Co-Evolution of Technology, Markets and Institutions - the Case of Fuel Cells and Hydrogen Technology in Europe

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2008

CO-EVOLUTION OF TECHNOLOGY, MARKETS AND INSTITUTIONS
The Case of Fuel Cells and Hydrogen Technology in Europe

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Lund Institute of Technology

This study was made possible by generous financial support from:

VINNOVA

Rubin Rausing Foundation

The Norwegian Research Council

Stiftelsen J. Gust Richerts Minne

Bocconi University

Vätgas Sverige

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Printed in Sweden by Media-Tryck, Lund

ISBN: 978-91-977285-0-8

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Acknowledgements

This book is the result of a PhD research project. During this project, I have benefited from the generous support of many people. First of all, I would like to thank my supervisors Annika Rickne, Stefano Pogutz and Susana Borrâs. Their help have been outstanding in all parts of the research process and I have enjoyed the many challenging discussions during this long and demanding journey. I am grateful for their encouragement and support when writing a PhD felt really like an impossible thing to accomplish. I am also thankful to Henrik Glimstedt for his important role in defining the project.

I started this PhD project four years ago as a student at the former Division of Innovation at Lund Institute of Technology. I would like to thank Pierre Bitard, Fabrice Coulon, David Doloreux, Charles Edquist, Marie-Louise Eriksson, Henrik Glimstedt, Devrim Göktepe, Leif Hommen, Per Högeselius, Jekaterina Novikova, Annika Rickne, Max Rolfstam, and Astrid Szogs for the great moments we had in the design centre.

Later the division of Innovation was merged with CIRCLE and we moved downtown. I would like to thank all the people at CIRCLE for the inspiring working environment I have had the pleasure of being part of, as well as for inspirational seminars and workshops. The supportive administration at CIRCLE has been helpful in making this book a reality. Christina, Elna and Ola have provided great service.

I am thankful for the help of Lars Coenen and Ingo Bunzeck in commenting on drafts and ideas, providing crucial input to the thesis. I would also like to thank Atle Midttun for his detailed comments on my final seminar and to the final seminar committee- Mats Benner, Lars Coenen and Astrid Kander- for giving clear directions on where I should go to complete the thesis.

The PhD project also provided me with an international experience. I spent nearly a year at the Department of Management at Bocconi University in Milan. I am very grateful for the friendly welcome and great working environment in Viale Filippetti. Stefano Pogutz kindly invited me for a stay and helped me with practical things as well as highly important aspects of my PhD thesis. I would like to thank the people at Bocconi; Stefano Pogutz, Angelo Russo, Paulo Migliavacca, Clodia Vurro, Antonio Tencati, and Francesco Perrini for their cooperation and hospitality. I would also like to thank Hans Dubois who truly improved my social life in Milano.

I am truly grateful to Elisabet Fjermestad Hagen for outstanding support and for inviting me to the Business Development sub-group at the European Hydrogen and Fuel Cells Technology Platform in Brussels. Without her support, my thesis would have looked very different, and I believe, less interesting. I would also like to thank the members of the Business Development sub-group for many interesting discussions and valuable input to my thesis. Also all the generous people that have participated in the interviews I owe a great deal. Their willingness to share their time and perspectives has been significant for the book.

I have received support from many financiers to conduct this research and I owe them all a lot for letting me complete this for me highly rewarding project. VINNOVA, Rubin Rausing Foundation, The Norwegian Research Council, Stiftelsen J. Gust Richerts Minne, Bocconi University and Vätgas Sverige all helped me in conducting the research and writing this book. Thanks.

Finally, I would like to thank my family and friends for kind support.

Abbreviations

APU	Auxiliary power unit
CEP	Clean Energy Partnership
CHP	Combined Heat and Power
C&S	Codes and Standards
CUTE	Clean Urban Transport in Europe
DMFC	Direct Methanol Fuel Cell
EU	European Union
EC	European Commission
EHA	European Hydrogen Association
FC	Fuel Cell technology
FCEu	Fuel Cell Europe
FC&H2	Fuel Cell and Hydrogen Technologies
FP	The European Framework Programme
HFP	European Hydrogen and Fuel Cells Technology Platform
HFCV	Hydrogen and Fuel Cell Vehicles
ICE	Internal Combustion Engine
IDAs	Innovation and Development Actions
IEC	International Electrotechnical Commission
JTI	Joint Technology Initiative
MCFC	Molten Carbonate Fuel Cell
MEA	Membrane Electrode Assembly
MNO	Multi National Organisation
MoU	Memorandum of Understanding
M&A	Mergers and Acquisitions
NDA	Non-Disclosure Agreement
NIP	National Hydrogen and Fuel Cell Technology Innovation Programme
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PEM FC	Polymer Electrode Membrane Fuel Cell
RCS	Regulation, Codes and Standards
R&D	Research and Development
RTD	Research and Technological Development
SET	Strategic Energy Technologies
SME	Small and medium-sized enterprises
SOFC	Solid Oxide Fuel Cell
TES	Transport and Energy Strategy
TIS	Technological Innovation System
TP	Technology Platform
UN	United Nations
VFCPP	The Virtual Fuel Cell Power Plant

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I. INTRODUCTION

1.The field of study

1.1. Setting the scene

The emergence of a new technological innovation system or a new industry is an uncertain and complex process taking place at several levels and including many different actors.[1] With its focus on the importance of understanding such dynamics, technological change and industrial dynamics have been a key theme in the Schumpeterian tradition, in which the birth, maturity and decline of industries, sectors and technologies has been the object of study (Malerba, 2006).

In particular, technological innovation systems as well as industries are believed to go through different stages, starting with a formative phase, followed by a growth phase and, finally, a mature phase (Abernathy & Utterback, 1978; Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2005). The formative phase of an innovation system is characterised by uncertainty in terms of technologies, markets and regulation (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2005, p. 17; Jacobsson & Bergek, 2004). Importantly, then, these dimensions are not fixed, but evolve over time due to the actions of different actors within the innovation system. As such, these elements of an innovation system co-evolve. Furthermore, since in the formative phase the innovation system is not fully developed, the networks and institutions also change and adapt.

Due to such dynamics and the associated complexities and uncertainties in the formative phase, it is a key wish of actors to create a stable situation for technologies, products, markets and companies to grow. From this basis, this thesis explores the mechanisms used to help reduce uncertainties for firms and thus create stabilisation for evolution in the formative phase. Such stabilisation mechanisms can be defined as the actions performed or the tools used by an actor or a network in

[1] A technological innovation system (TIS) has been defined as 'network(s) of agents interacting in a specific technology area under a particular institutional infrastructure for the purpose of generating, diffusing, and utilizing technology' (Carlsson & Stankiewicz, 1991, p. 21).

order to create a change in one dimension of an innovation system. The stabilisation mechanisms help to align technology, market and institutions, so that the system may evolve to a growth phase.

One highly interesting technological innovation system is that of fuel cell and hydrogen technology. This area has great potential and its formative phase has taken a long time to materialise. Presently, the system is slowly moving towards a breakthrough phase with clear strategies for commercialisation and opening of markets. This is evident in Europe, where the shift from creation of visions and strategy to implementation for commercialisation is taking place. One of the instruments is the European Hydrogen and Fuel Cell Technology Platform and a Joint Technology Initiative, formalised as a private-public partnership between industry and the EC. Another major force for commercialisation is the increasing commitment of major European firms to these technologies for application in the transport and energy sector. Clearly, the case of fuel cell and hydrogen technologies is an interesting case enabling us to study how technology, institutions and markets co-evolve in the formative phase of a technological innovation system. I undertake the analysis of two application areas, transportation and stationary (energy production), in the European sector.

1.2. Theoretical foundation

Technological innovation systems (TIS) as well as industries go through different phases (Abernathy & Utterback, 1978; Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2005), first a formative phase, later a growth phase and then a declining phase. Since a TIS is dynamic, it changes over time as a result of the interaction between a set of multiple actors developing technologies, creating regulation and standards, thus providing new products that replace old products or come in addition to new products.

Joseph Schumpeter is a key figure who advocated a perspective on industries as moving through birth, maturity and death with the concept of creative destruction and business cycles (Schumpeter, 1943). Researchers in evolutionary economics, most notably in Freeman's long waves (Freeman & Louçã, 2001), have perceived evolution as a process of qualitative change and recognise the important role of technology and institutions in this process. However, much of the literature discussing the formative phase of a new technology, from such approaches as evolutionary economics (Murmann, 2003; Nelson, 1995), industry life cycles (Abernathy & Utterback, 1978; Utterback, 1994), business cycles (Freeman & Perez, 1988), and transition management theory (Geels, 2005), tends to employ a long-term perspective on the evolution between the different stages. In this thesis, I propose to do something different: by going deeper into the formative stage, I intend to add precision to the explanatory factors in this initial phase, and thus expand our understanding of how innovation systems evolve.

Several strands of research have approached the evolution of industries and TIS in terms of analysing how certain dimensions relate to and affect each other. Industry studies (Nelson, 1995; Utterback, 1994) as well as studies of TIS share certain similarities, namely the focus on co-evolution between different dimensions. However, the literature has not been specific enough to explain the co-evolution of technology, market and institutions. The idea of co-evolution is certainly very appealing, but it tends to be historical and abstract, in the form of long waves and industry cycles over long periods.

Co-evolution does not happen automatically but is set in motion by strategic and intentional actions of firms, governments and other organisations. Consequently, an aggregated analysis loses some precision, such as in understanding actors' motivations, the interaction between actors and the coordination in the formative stage. Geels (2002), for instance, studied technological transitions and the problems that new technologies have with breaking through. Geels states that this perspective is 'described on an aggregated and abstract level without saying much about (the interactions) between actors' (Geels, 2002, p. 1273). Clearly, then, this picture can be improved by focusing on a deeper and more fine-grained analysis in a shorter period.

I argue here that there is a need to open up what actually happens in the innovation system in the formative phase and, by employing a perspective on cooperation and coordination between intentional actors, to look at the *stabilisation mechanisms* for technology, institutions and market to co-evolve.

Thus, this thesis is about dynamics and change within innovation systems, and in order to understand change, it is necessary to focus on actors more thoroughly than has been common in evolutionary studies. *Stabilisation mechanisms* are operationalised in this thesis as the means that actors use to understand change. These mechanisms relate to action and tool actors and networks use to bring about change in a TIS, these relate to agency and actor strategies. By approaching the formative phase of an innovation system with a focus on the stabilisation mechanisms for technology, markets and institutions to co-evolve, I provide a new approach for analysing emerging innovation systems.

The focus on stabilisation mechanisms as the means to understand co-evolution moves the discussion from the aggregated level, to particular actions performed by the group of firms operating within the TIS and by the policy actors associated with the field. As I have argued, previous research, such as that on the industry life cycle as well as that by evolutionary economists and transition management theorists, all tends to employ a long-term perspective at an aggregated level. There is room, therefore, for complementing these perspectives with a more detailed understanding of the formative phase. This thesis will fill this gap in understanding of the formative phase.

1.3. Empirical context

The problems of global warming and energy supply have experienced increasing focus over the last decade from governments as well as companies and interest groups. Issues have emerged around concerns with the global energy situation as well as concerns about increasing emissions. These factors have resulted in an increased search for new technologies to introduce into the energy system, thus increasing the variety of energy sources. These factors relate to emerging economies, which have increased the demand for more energy and raw materials, to environmental problems like global warming, and to the need to create variety in energy production in order to secure energy delivery. These factors have made the search for alternative energy *technologies* such as wind, solar and fuel cells a focal point in most countries. This increased exploration of alternative technologies must be seen against its background as a means for securing energy demand and reducing negative climate effects, but also as a means for nations to gain competitive advantage, both through energy independence and by providing solutions for a growing global market.

From this picture, a situation emerges in which different strategies and policies are being developed at different levels - regional, national and international - in order to meet the challenges facing the global community. At the centre of attention are innovation and the creation of new technologies. Innovation has thus become part of long-term policy making; it seems to promise new solutions to environmental problems and is simultaneously considered as a tool for economic growth, employment and competitiveness (Stern, 2006).

One such area of innovation is fuel cell and hydrogen technologies, which many actors consider a realistic alternative for large-scale as well as distributed generation of electric energy, and as a fuel in the transport sector (EC, 2000, p.: 43). The area of fuel cell and hydrogen technologies is mentioned, for instance, as one among several areas of technology that need to be developed in order to slow down climate change. The promises of new technologies seem vast, even though uncertainties about scientific solutions, technological applications and market development are still manifold.

The important role these technologies might play is evident in the recently published 'Stern Review' in which the cost and dangers of climate change were analysed (Stern, 2006). The report focuses on two issues to slow down and, it is hoped, stop negative climate change: policy and regulation on the one hand, and technological innovation on the other. The marked attention on innovation in the 'Stern Review' is a clear indicator of the importance of technological innovation for meeting the challenges that are facing the global community, and of the fact that policy plays a crucial role for these technologies to become commercial realities. Further, the International Energy Agency, which plays a key role in advising governments on energy strategy, identifies fuel cell and hydrogen technologies as an interesting energy carrier in the time to come (IEA, 2005).

It is clear that fuel cell and hydrogen technologies lie within the strategic frame of the European Commission (EC, 2000; HFP, 2005) as well as of national governments like the US, Japan, Germany and Norway. Clearly, hopes are high, though uncertainties are abundant.

Hydrogen is an energy carrier that can be produced in two ways: either by reforming a hydrocarbon source like natural gas, methanol, or coal, or by electrolysis of water. Hydrogen is thus an energy carrier like electricity and complements renewable as well as fossil energy sources. This makes hydrogen an interesting way to store electric energy from solar cells, hydropower, wind or nuclear power. As such, the hydrogen pathway is an attractive option for connecting renewable technologies with transportation. Furthermore, hydrogen can be produced by so-called 'peak shaving'. That is, when electric energy from, for instance, wind or nuclear power plants is not taken up in the grid it is lost, but if hydrogen electrolysers are connected to the power production unit, hydrogen can be stored and the energy can later be fed back into the grid or used as a transport fuel. Hydrogen is also a by-product from chemical factories and in most cases is vented into the air. This hydrogen can be used, however, either feeding electric energy back into the production process as a fuel for fuel cells, thus reducing production costs, or else the hydrogen can be stored and used for local transportation. Both solutions are a good way to use energy more efficiently and lead to reduced CO_2 emissions.

Fuel cells is a conversion technology that converts hydrogen, methanol, natural gas or biogas to electric energy. Their efficiency is comparatively high, which makes them an interesting option for use in transportation as well as power production. In addition, fuel cells, together with hydrogen, methanol or ethanol, are perceived as an alternative to the problem of battery shortage for portable consumer electronics such as mobile phones, digital cameras and laptops. These can either function as an extension of existing batteries or replace the batteries inside the gadget. Thus, hydrogen and fuel cells are inter-related technologies that clearly may have an important role in the energy system's change to being more diverse, secure and less polluting.

