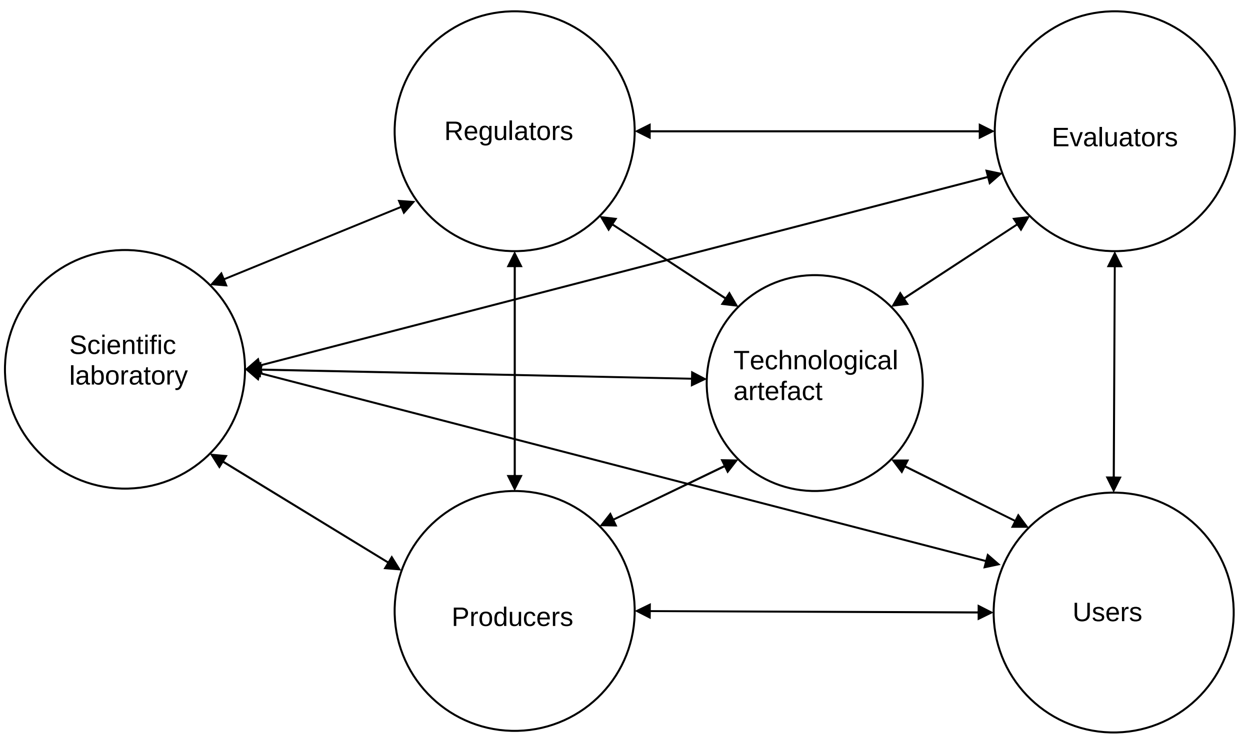
Demonstration projects promoting DUI-learning and innovation should also be emphasized, mainly because of the accelerated learning processes this might trigger, but also because of the positive contribution this might have on the utilization and diffusion of FC&RHT. The empirical material indicates that the DUI-mode is indirectly connected to the STI-mode, since know-what and know-why forms of knowledge are prerequisites of FC&RHT innovation processes. The opposite, however, is not true. The STI-mode needs to be connected proactively and consciously to the DUI-mode. If this fails to happen, commercialization and successful innovation might remain elusive for Norwegian actors. The national virtual hydrogen laboratory is a step in the right direction and it should be complemented with similar collaborative efforts emphasizing niche development where Norwegian actors have comparative advantages.

The combination of efforts promoting system openness and DUI-learning could reduce the negative effects of path-dependency, like lock-in to the fossil fuel path, considering the positive correlation between system openness and future competitiveness. The emphasis on the STI-mode is understandable and also partly justifiable in the sense that it reflects the very real scientific and technological challenges that must be overcome in order to reach the far-reaching goals of the Norwegian hydrogen strategy. However, the combined and interrelated dominance of the STI-mode and the fossil fuel path suggests that tendencies of group-think should be regarded as warning signs, which should be detected and questioned by innovation managers and policy makers alike.