The complexity of the commercialisation of the technology with respect to political and market conditions requires the active role of policy makers, and industry-government cooperation as well as inter-firm cooperation have been increasingly important. In Europe, an innovation strategy based on private-public cooperation is currently being formulated. This strategy, which encompasses the perspective of firms and national as well as regional governments, is formulated in the European Hydrogen and Fuel Cell Technology Platform (HFP). The concept of Technology Platforms (TP) has emerged as a new way of organising innovation activities at the European level in different fields of emerging technologies (EU, 2005). Since innovation at the European level involves national, regional and sectorial perspectives, the TP is therefore set up to establish coherence between the strategies at these different levels by synthesising the perspectives of all the stakeholders involved in the development and commercialisation of the technology.

Analysing the evolution of a TIS in Europe involves analysis of several levels, i.e. the regional level, the national level and, finally, the EU level. Another way of viewing the EU activities is in terms of prime movers or system builders, that is, powerful actors that have the influence to create change. There are quite large differences in interest and activities between the different countries and regions; among the countries in Europe Germany is a prime mover, with large devoted resources and commitment from industry. Leading companies from other European countries also participate in the German activities.

On the basis of the facts presented above, I regard the field of fuel cell and hydrogen technologies as an interesting case to analyse how co-evolution comes about in the formative phase of a technological innovation system. I take the situation in Europe, with the active role of industry and government creating the visions and strategies to establish coherence to overcome national and sectorial barriers as well as to reduce technological, market and political uncertainties. As such, I propose that this is a good example for further developing our understanding of evolution of technological innovation systems as a result of how actors create visions and strategies and, finally, implement these into actions. These processes lead to alignment between technology, market and institutions.

1.4. Research questions

The topic for this Ph.D. thesis is to understand what drives or determines early phases of the evolution of a TIS. It does so by taking an evolutionary approach towards TIS. This is investigated by means of stabilisation mechanisms. Thus, the main research question for the thesis is: W*hat kinds of stabilisation mechanisms are at play for the evolution of a technological innovation system in its formative phase?*

This question is highly central for understanding co-evolution of a TIS, but needs to be specified more clearly to see if the co-evolution is the result of spontaneous actions of individual actors or the result of more programmed coordination organised in platforms and formal networks. Thus, I also pose a second research question: *In which situations does co-evolution of a TIS occur as the result of stabilisation mechanisms by the spontaneous actions performed by single or few actors, and in which situation does co-evolution result from more programmed coordination such as in technology platforms and formal networks?*

The question is thus to understand in which situations and for what applications co-evolution is the result of spontaneous actions or of more orchestrated stabilisation mechanisms, and thus I contextualise the actor strategies affecting co-evolution in the formative phase.

1.5. Thesis outline

This book is organised in four sections. In section I, I present the technology description in chapter 2 and the case description in chapter 3. In section II, I present the theoretical framework in chapter 4 and the research design and methodology in chapter 5. In section III, I present the analysis, which is divided into four parts. In chapter 6, I analyse the alignment of actors; in chapter 7, I present the analysis of technology validation; and in chapter 8, I present market formation. Then in chapter 9, I conduct a comparative analysis of the eight examples I have explored. Finally, in section IV, I present the conclusions and the implications of the thesis.

2. Fuel cell and hydrogen technologies

Fuel cells and hydrogen technologies (FC&H2) are inter-related technologies that can provide energy to a diverse set of products.[2] FC&H2s range from powering cars and buses, to consumer products like laptops and mobile phones, to providing heat and electricity to buildings. The fundamental characteristics of these technologies are old. In fact, they date back to the mid-19th century, but it is only during the last decade that these technologies have achieved radical improvements such as the development of high-performance prototype vehicles, robust stationary systems providing heat and electricity to homes and offices as well as powering laptops and mobile phones. As such, they are highly generic technologies with application possibilities in a broad range of sectors and markets and have as a key feature the promise of high performance.

The basic principle of these technologies is an electrochemical reaction between hydrogen and oxygen that produces electricity and water. The fact that water vapour is the only emission in the energy conversion process makes the combination of hydrogen and fuel cell technologies an ideal solution for reducing CO_2 emissions and thus a strong component in a global move towards more environmentally friendly products and processes. Fuel cell and hydrogen technologies are complementary technologies and therefore meaningful to analyse together. As an example of this inter-dependence, hydrogen cars are dependent on a hydrogen infrastructure for practical use. There are today, according to the Fuel Cell Council, more than 40 fuel cell products now available for purchase, indicating that the industry is moving closer towards commercialisation.[3] Most companies still experience losses but have increasing revenues (PWC, 2007). However, the distance between revenues and costs is still increasing, due to the lack of mass production, and that makes production costs high.[4]

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[2] I use the abbreviation FC&H2 since the short form for hydrogen is H_2.
[3] <http://www.usfcc.com/resources/outreachproducts.html>, accessed 16 August 2007.
[4] According to PWC (2007), revenues of the fuel cell companies increased by 59% between 2005 and 2006 but at the same time, net loss also increased in the sector by 74%.

This chapter explains the fundamentals of FC&H2 and discusses the benefits, the critical barriers of the technology, different applications for use, and the characteristics of the value chain and the actors involved.

2.1. The promise of FC&H2

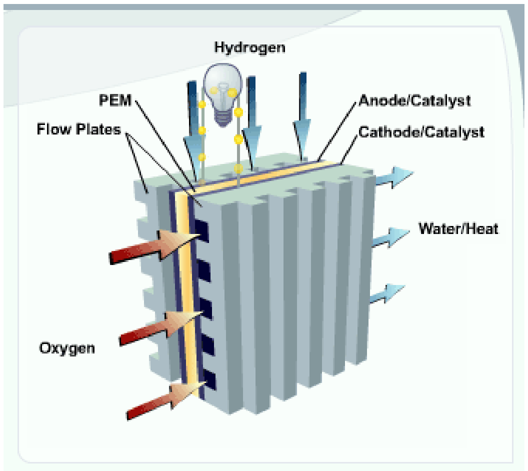
The problems with global warming, depletion of natural resources and supply of energy have become a key concern for governments, interest groups, research communities and companies across the globe. There are several critical factors concerning the global energy situation that have intensified the search for new ways of transforming the energy system from being solely dependent on carbon sources to also including new and less environmentally harmful alternatives (IEA, 2005). These factors relate, first, to the rise of China as a strong manufacturing nation and to the increase of prosperity in India. These emerging economies have increased the demand for more energy and raw materials. Second, environmental problems such as global warming critically affect the climate and have been related, for instance, to CO_2 emissions from the use of fossil fuels in energy production and transportation (IPCC, 2007; Stern, 2006). Finally, there are unstable political situations in the parts of the world where most of the present energy resources are located, implying that variation in energy production is necessary in order to secure energy delivery. These factors have amplified the importance of increased variation in the energy system and made the search for alternative energy technologies a focal point in most countries.

An area of innovation considered by many actors as a realistic alternative for large-scale as well as distributed generation of electric energy, and as a fuel in the transport sector, is FC&H2 (EC, 2000, p.: 43). The promises of the new technologies seem vast, even though uncertainties about scientific solutions, technological applications and market development are still manifold. The important role these technologies might have is evident in the recently published *Stern Review*, in which the cost and dangers of climate change were analysed (Stern, 2006), as well as in the analysis made by the *International Panel for Climate Change* (IPCC, 2007). The *Stern Review* focuses on two issues in slowing down or hopefully even stopping negative climate change: policy and regulation on the one hand, and technological innovation on the other. The strong attention on innovation in the *Stern Review* is a clear indicator of the importance of technological innovation for meeting the challenges that are facing the global community, and of the crucial role that policy plays for these technologies to become commercial realities. The *International Energy Agency,* which plays a key role in advising governments on energy strategy, identifies fuel cells and hydrogen technologies as an interesting energy carrier in the future to come (IEA, 2005).

2.2. Fuel cell technology explained

The fuel cell was invented in 1839 by the English lawyer William R. Grove, but it was not until the 1960s that F.T. Bacon demonstrated the first effective and useful cell. This is an alkaline electrolyte fuel cell, which was exported to NASA and used in its space programme. Ever since, fuel cells have provided NASA's astronauts with electricity and water for space travel. Briefly, the fuel cell is a technology that enables production of electricity by a chemical reaction between hydrogen and oxygen. In principle, the fuel cell works the same way as a battery, but it has two principal benefits. When hydrogen and oxygen react in the fuel cell, they combine and produce electricity, with water as the only exhaust. The basic chemical reaction is thus: $2H_2 + O_2 = 2H_2O$ + electricity. This process is visualised in Figure 2.1 below.

Figure 2.1: **Principles of a fuel cell**

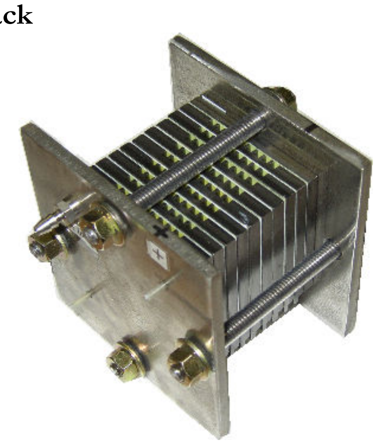


Source: Source: Wikimedia. [5]

[5] < http://commons.wikimedia.org/wiki/Image:Pem.fuelcell2.gif >,accessed 21 November, 2007.

The figure shows the two sides of a fuel cell, the anode side and the cathode side, with a membrane in the middle of the fuel cell, and the flow plates that enable hydrogen and oxygen to flow into the fuel cells and combine through the membrane. Clearly, the fuel cell has positive environmental effects since the exhaust from a fuel cell device, in a vehicle, for instance, is pure water, i.e. it has no dangerous emissions. The no-emission effect occurs when the fuel cell runs on pure hydrogen. Fuel cells can also, however, run on hydrogen-rich fuels such as methanol, natural gas or biogas, all of which involve some emissions of CO_2. A second crucial benefit with fuel cells is their high efficiency, which means that the fuel cell consumes less energy to produce the same amount of energy. As a result, fuel cells can considerably decrease energy consumption. Fuel cell technology is a modular technology in the sense that a fuel cell system consists of single fuel cells that are put on top of each other, i.e. they operate as stack. In the fuel cell stack, each single fuel cell provides some watts of energy, and when they are connected in stacks, the manufacturer can easily control the power output. Figure 2.2 shows a fuel cell stack with the different fuel cells layered on top of each other.

Figure 2.2: **The fuel cell stack**



Source: FuelCellStore. [6]

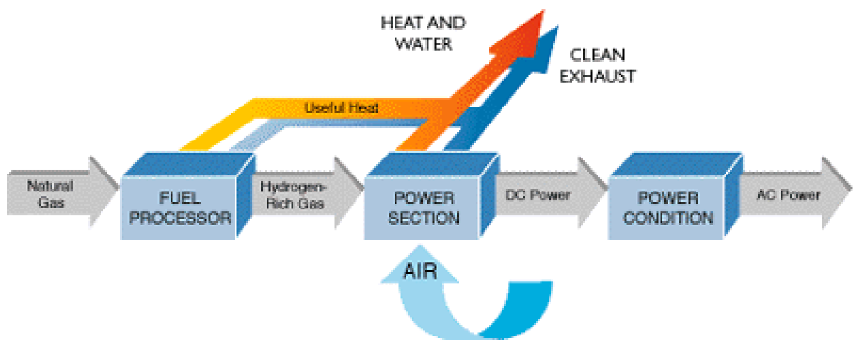
Due to the possibility of stacking the fuel cells, the system can range from a few watts to several megawatts, and from powering a consumer product such as a laptop, to producing power and heat for houses and

[6] <http://fuelcellstore.com/products/bcs/10W6V.jpg>, accessed 4 December, 2007.

buildings, to powering complete transportation systems such as buses, cars, motorbikes, and even trains and airplanes.

A further characteristic of a fuel cell system is that it is a highly complex product and its design can differ considerably depending on type and application. In general, however, fuel cells typically have three sections: the fuel processor, the power section and the power conditioner. These three sections are visualised in Figure 2.3.

Figure 2.3: **The sections of a fuel cell**



Source: US Department of Defense.[7]

First, the role of the fuel processor is to reform a fuel such as natural gas to boost the concentration of hydrogen. Second, the hydrogen-rich fuel and oxygen are then fed into the fuel cell stack (power section), which produces direct current electricity and heat. Finally, the output direct current electricity converts to alternating current electricity in the power conditioning section. Each of these sections consists of various components, which are made of materials created by companies in the chemical and advanced materials industries.[8]

2.2.1. Types of fuel cells

There are five different types of fuel cells, classified according to the electrolyte they use and to the operational temperature, i.e. the temperature in the fuel cell when it produces electricity. Two types of fuel cells, Alkaline Fuel Cell and Phosphoric Acid Fuel Cell receive little attention today. The Alkaline Fuel Cell has one advantage, and that is

[7] <http://dodfuelcell.cecer.army.mil/fcdescriptions.html>, accessed 22 August 2007.

[8] Section 2.4 explains the value chain of fuel cells and hydrogen in detail and thus goes deeper into explaining the various materials and components in the fuel cell system.

that it is relatively cheap, but it has a disadvantage, and that is that it needs pure hydrogen and is sensitive to CO_2. Therefore, it is used mainly in space flights. This was the first fuel cell system produced by Francis Bacon in 1959 and is not subject to much R&D today. The Phosphoric Acid Fuel Cell uses concentrated phosphoric acid as electrolyte, and carbon black-coated platinum as catalyst. The Phosphoric Acid Fuel Cell uses hydrogen from hydrocarbons as fuel and is employed for the most part in heat/electric cogeneration, but there have been trials in buses.

This thesis focuses on the Polymer Electrolyte Membrane Fuel Cell (PEMFC) and Direct Methanol Fuel Cell (DMFC) in transportation and on the high-temperature PEMFC, Solid Oxide Fuel Cell (SOFC) and Molten Carbonate Fuel Cell (MCFC) in stationary. This is because these types of fuel cells are the designs that firms are working with today. Most firms in the industry do not regard the PAFC and AFC as playing a significant role in the future. Of these four fuel cells designs, it is generally believed that PEMFC and DMFC are closest to commercialisation (Crawley, 2007; NIP, 2007), with the highest number of organisations characterised as 'commercial' rather than R&D organisations. Table 2.1 presents the types of fuel cells and shows their working temperatures, electrolyte and area of application.

Table 2.1: **The different fuel cell types**

	MCFC	**SOFC**	**PEMFC**	**DMFC**
Electrolyte	Molten Carbonate	Zirconium/oxide	Polymer	Polymer
Operating temp.	650°C	600-1000°C	80°C	50-200°C
Fuels	H_2/CO/ Reformate	$H_2/CO/CH_4$ Reformate	H_2 Reformate	Methanol
Reforming	External/ Internal	External/ Internal	External	Internal
Oxidant	CO_2/O_2/Air	O_2/Air	O_2/Air	O_2/Air
Efficiency (HHV)	50-60%	45-55%	40-50%	40-50%
Main application	Power prod.	Power prod.	Transport	Portable

Source: US Department of Defense, accessed 22 August 2007.[9]

Fuel cells are normally distinguished on the basis of whether they are high-temperature or low-temperature fuel cells. Thus, the PEMFC, and

[9] <http://dodfuelcell.cecer.army.mil/fcdescriptions.html>, accessed 22 August 2007.