6.3 A model for FC&RHT innovation: Bricolage integrated with science

The analysis has identified some shortcomings of the national hydrogen strategies of Denmark and Norway. It has been argued that the cognitive scheme breakthrough associated with the STI-mode misrepresents and misunderstands the nature of innovation and learning processes. The specific technological challenges facing FC&RHT as a whole, however, justifies a continued emphasis on both the STI-mode and the DUI-mode. But it is essential that science and the STI-mode are proactively and consciously combined with the DUI-mode and bricolage as a cognitive scheme. To visualize this new model for innovation, the following is proposed:

Figure 3: Bricolage integrated with science: Distributed agents involved in the emergence of the hydrogen technological path (Author's proposal)



In this model, the learning arrows describe interactive learning processes involving the distributed agents involved in the emergence of the hydrogen technological path. The basic reason to propose this model is that the inclusion of what is termed scientific laboratory into the model is meant to connect the sphere of science with the other agents proactively. The idea is to expose basic science to the multiple requirements of regulators, evaluators, producers and users at an early stage, while the hope is that this will result in fruitful cooperative learning processes geared towards successful innovation and commercialization.

This does not suggest that all basic science should become applied science, but it means that attempts should be made to establish a constructive dialogue leading to interactive learning processes between all agents involved in the emergence of the hydrogen technological path. In this way, tacit forms of knowledge like know-how and know-who will be stimulated and distributed to a wider range of actors, contributing to system openness and therefore also future competitiveness.

The model is also meant to increase the awareness of the multitude of perspectives and scenarios contained among actors themselves, hopefully stimulating a wider variety of innovation and learning strategies. The model does not attempt to steer or plan innovation; rather it attempts to raise awareness on the policy level of unexploited synergies that already exist within the emerging hydrogen technological system. Such synergies, however, are not limited to this system; they also exist outside the system. The possibilities are too numerous to account for here, but an obvious example is to create linkages to the wider renewable energy technological system. As Carlsson's definition of technological systems hints:

> Technological systems are defined in terms of knowledge/competence flows rather than flows of ordinary goods and services. They consist of dynamic

> knowledge and competence networks. In the presence of an entrepreneur and sufficient critical mass, such networks can be transformed into development blocs, i.e. synergistic clusters of firms and technologies within an industry or group of industries (Carlsson & Stankiewicz, 1995, p. 49).

The model aims to contribute to the development of an awareness of the inherent, but underutilized possibilities that already exist, waiting for the arrival of an entrepreneur and sufficient critical mass.

7. CONCLUSIONS

The goal of this thesis has been twofold: to provide a better understanding of the role of learning in innovation processes, and to make this understanding available in a utilizable manner for the actors of the emerging hydrogen technological systems in Denmark and Norway. The focus has been on the importance of developing a conscious learning and innovation strategy that is informed by the institutional context surrounding the innovation process. The comparative approach has allowed for insights on how particular national institutional set-ups influence innovation and learning, by blocking or promoting innovative efforts. Some aspects of the role of learning are clearly path dependent and country-specific, exemplified by the powerful influence scenarios, cognitive schemes and innovation modes exert. Other aspects are more general, exemplified by the statements on the importance of DUI-learning in the personal learning experience.

The fundamental importance of learning in innovation processes has been confirmed by this thesis. It has also revealed how the composition of knowledge and learning strategies play a central role in the defining phases of the innovation process; the searching, creation, utilization and diffusion phases. This supports Sagar & van der Zwaan's hypothesis that the composition of learning strategies perhaps plays a more important role in explaining the diffusion of new energy technologies, than do the amount of invested financial resources. The path dependent nature of some aspects of learning suggests that there is a need to consciously forget or at least ignore the steering attempts of the surrounding institutional set-up. As Garud & Karnøe suggests, it is imperative to develop “a capacity to reflect and act in ways other than those prescribed by existing social rules and taken-for-granted technological artifacts” (Garud & Karnøe, p.2, 2001)

Ideally, the insights derived from this thesis will contribute positively to the capacity of Danish and Norwegian actors to mindfully and consciously deviate from path dependent relevance structures, facilitating path creation. Even though the primarily Danish Bricolage/DUI-mode has been described in quiet positive terms as a well-informed learning and innovation strategy, it has also been emphasized that this approach has its inherent limitations, since it might experience difficulties once the ‘easy’ technological niches have been explored. Likewise, the Norwegian ambivalence between Bricolage/DUI versus Breakthrough/STI and the sometime inability to exploit synergies illustrates how it is essential to combine cognitive schemes and innovation modes, in order to adapt them for the goals of innovation efforts. Cantwell pointed out how creative learning processes are open-ended and generally allow for multiple potential avenues to success, thereby indicating the advantages associated with broad cooperation at a pre-commercial stage. Policy should therefore accept that a variety of actors, embodying varying scenarios and cognitive schemes, jointly increases the chances that one or more of these actors will succeed in their innovative efforts.

The technological specificity of the challenges confronting FC&RHT have shown strengths and weaknesses of the emerging hydrogen technological systems. The conclusion is that

Danish and Norwegian actors have a lot to learn from each other, which motivated the construction of the proposed model: Bricolage integrated with science (Figure 3). It visualizes the character of learning in an interactive technological system aiming to produce technological artefacts, or innovations, within FC&RHT. The model summarizes the insights derived from the systemic perspective on innovation and the interviews and basically suggests that science should be incorporated at an early stage, allowing it to shape, but also to be shaped by interactive learning patterns, thus creating a wider variety of technological options from the outset.

The thesis has illustrated the importance of analyzing each new technology on its own merits, by addressing its particular challenges. If such knowledge can be utilized by innovation managers and policy makers actively engaged in FC&RHT innovation remains to be seen, the hope has been to make a positive contribution.

The thesis has been an exploratory effort. It has confirmed that learning is an interactive and socially embedded process, which has to be understood in its social, institutional and cultural context. It has also revealed the importance of the composition of learning strategies for innovation in FC&RHT. Further studies should focus on these two aspects of learning within new energy technologies, not only because of the theoretical implications this might have for innovation theories, but more importantly, because it might help transforming the energy system into a more sustainable direction.

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APPENDIX A

1) How do you acquire new knowledge and learn about new technologies within fuel cells and related hydrogen technology?

2) Can you give an example of any past or on-going collaboration projects that have influenced the current direction of your innovative activities within the fuel cells and related hydrogen technology field?

3) Do you consider learning to be an important part of your innovative activities?
    a) If yes, why?
    b) If no, why?

4) How would you characterise the existing learning arenas within the fuel cells and related hydrogen technology field in your country?

5) Is it important for you to be linked to other actors in the expected, but not yet realized value-chain of the fuel cells and related hydrogen technology?
    a) If yes, why?
    b) If no, why?

6) What is your main motivation for continuing innovative efforts within the fuel cells and related hydrogen technological field?

7) Could you select an essential area within the fuel cell and hydrogen field, related to your own activities, where there is a need for learning in order to achieve a successful, commercial innovation?
    a) If so, does that involve interaction with actors outside your organization?

8) Do any of the following actors facilitate learning within the fuel cell and hydrogen related field in your country?
    - Local, regional, national, Nordic, EU authorities
    - Industrial networks/associations
    - Environmental organizations

- Universities/research institutes
- Collaborating firms

a) If yes, how do they facilitate learning?
b) How would you rank the learning facilitation abilities of these actors on a scale of 1-10, where 1=low score and 10=high score?

9) Do you feel that there exists a strategic leadership guiding the innovative activities of the actors within the hydrogen and fuel cell field in your country?
    a. If yes, how does this affect your innovative activities?
    b. If no, how does this affect your innovative activities?
    c. If yes, which actors provide this leadership?

10) If you could select and rank the three most important public policy measures needed to implement a national learning & innovation strategy within the fuel cells and related hydrogen technology in your country, which would they be?