DMFC are low temperature, while the MCFC and SOFC are high temperature. The areas of application are also different, so that the low-temperature fuel cells are appropriate mainly for transportation, while the high-temperature fuel cells are used for electricity production. The DMFC, which is a form of PEMFC, is the preferred alternative for micro portable applications such as laptops and mobile phones, as well as for auxiliary power units in transport applications. The PEMFC operates at low temperatures, and this makes it suitable to for a car with short starting time. The SOFC needs to be heated to 600 degrees Celsius and thus requires a very long start-up time.

PEMFC

General Electric invented the Polymer Electrolyte Membrane Fuel Cell (PEMFC) in the early 1960s. It has an electrolyte made of a thin, acidic ion exchanging membrane and this acts as a proton conductor. The Nafion membrane developed by Dupont in 1966 is the industry standard for membranes, but a great deal of work is being done to develop better and cheaper membranes, both by companies and by universities.

Inside the PEMFC, the key part is the Membrane Electrode Assembly (MEA), known as the heart of the fuel cell and crucial for the performance of the cell. The MEA consists of the electrodes (anode and cathode), a catalyst, and the polymer electrolyte membrane. The electrode embeds the catalyst active layer inside the MEA.

The anode, which is the negative side of the fuel cell, conducts the electrons that are freed from the hydrogen molecules so they can be used in an external circuit. Channels engraved in the anode diffuse the hydrogen gas over the surface of the catalyst. At the positive cathode side of the fuel cell, oxygen is distributed to the surface of the catalyst through channels and the electrons are conducted back from the external circuit to the catalyst, where they recombine with the hydrogen ions and oxygen to form water. The polymer electrolyte membrane is a material that looks similar to ordinary kitchen plastic wrap but has a particular function, namely to conduct only positively charged ions and to block the electrons. When a fuel cell's system produces electricity, the reactions occur very slowly at a low operating temperature. In order to speed up the reaction process the electrodes are coated on one side with a catalyst layer, in most cases made of platinum powder thinly coated onto carbon paper or cloth. The platinum is thus a critical component for catalysing reactions in the fuel cell.

The PEMFC operates at low temperatures, which makes it ideal for transportation purposes. The low operating temperature makes it possible to start and stop the fuel cell continually, and this feature is important for transportation use. Transport applications require a dynamic operation of the fuel cells compared to stationary fuel cells that might run for weeks without interruption.

A key problem with PEMFCs is that the membrane can dry out, and this makes water management important. Another problem is that PEMFCs require extremely pure hydrogen, in the range of 99.999% purity. Thus, advanced reforming technology is required to remove impurities in the hydrogen. This increases the cost of the system. Some firms are currently developing high-temperature PEMFCs for stationary and portable applications in order to reduce problems with hydrogen poisoning of the membrane.

DMFC

The DMFC is a related PEMFC but operates directly on methanol (CH_3OH) as fuel. The methanol is not reformed, but fed directly to the fuel cell, thus a Direct Methanol Fuel Cell. A clear benefit of this design is that since methanol feeds directly into the fuel cell, complicated catalytic reforming becomes unnecessary. Another benefit is that methanol is more convenient to store than hydrogen because methanol, being a liquid, does not need to be stored at high pressures or low temperatures. The fact is that the energy density of methanol is much greater than that of highly compressed hydrogen. A problem with ;he DMFC, however, is its low efficiency compared to the PEMFC due to the high permeation of methanol through the membrane, what is known as methanol crossover. Another problem with the DMFC is the management of the carbon dioxide created at the anode. Current DMFCs are limited in the power they can produce, but they can still store a large amount of energy in a small space. This means that they can produce a small amount of power over a long period. This fact has made DMFCs the chosen design for companies working with consumer electronics that need the energy tank in a small space. For powering vehicles, however, they are not a good match.

SOFC

The Solid Oxide Fuel Cell (SOFC) is a high-temperature fuel cell that uses an electrolyte consisting of an oxygen ion-conducting ceramic. It is typically used for stationary combined heat and electricity plants (CHP). There is some ongoing research on using small SOCFs in transportation, but this is mainly for auxiliary power units (APU), that is, for purposes other than propulsion of the vehicle. The high temperature makes it possible to convert hydrocarbons such as natural gas directly, and thus removes the need for a reformer. For a fuel cell such as the PEMFC on the other hand, which can only operate on hydrogen, there is a need for additional reforming technology to convert natural gas, etc. to hydrogen in the system.

Baur and Preis developed the SOFC in 1937. This design is heavily researched today as it has high efficiency; in fact, it can exceed 60%, which makes it very suitable for power production. In cogeneration of heat and power, its efficiency can reach over 90%, a considerable achievement for a technology. SOFC is also used in hybrid systems together with gas turbines for combined heat and power production (CHP), and can reach efficiencies over 70%. One of the advantages of the SOFC is that the high temperatures remove the need for a metal catalyst, thereby enabling cutting costs in fuel cell production. It is also less vulnerable to impurities in hydrogen, thus lowering the need for reformation as compared to PEMFC.

MCFC

The Molten Carbonate Fuel Cell (MCFC) operates at high temperatures and is used in electricity production in large-scale plants. Carbonate salts are used as the electrolyte in the cell; they melt when the cell is heated to 650 degrees Celsius and conduct carbonate ions (CO_3) from the cathode to the anode. Hydrogen reacts with the ions at the anode to produce water, carbon dioxide and electrons. A clear benefit of MCFCs is that hydrogen can be extracted from various fuels, using either an internal or an external reformer. Another benefit of their high temperature is that they become less vulnerable to carbon monoxide poisoning than the lower-temperature fuel cells. MCFCs can also use catalysts made of nickel, which is much less expensive than platinum. The efficiency can be very high, up to 60% in the system itself, and if the waste heat is utilised for cogeneration the overall efficiency can rise up to 80%.

There are currently two major difficulties with MCFCs, which makes them less attractive as compared to solid oxide cells. First, there is a complexity involved in working with a liquid electrolyte rather than a solid. Second, as an effect of the chemical reaction inside a molten carbonate cell, the carbonate ions from the electrolyte are consumed in the reactions at the anode, making it necessary to compensate by injecting carbon dioxide at the cathode.

2.2.2. Fuel cell barriers

This section discusses the four types of fuel cells that are in focus in this thesis. There are particular technological and market-related barriers that are relevant for all types of fuel cells and some that are unique to each type. The main barriers are *cost*, *reliability*, *durability and infrastructure*. Table 2.2 shows the different barriers for the various applications.

First, the largest barrier for commercialisation of fuel cells in general is the *cost*. Fuel cells cannot compete in price with other technologies such as batteries, generators, or the combustion engine in cars. Thus, the technologies must have additional performance to defend their higher price. While low production volumes (i.e. demo units) are currently a factor in cost, a key barrier relating to cost is the use of expensive and exotic materials in fuel cells to increase performance. One cost problem is the use of platinum (Pt) as a catalyst. One key target in most fuel cell programmes, that of the US Department of Energy, for instance, is to reduce the amount of platinum by at least a factor of 20 or ideally eliminate it altogether in order to decrease the cost of fuel cells to consumers. In addition, the price of membranes is very high and their durability is not yet satisfactory. The effect of economies of scale (i.e. prices falling due to mass production) could be a solution in getting lower prices. The problem for platinum catalysts, however, is that platinum is a scarce resource, and its price will not fall due to larger quantities. Cost barriers for SOFCs relate to expensive materials, and because the producers are uncertain about the resistance of materials, and therefore increase the thickness in the components, this too leads to higher prices.

Table 2.2: **Main technological barriers for stationary and transport fuel cell applications**

	Micro CHP	**Industrial CHP**	**Road Transport**	**APU (Transport)**
Cost: Catalyst	PEM: Pt loading of MEA factor 2-5 needed	Low-cost catalysts (SOFC & MCFC)	Pt loading of MEA factor 2-5 needed	SOFC: Low-cost catalyst PEM factor 2-5
Cost: Membrane	Not relevant for SOFC	Not relevant	Decrease membrane cost	Decrease membrane cost for PEM
Lifetime and durability	~ factor 5-10 needed	~ factor 5 needed	~ factor 2-5 needed	~ factor 2-5 needed
Power density	Sufficient	Sufficient	Sufficient for smaller cars	Sufficient for trucks, boats
Infra-structure issues	Solved (NG fuelled)	Solved (NG fuelled)	Open	Solved (reforming of diesel/ gasoline)

Source: Based on HFP Deployment Strategy (2005).

Second, *durability* of the FC systems is a critical barrier because these still need to be improved by a factor of 2 to 10. The durability issue is most critical for micro combined heat and power production (CHP). Lifetime of the systems must improve in order to make them competitive in relation to gas boilers and turbines. The stack lifetime in a stationary system must exceed 40,000 hours, while for transport the target is 5,000 hours. However, the overall cost reduction target of transport applications is much higher. The durability problems for SOFCs relate mainly to corrosion in the cells. The high operating temperatures of SOCFs make corrosion a problem, and this requires expensive materials and protective layers in the cell, further increasing the costs. Regarding the third concern, the firms have managed to develop fuel cells with sufficient *power density* for the smaller cars and for stationary use. Thus, this is no longer a barrier. The fourth barrier relates to *infrastructure issues*. For the stationary applications of micro

CHP and industrial CHP, this issue has been solved by using natural gas, while for transport it is still an open question. For auxiliary power units, the firms have solved this by using reformer technology.

2.3. Hydrogen technology explained

Hydrogen is the most abundant element in the universe, constituting about 80% of its elementary mass. It is the most flexible of all energy carriers and can be utilized in the same way as electricity, but this also means that hydrogen has to be produced from a primary energy source. As a fuel, hydrogen can be used to power mobile phones and large-scale centralised power stations in the megawatt size, as well as anything in between. Hydrogen has a strong relation to fuel cells, since hydrogen is the crucial energy carrier in fuel cells.

Hydrogen technology currently holds a more prominent role in the transportation sector, as the major companies view it as one of the key fuels of the future. For stationary applications on the other hand, the natural gas infrastructure will be in use at least until 2020. However, hydrogen will play a key role in some niche markets and special markets, in the form of by-product hydrogen from the chemical industry, for instance, and for applications not connected to the grid, such as remote islands.

2.3.1. Production of Hydrogen

A challenge involved with hydrogen is how to obtain it. Though hydrogen is the most abundant component in the world, the problem is that it does not exist in a pure form; it always combines with other atoms. Thus, hydrogen must be obtained from somewhere, and that involves the use of energy. It is therefore important that hydrogen is produced at an acceptable price and that its production involves a process that in the end will have positive environmental effect.

The ways hydrogen can be produced are:

- Steam methane reforming from fossil raw materials, mainly coal and natural gas
- Bio-mass and solar-thermal for direct production of hydrogen

- Electrolysis of water with electricity from renewable sources such as wind, solar and hydro
- Electrolysis of water with electricity from nuclear power[10]
- Directly from nuclear heat

The important differences between the various means for producing hydrogen are defined by the use of renewable sources, the use of fossil fuels, and the use of nuclear power.[11] This difference also separates the EU and the US in their respective attitudes towards hydrogen production in the future. While the EU seeks, in the long term, to produce hydrogen from renewable sources, the US wants to use fossil and nuclear energy sources (Economist, 2003). The US alternative makes the cities cleaner because of zero-emission cars, but requires either complex carbon capture and storage technology to avoid CO_2 or the acceptance of increased use of nuclear power.

One interesting and cost-effective alternative is hydrogen produced from electrolysis by so-called 'peak shaving'. When the grid is not able to consume the electric energy from, for instance, wind or nuclear power plants (peak production), it is lost. However, by connecting hydrogen electrolysers to the power production unit, hydrogen can be stored and the energy later fed back into the grid or used as a transport fuel. Hydrogen is also a by-product from chemical factories and in many cases is just burnt. By using the hydrogen, electrical energy can either be fed into the production process, thus reducing cost, or stored and used for local transportation. Both solutions are a good way to use energy more efficiently and lead to reduced CO_2 emissions. In the following, the two major ways of producing hydrogen will be explained; these are steam reforming of natural gas and electrolysis of water.

Steam methane reforming

Steam methane reforming (SMR) is the dominant method of producing hydrogen and constitutes about 50% of global production (Romm, 2005). SMR is used to produce commercial bulk hydrogen for use in

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[10] There is an ongoing debate about whether using nuclear energy to produce hydrogen is an environmentally sound solution.
[11] Many consider nuclear power an option with far too many risks.

industry, for example, in the industrial synthesis of ammonia and in oil refineries. In addition, small-scale steam reformers are currently in development to produce hydrogen on-site for transportation applications. These are the most common hydrogen production methods today for industrial and transport applications. Steam reforming, based on natural gas or some other hydrocarbon as feedstock, produces the hydrogen at high temperatures (700-1100 °C), when the steam reacts with methane in the presence of a metal-based catalyst (nickel) to yield carbon monoxide and hydrogen.

There are several challenges that have to be solved with steam reforming. First, since the reforming reaction occurs at very high temperatures the start-up of the process is slow. Second, the reformer requires costly materials suitable for high temperatures. Third, the carbon monoxide produced can poison the fuel cell, making it necessary to include complex carbon monoxide removal systems. Fourth, the catalyst is very expensive.

Electrolysis of water

Electrolysis of water is the opposite reaction to what occurs in a fuel cell. While the fuel cell produces electricity and water from oxygen and hydrogen, the electrolyser uses electricity to split water into hydrogen and oxygen. Electricity is fed into water, and the electric current causes oxygen to flow from the anode side and hydrogen from the cathode side.

With hydrogen electrolysis, a renewable energy source like wind or solar can be used as the primary energy source to produce hydrogen totally without pollution. Similar to fuel cells, electrolysers consist of an anode and a cathode separated by an electrolyte. The electrolyte determines the type of electrolyser and its operating conditions. Alkaline electrolysers are used mainly for large-scale applications (megawatt size) while PEM electrolysers are used for small-scale applications (kilowatt size). Thus, PEM electrolysers are used for on-site generation of hydrogen while alkaline electrolysers are used for mass production off site and the hydrogen is transported to the distribution site. The alkaline electrolyser is a mature technology; the first system was built in Norway in 1927. The electrolyser uses an aqueous potassium hydrate (KOH) solution (caustic) as an electrolyte. PEM electrolysers are a less mature technology than the alkaline; the first significant adoption occurred in the 1980s by the UK Royal Navy and the US Navy to generate oxygen in nuclear submarines (Newborough, 2004). PEM electrolysers are similar to PEMFCs in the sense that they use a polymer electrolyte membrane to induce the process. The water on the anode side separates to form oxygen and positively charged hydrogen ions. The hydrogen ions then move through the membrane to the cathode. Finally, on the cathode side, hydrogen ions combine with electrons from the external circuit to form hydrogen gas.

2.3.2. Storage and distribution of hydrogen

One of the major barriers with regard to hydrogen as an energy carrier is the lack of satisfactory storage alternatives. Hydrogen takes up a lot of space, and if hydrogen is to be used in large scale, then basic problems related to storage have to be solved. Several possible solutions to this problem have been proposed, and there are, in essence, three options for hydrogen storage:

- Hydrogen may be compressed and stored in a pressure tank, currently at 350 or 700 bar.
- Hydrogen may be cooled to a liquid state and kept cold in a properly insulated tank.
- Hydrogen may be stored in a solid compound such as a metal hydride, in carbons, in methanol, or in gasoline and other hydrocarbons.

Hydrogen storage in the vehicle is a substantial barrier to commercialising hydrogen vehicles. In order for the vehicle to travel far enough, the hydrogen needs to be compressed, liquefied or stored in a solid compound. This has further implications for increased cost and increased complexity.

Hydrogen can be distributed via pipelines, trucks or on-site generation. It can be retailed through fully automated fuel dispensers that do all the operations or through something like a traditional gasoline dispenser.

2.4. The value chain for FC&H2

This emerging technological field encompasses firms from many diverse industries and knowledge fields that are developing materials, components and systems. The field is a result of convergence between new fields of knowledge such as material science, nano-technology and energy storage, and mature industries such as automotive, energy production, industrial gases, chemicals, electronics and information technology.

Many products on the market today consist of different modules fitted together by system integrators (Baldwin & Clark, 2000). Increasing vertical disintegration in a broad range of industries has decentralised the value chain, with small firms specialising in production of specific components for use in different products. This process has led to system integration and component development being two different sides of business strategy (Prencipe, Davies, & Hobday, 2005).

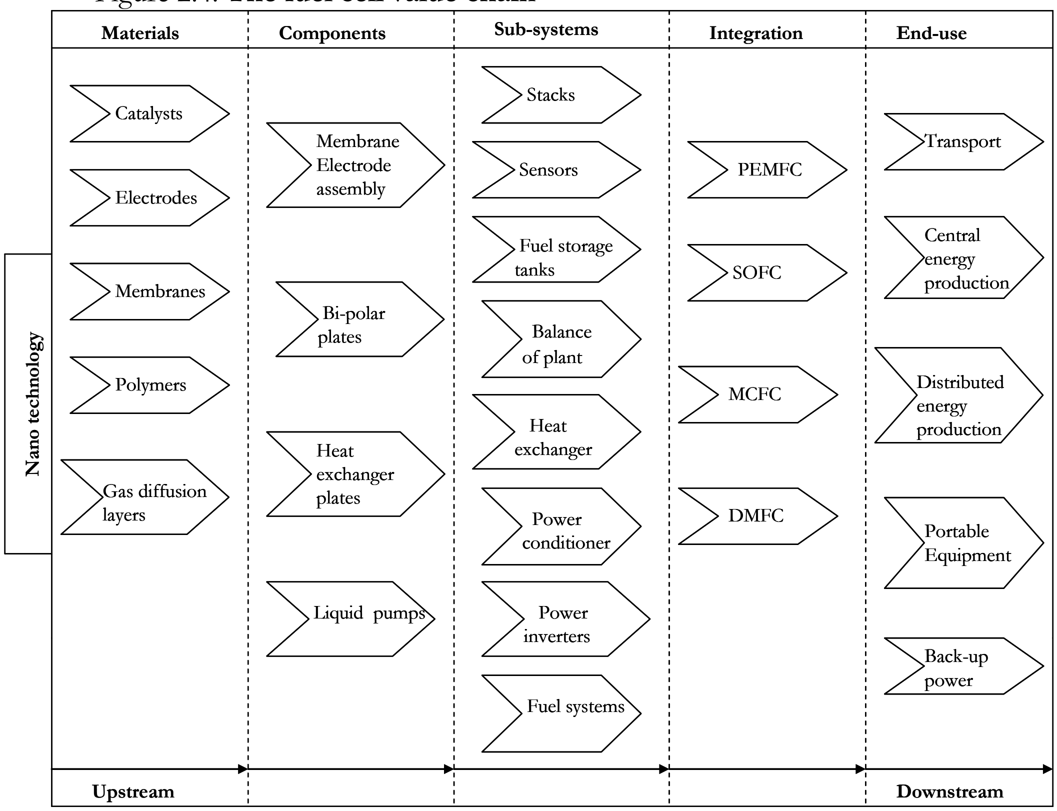
The value chain for fuel cells and hydrogen technologies is clearly decentralised, with firms specialising in various fields. In Figure 2.4, the value chain for fuel cells is visualised and which includes related hydrogen technology. In figure 2.5 the value chain for hydrogen production and distribution is presented.

In the fuel cell value chain, the first level is what can be called *materials* and includes new materials for basic processes, such as catalysts, electrodes, polymers, membranes and gas diffusion layers. These are usually generic products and processes and thus fit into a range of products belonging to several sectors, of which only a few relate to the fuel cell and hydrogen field.

The second level is *components* and *sub-systems*, (columns 2 and 3) such as sensors, membrane electron assembly (MEA), stacks, bipolar plates, fans, hydrogen and other fuel storage systems. Many of these components are generic for fuel cells, so that they can work for all types of applications. Other components relate to a certain type of application.

The third level is *integration*, where the components and sub-systems are integrated into a fuel cell system or electrolyser systems (the two main technological systems). These systems are usually utilised by other firms, original equipment manufacturers (OEMs), in complete products, such as an automobile, a hydrogen filling station or a laptop. They can also function as a Stand Alone Power System to power a device.

Figure 2.4: **The fuel cell value chain**

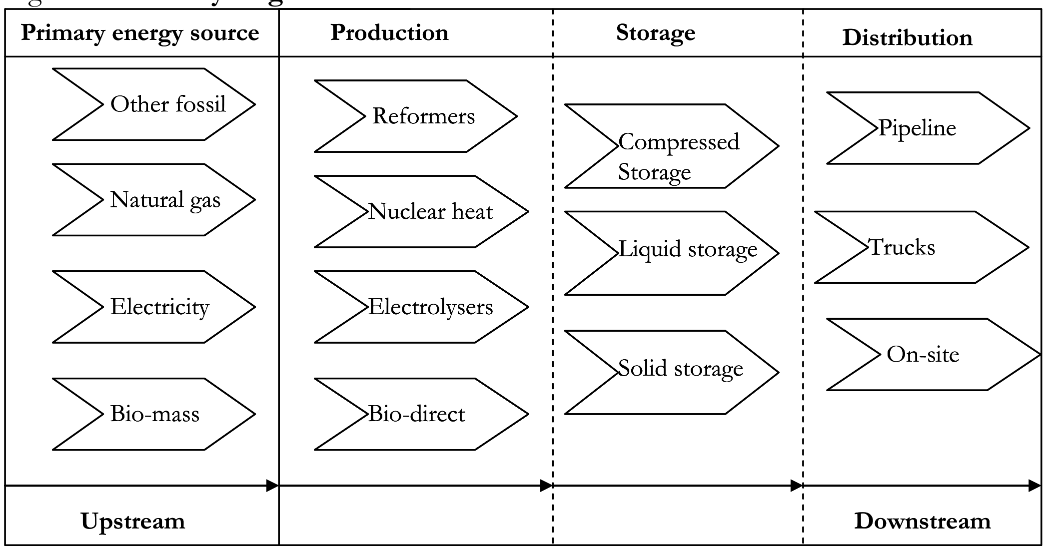


Source: Interviews with companies.

Finally, the fourth level is *end-use*, where a firm transfers technology into a product, that is, a car, a laptop or a back-up power system for a large firm, such as a telecom service provider. These firms belong to a specific user industry and search for novelty and new technologies that can give them an advantage in their product development.

The value chain for hydrogen technologies can be separated into three parts: *hydrogen production technology,* that is, steam reformers and electrolysers; *hydrogen storage* at the filling station and in the vehicle; and finally, *distribution and retailing*. Figure 2.5 presents the value chain with the various parts from production of hydrogen based on various feedstocks of primary energy sources, to storage and distribution.

Figure 2.5: **The hydrogen value chain**



Source: Interviews with companies.

A central type of actor is the industrial gas companies. These have produced and distributed hydrogen for almost a century, and for companies that have worked with hydrogen for such a long time it is not such an exotic chemical. So when it comes to the introduction of hydrogen in the transport sector, industrial gas companies have the possibility to leverage on decades of handling hydrogen in industrial settings. For industrial use, then, this is a mature technology. The oil companies are currently involved in the distribution of hydrogen using the existing gasoline distribution network. In the hydrogen production field there have been a lot of acquisitions in terms of electrolyser producers, and there are few companies now with a product on the market. The newcomers are appearing in storage technology, where companies are developing advanced systems for compressed, liquid and solid state storage

2.5. Summary

This chapter has explained the particular features of the technologies and value chain. This constitutes the empirical case for the thesis and includes actors from various knowledge fields and industries. The technologies still have many uncertainties, which firms need to solve before mass-market introduction will take place. The value chains for FC&H2 technology are also decentralised, with various firms specialising in particular technologies. Thus, cooperation along and across value chains is a key activity of the firms.

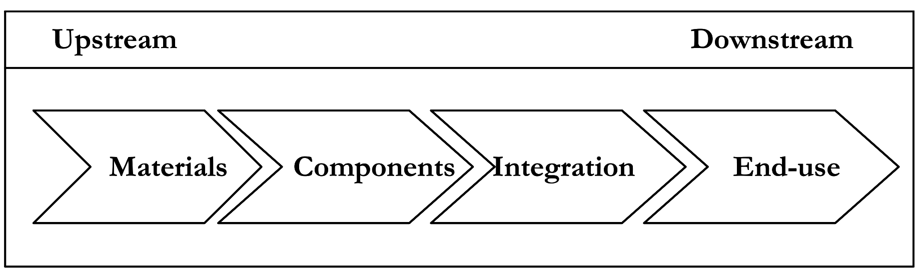
3. Characterising the applications

This chapter describes the two types of applications (the two cases) that the thesis analyses – stationary versus transport applications – and the four product examples that are elaborated in each case. In fact, each of the examples I use is a specific product consisting of various systems that fit together. Each system, again, consists of different components and each of these is built from different materials. First, however, in order to guide the reader through the empirical material and make sense of the various firms' strategies as related to their positions in the value chains, I present the various types of actors in a 'stylised' form.

3.1. The value chain and its stylised actors

In this section, I present the various actors involved in the different cases used in the thesis, and relate them to their role in the value chain and their role in technology versus market development respectively. The actors involved in technology development come from the whole value chain, while the actors important for market development are the end-use integrators and system integrators.

Figure 3.1: **Simplified version of the FC&H2 value chain**



First, the firms responsible for defining the products in the transportation sector are the *end-user firms* (see the rightmost column in the figure), such as oil companies and the automotive OEMs. For the end-use level (product definition), I include three different types of firms (see Table 3.1). The first end-user firm is the *automotive OEM* working with integration of vehicles.[12] The HFCV has a modular design, where the auto OEM designs the specifications of the vehicle

[12] Some of the OEMs also have system integration in-house, as this is a strategic component in the vehicle.

while the different suppliers develop components according to these specifications. The automotive OEMs have approximately 15 different suppliers involved in this process, and the key relationships are to the fuel cell system integrator and various key component suppliers, i.e. their tier-1 suppliers.

Table 3.1: **Stylised actors involved in FC&H2**

Part of value chain in Figure 3.1	**Type of actor**	**Technology focus**	**Strategic focus**
End-user	Oil company	Fuel distribution	Infrastructure for hydrogen
End-user	Automotive OEM	Vehicle production	Develop variation in vehicles, establish technological leaderships
End-user	Heating company	Energy and heat production	Integrate fuel cells for homes and businesses
System integrator of hydrogen technology	Industrial gas company	Electrolysers, reformer technology, storage technology	Hydrogen production and distribution technology
System integrator of fuel cells	Fuel cell system integrator	Fuel cell system development	Integrate component technologies into a complete system
Component and sub-system developer	Specialised firm for components to FC&H2, and other sectors	Specific components: MEA, bi-polar plates, liquid pumps, etc.	Integrate new material knowledge into components
Material developer	Firm with strong knowledge of basic science	Materials: polymers, membranes, catalysts, etc.	Functionality and cost of materials

Source: Based on interview data.

The end users are also important for market development. One type of key actor is an *oil company* that targets hydrogen distribution. The key strategy of the oil companies relates to using their existing gasoline retailing networks to build a market for hydrogen. The key relationships are towards the automotive OEMs in terms of product development, while technology development takes place externally with industrial gas companies. In addition, the *industrial gas companies* focus on development of hydrogen production and distribution technology, and target technology development to the fuel retailers. The final end-user firm is for the stationary applications, where a key actor is an end-use firm targeting micro CHP in homes and for businesses. This firm develops relationships to the end-user firms to integrate the product into buildings, as well as to component suppliers to improve the product.

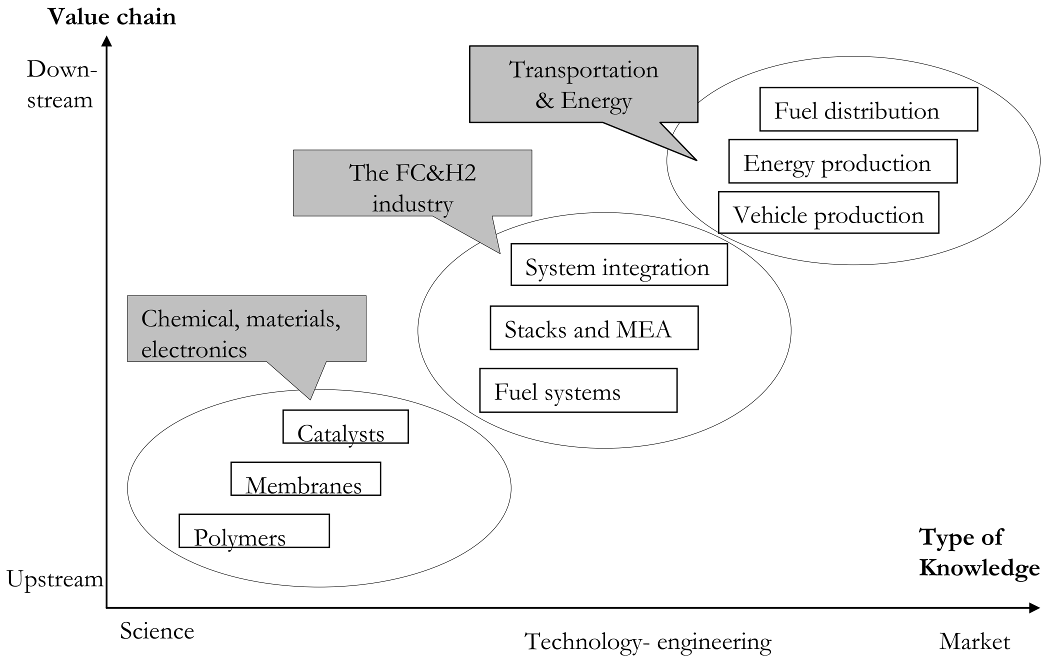
Second, at the *system integration level*, actors have a key technology strategy function in connecting the different component and materials developers and integrating their technologies into a fuel cell system. The key strategy is thus to cooperate with the leading component and materials developers, as well as to establish links to leading end-use firms in the stationary and transport markets. With regard to their importance also as market developers, the system integrators can be categorised according to the various end-use solutions they target. Thus, the system integrators in this thesis target such applications as back-up solutions for the telecom market, by-product hydrogen, consumer vehicles, large-scale FC systems for the energy sector, forklift applications, and auxiliary power units for the leisure market.

Third, at the *component level,* this firm develops components and sub-systems for the system integrators. Thus, the key relationships for this firm are towards system integrators, as well as to materials producers and universities. These firms are specialised FC&H2 firms and belong to the fuel cells and hydrogen industry.

Forth, at the *materials level*, this firm develops various materials for the component and system integrators. This firm has key connections to a system integrator, and its key strategy is to be a tier-1 supplier in the automotive value chain to one or more OEMs as well as in the value chain for stationary applications. These firms belong to the chemical and materials industries.

Clearly, the firms at the upstream side of the value chain – that is, materials developers and component developers (the left columns in Figure 3.2) – play a crucial role in technology development as they improve the functionality of the various components that are crucial for improving the performance of the whole system. These firms are highly specialised in one particular component or sub-system. Here, firms are active in all application areas. As such, they have relationships to many downstream actors in the value chain, that is, to both stationary and transport applications. In contrast, firms in the downstream part of the value chain are mostly specialised in one application area and play a decisive role in market formation. The position of the firm in the value chain and the focus of the firm is visualised in Figure 3.2.

Figure 3.2: **Knowledge type and position of the firm in the value chain**



Source: Analysis from interviews with companies.

This figure shows the type of knowledge the firm works with and the industry to which it belongs[13].

3.2. Case 1: The market for transport applications

Transport applications that involve fuel cells and hydrogen technologies range from consumer vehicles and public-use vehicles to auxiliary power units for caravans and sailing boats, and to specialist vehicles like forklifts. Furthermore, fuel cells and hydrogen can be both a supplementary technology and a substitute for batteries and internal combustion engines. As a supplementary technology, for instance, FC&H2 can provide power to electronic equipment when the technology is not on the road and thus save fuel and reduce emissions. This section will explain the important aspects of the various

[13] The role of the actors in the value chain will be further analysed in chapter 7, Validation of technology

submarkets, including the actors involved and their basic strategies for commercialising the FC&H2 in a particular market.

3.2.1. Auxiliary power units for caravans

Fuel cells can function as auxiliary power units (APU), a technology that is being used to provide additional energy for vehicles in the recreational market, such as caravans and sailing boats, as well as for police cars and military vehicles. Using fuel cells as APUs in caravans creates additional performance in the sense that caravans are requiring increasing quantities of electricity to power TVs, computers and other electronic equipment. Due to the increased use of electronic devices in the caravan, the battery discharges rapidly. This means that the caravan needs to run its engine to recharge the batteries, and using a diesel engine in a camping site generates pollution and noise. This is therefore not a satisfactory solution. By installing a small fuel cell system that runs directly on methanol (DMFC) or propane, the user can obtain electricity directly without using the batteries, and the need to idle the engine disappears. Thus, the fuel cell system adds performance in terms of less noise and pollution, and in the form of more electric energy for electronic equipment.

This application area has proven to be an important niche market for fuel cell developers and has created initial revenues for some companies in Europe. One company in particular is a market leader in fuel cell market deployment due to its success in commercialising fuel cell technology in the caravanning market. This typical system integrator firm operates with a strategy based on the existence of some niche markets in which the firm is able to employ the technology and the users are willing to pay a premium price for that technology. At a later stage, when scale and learning effects improve the performance of the technology and the cost decreases, the firm can target other markets with stricter cost/performance criteria. The strategy of this firm has been to identify the particular features of fuel cell technology and to search for market contexts in which the technology offers benefits to users at the present stage of technology performance. One of this firm's key achievements is that it created its own infrastructure for methanol distribution to secure for users a wide distribution of fuel for the firm's fuel cell systems. This example is a highly interesting case for studying firm strategy in new technological areas.

3.2.2. Forklifts

The industrial market is a niche market for several firms targeting special-purpose vehicles like forklifts. These constitute an application area for fast market introduction where fuel cell systems have the potential to replace battery systems in small- to medium-sized forklifts. Several companies as well as strategy reports consider the forklift application area to be an economically viable proposition even in low volumes and at high costs (HFP, 2005, , 2007). For example, Hugh et al. (2007), commenting on the latest industry trends in 2007, observed that the extent of early market opportunities has increased dramatically in the last years. The example they highlight as the most promising market is the forklift market, in which 'fuel cells have a great prospect for rivalling the existing battery-based forklift power systems as they present lower total costs of ownership than the incumbent technologies deployed and have quick refuelling' (Hugh, Todd, & Butler, 2007). Hydrogen fuel cells have two major benefits for the materials handling firms that use forklifts. First, the fuel cell systems offer advantages in terms of environmental benefits, since most of these operate indoors at least part of the time. The indoor operation of forklifts makes exhaust from diesel engines a major problem. Clearly, forklifts powered by hydrogen fuel cells with no emissions have an obvious advantage for the users. Second, the fuel cell systems also offer benefits in terms of ease of use, as batteries take a considerable time to recharge, and with lower total operating cost, they have a financial advantage over battery technology. [14]

The system integrator firm is a key actor for the forklift applications. The specific strategy of this firm is based on the fact that users are willing to pay the premium price for the technology, and the low complexity of infrastructure development reduces uncertainty in market formation. Since the vehicle operates inside or close to a building, a single filling station is sufficient. This market is thus possible for a single actor or a small consortium to develop. In this case, relationships exist between a system integrator, a forklift manufacturer and a fuel distributor. The firms develop the fuel cell system in such a way that it

[14] Another supporting factor for fuel cells is that each forklift requires two batteries for continuous operation, one in use, one recharging, and perhaps even one dedicated charging unit.

fits directly into the battery compartment of the forklift, thus offering forklift users ease in making the transition.

3.2.3. Fleet vehicles

The third type of transport applications is 'fleet vehicles' or 'return-to-base vehicles'. This is a product group consisting of regular vehicles that are used only within a limited area, such as a city or region. These products require less coordination between technology and infrastructure than consumer vehicles because the users of fleet vehicles operate within a small geographical area and have limited infrastructure requirements. Thus, it is much easier for the firms involved to plan and carry out market development. The fleet users are public and private actors like taxis, delivery vans and postal services, as well as all others with limited range requirements.

Fleet vehicles are a key product in the market strategy of OEMs and oil companies, having fewer requirements for technology coordination (fuel and car) and constituting a smaller market where firms can identify and analyse user requirements. The approach targets local market actors such as public users that procure vehicles. The key actors are a small network of firms in which one firm is responsible for the supply of vehicles, one firm is responsible for fuel distribution and a third firm provides the hydrogen production technology. I label the strategy of these firms a 'cluster approach' for creating and building the market.

The cluster approach relates to the fact that the supporting framework, such as required infrastructure, codes and standards for fuelling and safety, is coordinated in a city or a region, where the firms build an infrastructure such as a cluster of several filling stations offering a limited range to a number of vehicles. The strategy of these firms is to enable an early market, i.e. for HFCVs, which can later expand into mass markets, i.e. for consumer vehicles. This will require a much larger infrastructure, however. Demonstrating fleet vehicles prepares a bridge into early markets and is thus a key strategic tool for the various large actors in the automotive and fuel industries. This occur as they can create variety in their portfolios and gradually upgrade production if and when FC&H2 fulfils the technology requirements of users and the early market users respond positively.

3.2.4. Consumer vehicles

The largest and most difficult of all the transport applications for FC&H2 is the global consumer vehicle market. FC&H2 stands in direct competition with the internal combustion engine (ICE), which has experienced a century of incremental innovation, and with other experimental vehicles such as electric and hybrid vehicles. In terms of performance, the consumers are more than satisfied with the ICE vehicle; in fact, performance has gradually improved over that century of incremental innovation to make today's vehicles impressive in terms of speed, driving range and comfort. Thus, in order to be competitive, FC&H2 vehicles need to offer the customer an equal or better performance, and for this, performance improvement is required.

The key actors in this example are automotive OEMs, and I have found two different strategies in these firms. The first strategy is to use small-size city cars with fuel cells. For this firm, the cases of fleet cars and consumer vehicles are related, since the key strategy is first to develop the market for fleet vehicles; then, as the technology matures and infrastructure is gradually built up, the vehicles will be introduced into consumer markets. The second strategy is to use a fleet of large executive cars, running on hydrogen ICE. This strategy is based on creating a high level of visibility for hydrogen as a transport fuel and providing demonstration vehicles directly to key decision makers in the US and Europe. This will then affect the attitudes of the decision makers positively towards hydrogen as a transport fuel and help build a market for hydrogen as a fuel. The infrastructure companies that coordinate development with the automotive firms are another set of key actors. These are major oil companies. In addition, policy makers are crucial for supporting market introduction and providing the right institutional framework.

3.3. Case 2: The market for stationary applications

Stationary applications consist of product groups that are small scale and large scale. Small-scale applications can power different products with functions like producing heating and electricity in a home, backing up a telecom base station or generating off-grid electricity, while large-scale applications are industrial power production in the megawatt size. An important distinction in stationary applications is between centralised and decentralised power production; another is cogeneration, where the fuel cell system produces heat and power (CHP) simultaneously. This section presents four different examples of stationary applications that are analysed in the thesis: micro CHP, large-scale power production, by-product hydrogen and telecom back-up.

3.3.1. Micro CHP

Micro CHP is combined heat and power production, and is also known as on-site generation, distributed generation or decentralised generation. Micro CHP is a method of generating electricity from numerous small sources, which includes, for instance, solar panels on roofs of houses and natural gas-fired micro-turbines and fuel cells located in homes and office buildings. The application area is a potentially large and important market that offers benefits in terms of energy security, efficiency and reduction of pollutants.

This market stands in contrast to the dominant production of electricity in large power plants. The latter have excellent economies of scale, but the transmission of electricity over long distances leads to losses, and most plants do not allow for utilisation of waste heat. Distributed generation offers the benefits of reducing the amount of energy lost in transmitting electricity, because the electricity generation occurs close to where it is used. It also reduces the number of power lines that must be constructed and reduces peak power (HFP, 2005; Hydrogen-strategy-group, 2005).

The key actors in this application area are system integrators and end-use integrators that integrate SOFC systems into homes and small businesses. The strategy is to use SOFC technology fuelled by natural gas to replace conventional gas boilers. The SOFC technology is particularly suitable for micro CHP because the requirements for reformer technology are limited and the high temperatures allow for combined heat and power production. When a fuel cell CHP system replaces a gas boiler, the user gets electricity and heat, while the gas boiler only provides heat. Thus, this is a beneficial business proposition for the user.

The technology strategy is to validate the technology performance, to reduce costs and to improve the durability and efficiency of the system, thereby offering increased performance to users. The key market strategy is to develop links to the user industry, that is, the energy and utility companies. This is crucial, since the grid providers regulate market access, and this market as such is not one where any actor can supply energy directly to users.

3.3.2. Large-scale power production

This application area includes stationary power in the 1MW to 10 MW range. Centralised power stations are still considered to be the backbone of Europe's energy supply (HFP, 2005, p. 43) and include large-scale power production with MCFC and SOFC systems. In the deployment strategy, the analysts found three general aspects for the stationary power markets (HFP, 2005, p. 41). First, power plants with capacities in the order of several hundred GW will have to be replaced or expanded in the next two to three decades in Europe. Second, centralised power production will remain the main source of electricity generation in the coming years, and as such, will remain the benchmark. Finally, centralised power stations with higher dynamic and operational flexibility (used also as balancing and reserve power for renewable energy sources) will also be introduced. Thus, there are opportunities for FC&H2 due to replacement of old technologies and increased demand.

In this application area, fuel cells are in direct competition with existing power technology, and since many of the power plants in operation today across Europe need to be replaced in the coming decades, FC&H2 technology has an opportunity to acquire a market share. In Germany alone, one estimate is that 40,000 MW (more than one-third of existing power plants) must be replaced within the next twenty years (Hydrogen-strategy-group, 2005, p. 31). Thus, the energy sector will make the key decision about the technological choices in the following decade.

Fuel cells are one of the choices that can be utilised, either with natural gas or with hydrogen. Hydrogen and hydrogen-rich gas have a clear benefit, as both put more flexibility into the system. As the strategy group of the HFP states, they can 'serve as a bridge between the energy system of the renewable sources like wind with its high fluctuation and the back-up power station' (HFP, 2005, p. 43).

The system integrators are developing two fuel cell technologies for this market, SOFC and MCFC. Both are high-temperature fuel cells and are fuel flexible. The fuel cells can work in combination with gas turbines, and in this hybrid solution achieve very high energy efficiency. The system integrators see them as complementary to gas turbines, rather than direct competitors, because energy production will grow in the next five to ten years, and there will thus be opportunities for all technologies. The key uncertainty facing the firms in this application area is costs, because this market is cost dependent and the cost of FCs remains high. Thus, a key strategy of the firms will be to lower the costs, as well as to get access to the market through links to the energy production companies.

3.3.3. By-product hydrogen

An early market opportunity for firms targeting stationary fuel cell systems involves using the hydrogen from chlor-alkali production to produce electricity for the factory on site. This market is large, with an estimate of global value of €200 million (Hugh, Todd, & Butler, 2007). The firms expect individual chlor-alkali plants to be able to produce between 15 and 90 MW of by-product hydrogen, based on the hydrogen the chemical industry currently vents into the atmosphere in large quantities. Thus, this is a prospect to obtain cheap energy for the factories. A group of analysts explains the particular features of this market:

> [C]ompanies … have spotted an opportunity, and realised that there is a sound business case for installing fuel cells on-site in these industries, hence sidestepping the problems associated with installing complex and expensive hydrogen distribution systems. (Hugh, Todd, & Butler, 2007)

Thus, this application can constitute an early market for fuel cell system integrators without their having to coordinate a large supporting infrastructure. The systems are in the megawatt size and consist of modular systems based on 50-200kW modules. PEMFC is the dominant technology used and operates on pure hydrogen, directly from the production process of the chlor-alkali and chlorate industry.

This application has several advantages. For instance, hydrogen is pure, which removes the need for costly reformer technology and makes it suitable for PEMFC systems. Second, it is easy for the chemical industry to accept, as hydrogen is part of its daily operation in the production process. Third, the fuel cell offers benefits like zero emissions of e.g. CO, CO_2 and NO_X. Finally, the stacks are recyclable and offer high system efficiency. Thus, this example is an economical as well as effective use of the by-product hydrogen. By connecting fuel cells and using the excess hydrogen that the factories normally vent, factory owners use less power from the grid. The strategy of the system integrator firm is to establish market links to factory owners of the chemical industries in which hydrogen is a by-product.

3.3.4. Telecom back-up solutions

System integrators of small stationary fuel cell systems have found an early market opportunity in the application area of telecom back-up systems. The market driver is the increase in demand for uninterrupted power supply (UPS) telecommunication installations.[15]

The majority of telecom systems currently use lead-acid battery back-up power systems to assure reliable power availability, and many systems back up the batteries with an engine-driven generator. Hydrogen back-up power systems based on PEMFC can replace both the batteries and the diesel generator with a single, integrated system with superior capabilities.

Fuel cells offer benefits in terms of being silent, minimising emissions into the environment, reducing costs and eliminating many of the problems that affect customers when there is a power interruption. Thus, they are an attractive opportunity for powering telecom stations

[15] Fuel cell back-up systems have similar benefits for users at hospitals, financial institutions and nuclear plants.

in areas where environment is an issue, such as national parks, protected areas and other places where there is no infrastructure.

The system integrators have fuel cell based back-up systems that can compete with the incumbent technology for telecom back-up solutions. The FC systems offer reliable performance over ten years and with a minimum of maintenance. Maintenance of the fuel cell systems, in fact, requires no special knowledge or training, and users can operate the fuel cell systems after only brief training. Users can maintain the systems remotely; because the systems have self-testing capabilities, no regular on-site maintenance is required, unlike battery systems or generators that run on fuel.

In terms of system costs, lead-acid batteries offer a smaller initial cost, but the total cost is much lower for fuel cells due to their lower maintenance cost. Several companies and analysts confirm this. Ernst and Nerschook (2004), for example, found that hydrogen-fuelled fuel cells offered the cheapest solution for telecom back-up systems based on a ten-year timeframe. Similar conclusions are drawn by the HFP strategy group (HFP, 2005, p. 43). Further benefits of fuel cells are high adaptability to power needs and the fact that they take up much less space and weigh much less than comparable back-up power systems. The key strategy for the system integrator is to develop market links to the users of telecom base stations.

3.4. Summary

This chapter presented the two cases and associated product examples with the actors involved and their particular role in technology and market development. These descriptions of the cases and the stylised actors are aimed to help the reader understand the analysis in the empirical part of the thesis. It is clear that for the field of FC&H2 the various product examples provide an array of uncertainties stressing that the actors need to put stabilising mechanisms in place.

II. THEORY AND RESEARCH DESIGN

4. Theory

This chapter poses the question of what drives or determines early phases of industrial evolution. It does so by taking an evolutionary approach to industrial change, which I study as a process of co-evolution of technology, markets and institutions. In order to operationalise such industrial change I use the concept of Technological Innovation System (TIS) and link this to the co-evolution of technology, market and institutions. The early, formative phase of a TIS is characterised by a high level of uncertainty in terms of markets, institutions and technologies, and in this phase what firms and other actors try, above all, to achieve is to reduce uncertainty and create stability. The analytical lens in this thesis is therefore the notion of *mechanisms for creating stability* in the technological innovation system.

In section 4.1 of this chapter, I present the concept of evolution from evolutionary economics; in section 4.2 I discuss the concept of co-evolution; in section 4.3 I discuss co-evolution of an innovation system; and in section 4.4 I explain the causes of co-evolution in terms of evolution of technology, institutions and markets. In section 4.5 I explain how co-evolution is driven by the strategic actions of actors, and in 4.6 I present the concept of stabilisation mechanisms as a means to understand the co-evolution of a TIS. Then, in section 4.7, I explain the different stabilisation mechanisms and how they affect evolution of technology, market and institutions. In section 4.8 I formulate the research questions and in section 4.9 I discuss the theoretical contributions of the thesis.

4.1. Evolutionary economics and the concept of evolution

Joseph Schumpeter is a key figure in the study of the dynamics of industries and of the economy as a whole, as he advocated a perspective on industries as moving from birth through maturity and death, with his concepts of creative destruction and business cycles (Schumpeter, 1943). He argued that industries are not static but change over time as the result of the interaction between a multiple set of actors engaged in technological development and the creation of regulation and standards, thus providing new products that replace old ones.

In fact, technological change and industrial dynamics has been a key theme in the Schumpeterian tradition, in which the birth, maturity and ultimately death of industries, sectors and technologies has been the object of study (Malerba, 2006). Building on Schumpeter's ideas about business cycles, researchers in evolutionary economics perceive evolution as a process of qualitative change and recognise the important role played by technology and institutions in the evolutionary process characterising the economy. Evolution in this sense is related to 'a process of qualitative change in historical time, driven by firms, governments and other organizations with a diverse set of motivations, decisions, rules and capabilities' (Fagerberg & Verspagen, 2002, p. 1292). The perspective is most often historical, with a long-term attention on change of industry structure, technology base and institutions. Freeman, for instance, analysed industrial life cycles consisting of five long waves starting with the industrial revolution in the 1770s and ending with the ICT-driven industry of today (Freeman & Louçã, 2001; Freeman & Soete, 1997).

In evolutionary theory, the key concepts which explain the dynamics and transformation in the economy are variety and selection (Carlsson & Stankiewicz, 1991). Variety is how novelty is created in the economy by firms' search processes and, thus, how new technologies and products emerge. At some point, variety must be reduced so that standardised products become available to firms, public users and consumers (Metcalfe & Miles, 1994). Selection mechanisms reduce variety when firms focus on a particular design, and as such create compatible products that enable wider use of a technology. Evolutionary economists explain the reduction of variety as taking place in the selection environment, and occurring from selection processes in markets (Metcalfe, 1998) or from standardisation (Metcalfe & Miles, 1994).

Thus, variety and selection are the key processes in evolutionary theory and are crucial for understanding how new technological innovation systems and industries evolve. One key variety generator is firms, and they search through a wide range of sources in order, for example, to create new knowledge, to experiment and to demonstrate new technologies. The process of search is the source of variety in the economy, and thus of evolution. As such, search is the micro foundation of evolutionary theory as it deals with the creation and generation of new knowledge in firms, which is later selected in the market or by quasi market mechanisms (Nelson & Winter, 1982).

In general, one can state that firms have two main options in creating knowledge: through *local search* via internal R&D and other activities (Nelson & Winter, 1982), or through *external search* from sources outside the firm (Ahuja & Katila, 2004; Powell, Koput, & Smith-Doerr, 1996; Rosenkopf & Nerkar, 2001). External search includes cooperation between various organisations.

In the evolutionary theory of the firm, dating back to the work of Nelson and Winter (Nelson & Winter, 1982), search is related to the way firms develop skills and routines for solving problems. The evolutionary approach established itself as a counterview to neo-classical economics, which lacks a focus on how firms create products and technology. From the neo-classical point of view, knowledge is an externality, that is, a free good available to all in equal amounts, and at equal cost. Evolutionary theory, on the other hand, states that what firms do is to develop skills in a specific area, and what the firm knows predicts what it can produce. Thus, knowledge is a scarce resource, and knowledge development and exploitation is a path-dependent process.

Internal search, in the words of Nelson and Winter, is 'identified conceptually with the firm's research and development, operations analysis and related activities' (Nelson & Winter, 1973, p. 441). In other words, internal search comprises problem-solving activities that take place within the borders of the firm. If the firm is fully devoted to internal search, the complete product is, hence, a result of internal processes, and the firm is typically vertically integrated.

External search relates to sources outside the firm and indicates that firms get access to and use knowledge from, for example, other firms, research institutes or universities. The focus on knowledge and competences from network interactions relies on the firm's ability to move beyond internal search and to reconfigure its knowledge base with that of its partners (Rosenkopf & Nerkar, 2001). The rise in the importance of networks for knowledge creation has been explained by the inter-disciplinary character and increasing complexity of the knowledge base of products (Owen-Smith & Powell, 2004; Powell, Koput, & Smith-Doerr, 1996). This means that no one can do everything alone, at least not successfully; the network form of organisation enables firms to share their resources and thus combine their knowledge with that of other organisations (Dyer & Singh, 1998; Mowery, Oxley, & Silverman, 1996). It is important in this context to note that the ability to combine resources successfully is dependent upon the ability of firms to absorb knowledge, their absorptive capacity (Cohen & Levinthal, 1990).

The focus on network relationships in the literature on industrial dynamics indicates a shift from looking merely at internal processes for creating knowledge to looking at external relationships. This is evident in the shift from viewing firms as vertically integrated, as seen, for example, in Chandler (1990) and the early work on the resource-based view (Penrose, 1995; Peteraf, 1993), to a perspective emphasising external relationships and inter-firm relationships as focal in the knowledge-creating process of firms (Dyer & Singh, 1998; Freeman, 1991; Gulati, 1998).

4.2. Co-evolution

Co-evolution is an important concept to understand how change occurs in industries, innovation systems and the economy. Co-evolution is a concept from biology that has to do with the mutual evolutionary influence between two species. Each party in a co-evolutionary relationship exerts selective pressure on the other, thereby affecting one another's evolution (Boer, 2007). Importantly, the selective pressure on one another forces both of the co-evolving parties to keep evolving at higher rates than they would do apart. Thus, co-evolution enables synergies that would not have been possible without the mutual influence of the parties.

The concept of co-evolution has been introduced into the social sciences, and in particular to evolutionary economics. I will present two different approaches to co-evolution here.[16] First, there is the literature that has identified the co-evolution of technology and industry structure, namely the Abernathy-Utterback model of industry evolution (Abernathy & Utterback, 1978). Second, there is the literature that has studied the evolution of institutions and technology in response to changing economic conditions, incentives and pressures (Nelson, 1995).

Abernathy and Utterback (Abernathy & Utterback, 1978) studied a range of industries in the US and created a model of the evolution of industry. The A-U model, as it is called, states that industries relating to assembled products start in a fluid phase characterised by product experimentation and market uncertainty. The industry then moves into a transitional phase, where a dominant design emerges and the focus of firms shifts towards competition on specific products based on this design. Finally, the industry reaches the specific phase of highly defined products, mass production and competition on quality to cost ratio.

According to Utterback (1994, p. 93), most early innovations do not enjoy an established market, but markets do tend to grow around the new technologies. Thus, markets and technology co-evolve during the different phases of the industry. In the A-U model, the market is seen not as stable, but shifting through the different phases. The A-U model, then, is an account of co-evolution between technology, industry structure and market.

Even though many authors had had arguments supporting co-evolutionary processes in their writings, the idea of co-evolution was not explicitly stated in economic theory before Richard Nelson's 1995 paper on the co-evolution of technology, institutions and industry structure. Nelson recognised an industry's evolution in terms of co-evolution between these three factors (Nelson, 1994; , 1995).

To explain the phenomenon of co-evolutionary processes in the course of an industry's life cycle, Nelson specified several conditions that have been proved to be important. The most relevant relate to the evolution

[16] Another notable example of ideas about co-evolution is Freeman and Perez's concept of techno-economic paradigms, which suggests that matching between technology and society is needed for technologies to emerge (Freeman & Perez, 1988).

of institutions, which adapt and change according to changes in technology. According to Nelson, 'Various features of the institutional environment themselves tend to adapt and change in response to pushes and pulls exerted by the development of a new industry' (Nelson, 1995, p. 55), and this process he explains not in terms of structural arguments or some sort of external event, but in terms of strategic intent by actors. These 'involve the forming of collective bodies, decisions of voluntary organizations, government agencies and political action' (Nelson, 1995, p. 55). Nelson sees industry or trade associations as key instruments, since they lobby for regulation on behalf of the technology in order to get protection from competition outside the group, or to get public programmes to support the technology. Thus, Nelson argues for a focus on interaction between the actors in an innovation system, as specific interest groups create the adaptation of institutions to technology.

In their respective studies of co-evolution, Nelson on the one hand, and Abernathy and Utterback on the other, recognised different dimensions of industries or TIS as co-evolving. Nelson (1995) stressed the three dimensions of technology, industry structure and supporting institutions, while the A-U model identified technology, industry structure and market, as co-evolving during the different phases of an industry (Utterback, 1994). Between them, these two perspectives on co-evolution cover four dimensions: technology, market, institutions and industry structure.

Having discussed the dimensions of an industry or TIS that co-evolves, I will here conclude by stating that while the literature on co-evolution presented above takes an *industry* as the unit of analysis, the concept of co-evolution is likewise valid for understanding the formative phase of an innovation system.[17] It is an innovation system that is the object of study for this thesis, that of fuel cell and hydrogen technologies (FC&H2). In accordance with the literature on industry evolution, the

[17] The innovation system approach is different from an industry perspective in two ways. First, the focus is on a broader variety of actors than the industry approaches, and a system most often comprises actors from several industries. Second, there is more attention on how coordination between the different actors results in innovation and evolution.

thesis will analyse the co-evolution of technology, institutions and markets.

4.3. The evolution of an innovation system

An innovation system is defined by Lundvall as 'the elements and relationships, which interact in the production, diffusion and use of new and economically useful knowledge' (Lundvall, 1992, p. 2). Within the systems of innovation approach, the role of actors and the interaction between them has been a key tenet. Innovation, according to this perspective, occurs (for the most part) as a result of cooperation between heterogeneous actors, including individual firms, national governments, universities and trans-national organisations (Edquist, 1997; Lundvall, 1988; R. Nelson, 1993). This means that innovation processes are viewed as interactive and distributed among many actors (Klein & Rosenberg, 1986; von Hippel, 1988). Further, the approaches that can be labelled 'systems of innovation' focus on systemic relationships between actors defined by geography, by sector or related to technology.

The structural elements of an innovation system are knowledge and technologies, actors and networks, and institutions (Malerba, 2004). An innovation system may cross industrial and geographical borders. In fact, to deal with different objects of analysis, scholars have developed the analytical tool into different paths. Various innovation systems approaches exist in relation to national or regional level, and in terms of technology or sector. While all these approaches have their relevance as analytical constructs, this thesis uses the terminology of the TIS, where the system is defined and components identified on the basis of the underlying *technological* base, not sectoral belonging or geographical borders. [18]

The evolution of an innovation system has been discussed in terms of phases by both Carlsson and Jacobsson (1997) and Jacobsson and Lauber (2006). Jacobsson and Lauber emphasise that the formative phase is characterised by the existence of a range of competing designs, small markets, many entrants and high uncertainty in terms of

[18] The system under analysis spans regional and national borders, and could not be defined as a national or regional innovation system.

technologies, markets and regulation. Thus, there is a need to reduce these uncertainties so the system can move to a growth phase. In addition, the time span involved in the formative phase can be long, up to several decades, in fact (Jacobsson & Lauber, 2006). Carlsson and Jacobsson state that in the formative phase, initiatives must be taken to foster experiments with the technology, leading to the spread of entrepreneurial activity and competence among suppliers and users (Carlsson & Jacobsson, 1997, p. 272).

The focus of this thesis is on the early, formative phase, where there are large uncertainties in terms of technology, markets and institutions. In fact, the evolution of the TIS is formed by the evolution of the technology, the markets and the institutions, hence, by the co-evolution of the three.

Importantly, a key feature of several strands of the evolutionary theory that started with the work of Schumpeter is that innovation systems as well as industries go through different phases. This evolution is believed to start in a formative phase, followed by a growth phase, and finally a mature stage (Bergek et al, 2005). The feature of the formative phase is that it may take a long time to materialise, where the stage of prototyping, demonstration and small markets may last for several decades. This was the case for the semiconductor industry (Langlois & Steinmueller, 1999). Furthermore, since in the formative phase the TIS is not fully developed, the components are also changing and adapting, thus going through a phase of evolution. According to Bergek et al. (2007, p. 5), three structural processes take place in the formative phase: entry of firms and other organisations, formation of networks, and institutional alignment. Thus, the TIS goes through a process of transformation in which supply chains and different networks emerge, with firms scouting each other's activities. According to White (White, 1981), since no firm perceives possibilities, barriers and opportunities in exactly the same way as the others, they find their specific niches in the TIS.[19] In any event, there is high uncertainty indeed facing entrepreneurial actors, investors and policy makers in terms of

[19] White (1981) claims that firms view products and markets differently, and thus, rather than engaging in pure competition, find complementary roles to each other in a market.

technologies, markets and regulations (Jacobsson & Bergek, 2004; Kemp, Schot, & Hoogma, 1998; Klepper, 1997).

First, t*echnological uncertainty* relates to competing technological alternatives as well as to competing technologies, both existing and emerging. Regarding technological uncertainty, the price/performance of the technology is most likely poor (Adner & Levinthal, 2001). This relates to the degree of technological performance the technology must achieve. For instance, in order for a technology to be commercialised, it must have a performance in some dimension equal to that of the incumbent technology. Competing alternatives might also hinder the commercialisation. Clearly, the degree of technological uncertainty varies between different TIS. For a TIS in the formative phase, such as for FC&H2, the technologies are emerging, hence, the technological uncertainty is high.

Second, *market uncertainty* relates to the fact, generally understood in the literature, that markets for an emerging TIS do not exist, as the technology is unknown to users (Bergek, Hekkert, & Jacobsson, 2006; Christensen, 1997; Rosenberg, 1976). The market uncertainty firms' face in the formative phase is high since customers have no experience with the technology, therefore they have no perception of the benefits the technology can bring. How markets will develop and which users will adopt the technology first are thus highly uncertain for firms, along with whether customers will accept the products at all once they arrive in stores. There are also uncertainties about what type of business model will work and how to reach the market. Timing of market entry is also important: for instance, if first mover advantages are present or if it is better to adopt a second mover strategy. Emerging technologies often belong to different industries and product groups, which makes their possibilities for commercialisation different in terms of timeframe, size and price sensitivity (Nygaard, 2006).

Third, *institutional uncertainty* relates to issues of political support for the technology. Institutional issues involve government and policy actors but also firms, research groups and users. Institutions might be fitted to incumbent technologies, posing contingency problems for the new technology (Freeman & Perez, 1988; Nelson, 1994). Standards are also lacking, making the deployment or use of the technology difficult. Furthermore, if there are network effects, technological substitution will most likely be difficult (Liebowitz & Margolis, 1998).

The formative phase, as such, is characterised by uncertainty in these three dimensions. The uncertainties furthermore make it important for the actors to create stability so firms can achieve a perception of control (Fligstein, 2001). By reducing uncertainty, actors will then be more willing to enter the field and which will have a positive feedback on evolution.

4.4. Causes of co-evolution in innovation systems

In the formative phase of a TIS, there are three dimensions that co-evolve: technology, institutions and markets. This section describes the features of evolution of these three dimensions and how evolution has been perceived the in literature.

4.4.1. Technology evolution

The evolution of technology is a principal cause of the evolution of a TIS; thus, technology development is a significant part of the formative phase. Technology development means 'the processes by which an organization transforms labor, capital, materials, and information into products and services of greater value. This concept of technology therefore extends beyond engineering and manufacturing to encompass a range of marketing, investment, and managerial processes' (Christensen, 1997, p. xvi). A key insight is that technology evolution takes place because of interaction between different actors, that is, different firms as well as research centres and universities (Malerba, 2002, , 2006). Interaction between the actors in the TIS is thus an important factor for evolution.

Technological change in most instances consists in small improvements on an existing technology. Sometimes, technological change may mean a break with existing technology. The concepts most used in dealing with this type of change are disruptive, discontinuity, and radical.[20]

Technological development often starts with crude variants offering low performance and uncertain user benefits (Christensen, 1997; Utterback, 1994).[21] The evolution of technology may follow a specific trajectory (Dosi, 1982) driven by the gradual development of firm capabilities (Richardson, 1972; Teece, Pisano, & Shuen, 1997). As firm capabilities are improved by search processes (Nelson & Winter, 1982), each new model or prototype will, for example, have increased performance or lower costs or be more user friendly than the previous model (Abernathy & Utterback, 1978; IEA, 2000; Utterback, 1994).[22]

In the case of a TIS in the formative phase, there are often one or several technologies in their infant stage, displaying high degrees of uncertainty. Knowledge search and validation of performance are thus critical activities for the TIS to move to a growth phase. In some cases, the new technology might stand in direct competition to an incumbent technology, but in other situations, the new technology finds application in a new market. FC&H2 technology can both replace an incumbent technology and find application in new markets, as we will see. Importantly, the technologies co-evolve with the evolution of institutions and markets.

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[20] When incremental innovations are interrupted by a radical innovation, this is often referred to as a punctuated equilibrium (Loch & Huberman, 1999; Tushman & Anderson, 1986), a technological paradigm shift (Dosi, 1982), or a technological discontinuity (Ehrnberg, 1996).

[21] This process has been termed experience curves (IEA, 2000) or learning curves (Klein & Rosenberg, 1986).

[22] There is a limit to performance of a technology, which has been analysed in terms of S-curves (Foster, 1986). Where the evolution of technology follows an S-shaped trajectory where there is a slow beginning when learning is difficult, there are many uncertainties, but as the knowledge base increases, learning effects improve rapidly. At a later stage, evolution slows down as the limit of the technology is reached. This may then be used as a price/performance tool to judge if the emerging technology might be disruptive and cause a discontinuity in the industry. The S-curve tool has been used to analyse the competition between an incumbent and an attacking technology that constitutes a discontinuity with an industry (Anderson & Tushman, 1990; Tushman & Anderson, 1986). The idea of sibling S-curves has been proposed (Utterback, 1994), in which the performance of the incumbent technology is compared to the performance of the attacking technology in terms of two S-curves.

4.4.2. Evolution of institutions

Clearly, in an innovation system the evolution of institutions is key. In fact, in the innovation systems, traditional institutions play a key role for understanding the phenomenon of innovation. Edquist and Johnson define institutions as 'sets of common habits, routines, established practices, rules or laws that regulate the relations and interactions between individuals and groups' (Edquist & Johnson, 1997, p. 46). This means that institutions 'play a major role in determining how people react to each other and how they learn and use their knowledge' (Lundvall, Johnson, Andersen, & Dalum, 2002, p. 220).[23]

Institutions is important because of their effect on coordination of technology and market development. This relate to the regulatory aspects that are necessary so that coherence between the technology and the supporting institutions is established. This means that the technology can get the vital support in order to move the technology from the R&D and demonstration stage to the first real market applications. The existence of supporting codes and standards is furthermore important to secure interoperability between technologies and that technologies are safe and possible to use in real life applications. As such, an institution is in many cases the element that connects technology and markets.

Institutions are specific for a particular technology; thus, in the formative phase, where the technology is new and unknown, institutions are not suited to supporting the technology. The creation of institutions, as such, to match the technology is a crucial factor for co-evolution and constitutes a major uncertainty in the formative phase, for firms as well as policy makers. Without the proper institutions in place, it is not possible to use the technology in real life (missing legislation and codes), or the various parts might not fit together (lack of standards). Thus, institutional creation occurs because of the interaction between firms and policy makers as they try to shape the institutional framework to the technology and in line with their

[23] A narrower understanding is to see institutions as formal arrangements, laws, regulation, legislation, codes and standards.

intentions. Firms need approval and support for their technology, while policy makers regulate the economy to fit with policy and set the requirements that technologies must fulfil. The important institutions that are relevant to co-evolve with technology and markets are regulations, codes and standards. These types of institutions are discussed below.

Regulation relates to politics and how governments and other actors influence the evolution of a TIS by regulating behaviour. Hence, the use of various forms of regulation can be important policy tools that establish the required framework for technology and markets to co-evolve in the formative phase. First, this is the way policy makers are able to affect the evolution of the TIS, by regulating what is desirable or not, or even stronger, what is allowed or not. This means that when certain aspects are sought after, having to do, for example, with the degree of emissions of technologies in power plants or cars, regulation can ban other alternatives. Regulation in this sense may be referred to as a 'stick', since it denotes the possibility of governments, for instance, to prohibit and regulate behaviour (Bemelmans-Videc, Rist, & Vedung, 2003). Legislation is a specific instrument for regulation based on law. By creating laws that make a certain product illegal, as was the case for chlorofluorocarbon gases in refrigerators, a government has the possibility to affect what companies can and cannot do (Ashford, Ayers, & Stone, 1985). The lobby groups and political networks that actively promote the industry view for particular technologies or products are another type of actor involved in regulation.

Second, regulation can be used to reward specific desirable actions, so-called 'carrots' (Bemelmans-Videc, Rist, & Vedung, 2003). For instance, when the cost of a technology might be too high for commercial markets, governments can creative incentives for adoption (market-based incentives) or support for production (production-based incentives) for the initial markets. One example is a tax reduction that favours less harmful alternatives, which might bring technologies into consumer hands at an earlier time.[24] Tax credits were crucial, for instance, in the establishment of markets for wind power and

[24] One example suggested, for instance, by Stern (2006) and by the IPCC (2007), is carbon taxes.

photovoltaic systems (Alic, Mowery, & Rubin, 2003: 28). Regulation can in addition be used to open protected markets to competition. In this, policy makers have the possibility to de-regulate markets. This means that in previously protected markets there is competition between several alternatives. Thus, a process of unlocking technology might occur through technology competition (Unruh, 2002).

The second type of institutions that are relevant to co-evolve with technology and markets is codes and standards. They may have a vast effect on commercialisation and diffusion of technologies. Standards are 'a set of technical specifications adhered to by a producer, either tacitly or as a result of a formal agreement' (David & Greenstein, 1990, p. 4). Most research on standards has used information and communication technology as an example (Katz & Shapiro, 1985; Shapiro & Varian, 1999), but there are also studies on the development of nuclear technology and the failure of the electric car (Cowan, 1990). The focus of these studies has been to understand the competitive dynamics between standards, or standard wars (Cusumano, Mylonadis, & Rosenbloom, 1992), and how, sometimes, inferior technologies win the war (Arthur, 1989).

Another focus of research on standardisation has been understanding its benefits and costs, for standardisation offers specialisation and focus at the expense of variety. Since standards offer interoperability, specialisation becomes possible, but this reduces variation, since the developers focus their development on a particular system. The downside is that the standard might be inferior; the upside is that standardisation offers focus on a specific solution, which might increase learning curves (David & Rothwell, 1996). A key issue therefore is to understand the correct timing for standardisation, and the breadth of standardisation. Standardisation, finally, can be driven by private and public actors, and can be seen as self-regulative or private regulative.

The examples presented above show that coordination of technology development and various types of institutions is crucial. Clearly, technology and institutions co-evolve. For example, the regulatory aspects are necessary so that coherence between the technology and the supporting institutions is established. Also supporting codes and standards is important in order to secure interoperability between technologies and ensure that technologies can be used in real-life applications. In many cases, then, an institution is the element that connects technology and markets, and it is the result of interaction and cooperation between several actors in the TIS, such as firms, policy makers and lobby groups.

4.4.3. Market evolution

In any innovation system, the evolution of markets is clearly a key dimension. Markets are a central feature of modern economies, since they constitute the form of coordination that makes exchange of commodities possible. A market transaction can be neutral, such as buying and selling standardised products for a set price, or it can include more long-term and close relationships, such as between users and producers. A market in this first sense relates to the way neo-classical economists have understood the market: as an abstract meeting place for supply and demand. A different view of markets can be found in the work of economic sociologists like Mark Granovetter and Neil Fligstein (Fligstein, 2001; Granovetter, 1985), or in the Austrian tradition, which perceives market as a mutual process of systematic discovery among market participants (Kirzner, 1992). This latter view sees markets as politics, networks and institutions, and the key insight from this approach is that social action takes place in arenas, namely in markets as instituted fields, domains, or social networks. Thus, market creation occurs because of interaction between different actors. This indicates that more interaction occurs between users and producers than merely a meeting of supply and demand among anonymous actors. It is clear from the discussion that a market can be seen as a neutral place for exchange between anonymous actors or as a place that involves both more coordination and long-term relationships.

Market evolution goes through different stages in an evolutionary process (Utterback, 1994). The first phase is the formative one, where the market is small. As the industry evolves and technology becomes standardised, for example, through the emergence of a dominant design, the market expands (ibid.). Finally, the market reaches momentum and slowly declines. Markets in a TIS is similar to industries, but as a TIS might include several industries, the market dynamics might be more heterogeneous than for a single industry.

As the discussion on markets show, the formative phase of a TIS is characterised by markets being small or non-existent. Furthermore, firms focus either on niche markets in which the technology provides additional performance (Adner & Levinthal, 2001; Christensen, 1997) or on protected markets involving government subsidy (Alic, Mowery, & Rubin, 2003; Geels, 2002). Examples of the latter are government and military procurement, which established the foundation for the initial market for jet engines, semiconductors, lasers and computers before scale and learning effects made it possible to approach commercial markets (Alic, Mowery, & Rubin, 2003).

The key process of market evolution also relates strongly to institutional factors such as regulation, codes and standards. The technology needs to be standardised so that interoperability between technologies is achieved, and this requires that proper codes and standards be in place. These are crucial for making it possible to deploy new technologies in consumer and industrial markets. Thus, the market is dependent upon co-evolution with institutions and technology for market introduction to occur. Therefore, in the formative phase where technologies exist as prototypes and demonstration units, it is important for the firms to ensure that co-evolution between technology, market and institutions comes about; if not, the evolution of the whole TIS is hampered.

4.5. Co-evolution as driven by strategic actions and actors

Clearly, a TIS evolves through the intentional behaviour of a variety of strategic actors. This section therefore proceeds from defining the dimensions of a TIS that co-evolves, to defining the actors that make co-evolution happen. The emergence of a new TIS is obviously a highly uncertain and complex process involving many different actors. However, much of the previous literature has not been specific enough to explain how co-evolution happens through the *strategic* and *intentional* actions of firms, governments and other organisations. Much of the literature discussing the evolution of a new technology, in the areas of evolutionary economics (Murmann, 2003; Nelson, 1995), industry life cycles (Abernathy & Utterback, 1978; Utterback, 1994), business cycles

(Freeman & Perez, 1988), and transition management theory (Geels, 2005), tends rather to employ a long-term perspective on the evolution between the different phases. Geels (2002, p. 1273)for example, states that his account is 'described on an aggregated and abstract level without saying much about the interactions between actors'.

Furthermore, Coriat and Weinstein (Coriat & Weinstein, 2002) argue that the firm in the innovation system approach remains a passive, black box, acted upon by the macro-social determinants in which it is inserted. Thus, the actors in the innovation system are under-socialised and their actions a result more of the institutional framework than of intentional action. In fact, however, the aggregated analysis that is often used for understanding co-evolutionary processes loses some precision in such areas as understanding actors' motivations, the interaction between actors and the coordination in the formative phase (Geels, 2002). I argue here that there is a need to open up what actually happens in the TIS in the formative phase by looking at *cooperation* and *coordination* between intentional actors. This section describes the different roles that actors have in evolution in the formative phase and connects the actions of the actors with change in the innovation system. In addition, I look in section 4.5.3 at an explanation of firm behaviour that has been shown to impact the evolution of TIS in the formative phase, namely *niche cumulation*.

4.5.1. The roles of various actors

Actors in a TIS include firms in all parts of the value chain, as well as other organisations, such as universities, industry organisations, bridging organisations, other interest organisations and government bodies.

The firms are key actors in any innovation system because 'they are involved in the innovation, production, and sale of sectoral products, and in the generation, adoption and use of new technologies' (Malerba, 2004, p. 24). [25] As such, firms drive the evolution of the TIS and are clearly the key actors for creating co-evolution in the TIS. Firms can be

[25] In this thesis, I follow Malerba (2004), who states that firms play a key role in the co-evolutionary process as they develop and demonstrate technology, interact with policy makers and establish links to markets.

producers (of innovations), suppliers of components and subsystems, and users.[26]

Firms in a TIS can be incumbent firms from existing industries, or new firms. Thus, a TIS can be composed of a mix of new firms and incumbents from other industries. One strand of research has focused on the competition between incumbents and new entrants in developing a new technology (Christensen & Rosenbloom, 1995; Mitchell, 1989). A general understanding has been that incumbents do well with incremental innovation, while new entrants succeed in disruptive or radical innovation (Henderson & Clark, 1990). For instance, Christensen explored how new entrants were more successful with disruptive innovations in several sectors (Christensen, 1997; Christensen & Rosenbloom, 1995). One reason for this is vested interest in the existing technology, such as infrastructure and production equipment, due to which the incumbent avoids entry into the new technology for fear of cannibalising the existing investment. According to this perspective, incumbents will not move fast into the field but will wait to see if the technology gains ground before entry. Thus, this behaviour might hamper evolution of the TIS.

Another line of research has focused on the competitive relationship between incumbents and new entrants and has discovered that in some situations an incumbent does in fact succeed in commercialising radical technologies due to its complementary assets (Rothaermel, 2001; Teece, 1986; Teece, Pisano, & Shuen, 1997; Tripsas, 1997).[27] This perspective thus advocates for complementarities between incumbent and newcomers, where the latter develop the new technology while the former helps in upscaling production, in the development of supportive infrastructure and in market deployment.

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[26] In addition, the roles of the different firms vary among sectors. For instance, von Hippel (1988) revealed the importance of users in a range of sectors, while in other sectors suppliers have an important role as knowledge providers (Pavitt, 1984).

[27] Complementary assets are firm-specific factors such as brands, specialised manufacturing capability, access to distribution channels, service networks and complementary technologies (Tripsas, 1997).

Another relevant factor in the strategic behaviour of firms that can influence the path of evolution is whether to take the lead as a first mover. In fact, firms can be first movers or late movers into a new TIS, and this affects the pace of evolution of the TIS. Situations in which firms perceive that there are advantages to gain from entering the field before their competitors can result in early entry. Where firms can produce so-called *first mover advantages* (Lieberman & Montgomery, 1988, , 1998), entry barriers into the TIS may be created for other firms (Bain, 1956; Porter, 1979, , 1980). If firms manage to create entry barriers for other firms, they are able to maintain control of a large share of the markets and make it difficult for competitors to catch up. Clearly, evolution in the formative phase can be affected by how firms perceive the opportunities for creating first mover advantages.

Organisations like universities, governmental bodies and the military play various roles in different sectors, but their roles differ greatly between sectors (Malerba, 2004, p. 25). For instance, universities are a crucial source for innovation in the biotech industry (Malo, 2006), while the military built up the semiconductor and computer industries (Malerba, 2004, p. 24). Governments, on the other hand, play important roles because they provide funds for research and demonstration, allocate resources, and support (or obstruct) the emergence of new a TIS, either by providing broad frameworks supporting any technologies or by taking concrete actions, that is, picking winners. Governments and policy makers therefore play a central role in developing the frameworks to support the necessary R&D as well as the frameworks to enable the technology to move from R&D to demonstration and market deployment. By way of example, Fligstein (Fligstein, 2001, p. 42) argues that governments play a key role in creating stability in markets, since they can intervene, regulate and mediate in emerging markets. Governments have the possibility to intervene and regulate by deciding ownership in markets (who can own what); privatisation, for instance, changed the structure and competition in the telecom and energy markets. Another role of governments is to decide rules for intellectual property, such as patenting law. Governments also have the possibility to mediate in situations where there is a conflict between industry and the labour force, for instance. Finally, industry and government officials can interact and discuss specific common concerns, and these discussions may result in an industry policy. Organisations like industry associations and lobby groups also have an impact on the TIS, as they help to create legitimation for the technology (Jacobsson & Lauber, 2006) and can impact the decisions of governments and users to support the technology.

4.5.2. The role of network relationships

Innovation occurs as a result of cooperation and interaction among firms in all parts of the value chain. Therefore, an important feature of the formative phase in a TIS is the network relationships that are established between firms and the strategies for cooperation that are used. Networks indicate a focus on firms not as isolated entities employing external industry sources or internal resources and capabilities, but as embedded in networks of social, professional and exchange relationships with other organisations (Gulati, Nohria, & Zaheer, 2000).[28]

Networks are relationships between actors that involve a cooperative element of some kind, such as sharing R&D costs, co-developing a strategic component, creating a common standard or lobbying policy makers for a specific technological alternative.[29] In relation to this view, several researchers have explained network relationships and inter-firm cooperation as a key form of coordination due to their benefits in firms sharing complementary resources (Richardson, 1972). Gulati (1998) found out that an important reason for firms to enter into cooperation with other firms base on concrete strategic *complementarities* that they have to offer each other.

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[28] It is important to note that the term network can be used in two different ways. In focal networks, there is one specific organisation in the centre linking to various partners. In organised networks, the focus is on the network's purpose rather than on a specific organisation. In this thesis, networks will be referred to as 'webs of relationships'.

[29] Networks are usually termed a third mode of organisation in the modern economy, a hybrid form between the firm and the market. A network has the benefits of exchange like the market form and the benefits of coordination like the hierarchy (Williamson, 1985). While the market is a superior form of direct exchange of ready-made products that does not require much interaction between the actors (Arora & Gambardella, 1990; Chesbrough, 2002), the network is a better form of organisation when coordination of needs and activities is necessary.

Importantly, for a new technology to gain ground, different functions require different networks. Bergek et al. (2007), for instance, identify two forms as important for a new technology. First, learning networks 'can link suppliers with users, related firms, competitors, or university researchers and constitute important modes for the transfer of tacit and explicit knowledge' (ibid., p. 4). Second, political networks, which are 'made up of a range of actors sharing a set of beliefs, seek to influence the political agenda in line with those beliefs in competition with other coalitions' (Smith, 2000; Rao, 2004 in Bergek et al., 2007, p. 4). Political networks are recognised as playing an important role because they 'help create a vision for where the sector or society should be heading and which would help to coordinate the strategies of technology developers, investors, regulators and users' (Kemp, Schot, & Hoogma, 1998, p. 191). A third type of network targets market creation. These networks coordinate the actions of different firms in terms of product launch, complementarities between inter-dependent technologies such as hardware and software, and vehicle and fuel. As such, they have a key strategic function for most firms.

Networks clearly play a key role for explaining co-evolution of technology, market and institutions, and this thesis makes the assumption that a necessary condition for co-evolution is that the different networks be coordinated with each other. This process of inter-dependence between networks adds a rather complex dimension of coordination, in which actors form network relationships to reduce technological, market and institutional uncertainty, thus driving the evolution of the TIS.

4.5.3. Niche cumulation and evolution

Another strategic issue of importance for evolution is the extent to which evolution of the whole TIS can occur from evolution in small niches, with the collection of niches then tilting the system into a growth phase. This phenomenon is a key explanation in the transition management approach, which explains evolution in a new TIS as occurring through *hybridisation* and *niche cumulation*.[30] New technologies emerge in niches, meaning that technology can be introduced into small

[30] Hybridisation is a stabilisation mechanism and is therefore explained in section 4.6.7.

pockets of the economy and these pockets or niches later become connected, taking form as the dominant technology. This is known as *niche cumulation* and is a key explanation for how evolution from a formative phase to a growth phase occurs in a TIS.

According to Geels, break out from the niche level occurs when ongoing processes at the levels of regime and landscape create a window of opportunity, and it takes place because of niche cumulation: 'The general pattern by which radical innovations break out is that they follow trajectories of niche-cumulation. The step from niche to regime-level does not occur at once, but gradually as radical innovations are used in subsequent application domains or market niches, i.e. a cumulation of niches' (Geels, 2002, p. 1271). Niche cumulation thus relates to whether the gradual introduction of various niches (or applications) can tilt the TIS into a growth phase. Raven (2007) argues that *niche accumulation* starts as a radical distinction from the current technological regime and aims at preventing early rejection through smart experimentation in niche markets. Thus, niche cumulation is an external factor relating to the characteristics of the TIS. The extent to which niche cumulation can lead to growth affects the possibilities for firms to create the evolution of the TIS.

4.6. The concept of stabilisation mechanisms to understand evolution of a TIS

The topic of this thesis is an understanding of what drives or determines early phases of the evolution of a TIS. I investigate this by means of what I call *stabilisation mechanisms*. I understand a stabilisation mechanism as an action performed by an actor or a network to create a change in one dimension of a TIS. Hence, a stabilisation mechanism has the effect of reducing uncertainty in terms of technology, market or institutions. By introducing the concept of stabilisation mechanisms, I operationalise the actor-focused analysis of the formative phase.

4.6.1. Introducing the seven stabilisation mechanisms

This section and the one that follows will outline the mechanisms that actors use when they seek to minimise uncertainties and thus to create stability in the system. In the thesis, my primary focus is on firms, though I look at the actions of policy makers to some extent. These mechanisms are operationalised as *stabilisation mechanisms* and are extracted from a broad selection of studies dealing with the process of stability creation within emerging industries and innovation systems, as well as from close study of the empirical field at hand. They are defined, then, in the meeting of theory and empirical analysis.

For this thesis, seven stabilisation mechanisms have been selected from theory, identified as having an impact on the co-evolution of the dimensions of market, technology and institutions in the formative phase of a TIS.[31] The selected stabilisation mechanisms are summarised in Table 4.1 and each is explained in this section.

Table 4.1: **An overview of stabilisation mechanisms**

Stabilisation mechanisms	**Key literature**	**How do they work?**
Technology specific platform	Kemp et al. (2004)	Create joint vision, align stakeholders' perspectives, create legitimation
Political network	Jacobson and Lauber (2006)	Support technology vis-à-vis policy makers, create legitimation
Codes and standards	David and Greenstein (1990)	Interoperability between technologies; safety and quality assurance
Knowledge search	Nelson and Winter (1982) Freeman (1991), Gulati (1998) Hagedoorn (1993) Rosenkopf and Nerkar (2001)	Internal search: R&D new knowledge External search: inter-organisational cooperation for knowledge development
Demonstration projects	Kemp et al. (1998) Geels (2002) Harborne et al. (2007)	Protected space for the technology and learning curves before market selection
Market networks	Fligstein (2001), White (1981) Adner and Levinthal (2001) Maskell, Bathelt, and Malmberg (2006)	Markets as networks Market context Conferences and fairs as arenas for interaction
Hybridisation	Geels (2002), Raven (2007) Pistorius and Utterback (1997)	Add on to existing infrastructure Technology symbiosis

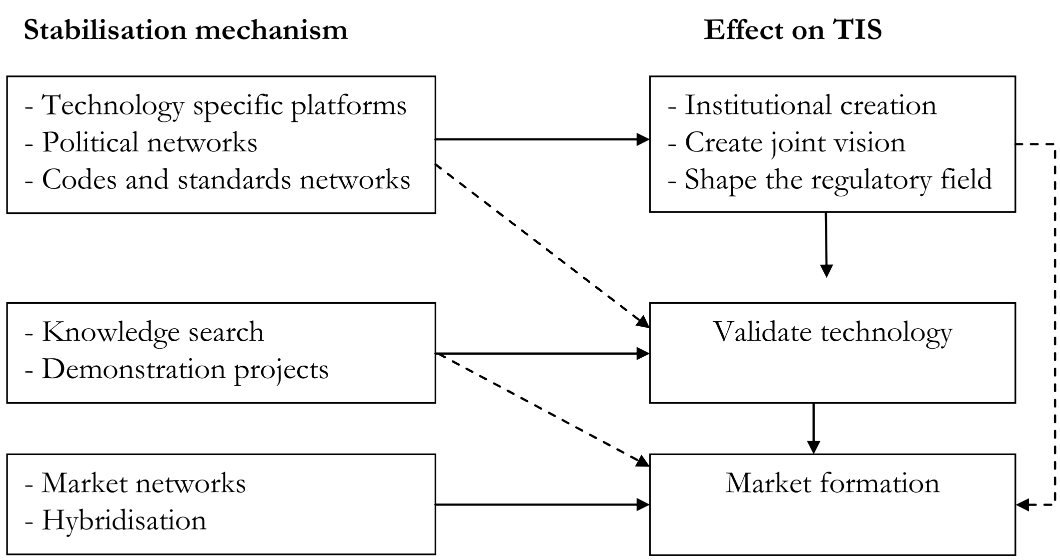
4.6.2. The effect of stabilisation mechanisms

The different stabilisation mechanisms are classified into three categories, according to how they work in practical terms. Each stabilisation mechanism has an impact on the evolution of technology,

[31] It is important to note that this is not a complete list of potential stabilisation mechanisms.

market and institutions, and has been used by firms examined in previous studies to reduce uncertainty in one of these dimensions. The relationships between stabilisation mechanisms and co-evolution of technology, market and institutions are presented in Figure 4.1. In the model, the normal lines indicate direct effects of the stabilisation mechanisms, while the dashed lines indicate indirect effects. Indirect effects are understood as weaker than a direct relationship between the mechanism and the dependent variable. The various stabilisation mechanisms constitute the independent variables used in the thesis, while alignment of actors, validation of technology and market formation are the dependent variables, the effects of the stabilisation mechanisms on the TIS.

Figure 4.1: **Stabilisation mechanisms in the formative phase**



A. Alignment of actors

An important part of the evolution of a TIS in the formative phase is the establishment of a common vision that gathers the various actors so that their development activities become coordinated. This is important for establishing the first set of mechanisms that have been used in theory to explain how stability creation within innovation systems in the formative phase is related to the way firms tend to align their perspectives and activities. A *technology specific platform* includes all the different stakeholders in a TIS and is set up to create alignment between the actors, therefore leading to visibility and coherence among the actors' perspectives. One important factor for creating alignment between actors is political networks. They help to create a *vision* for where the sector should be heading, and they help to coordinate the strategies of technology developers, investors, regulators and users behind this vision (Kemp, Schot, & Hoogma, 1998, p. 191). Thus, the actors' activities become coordinated, and this helps in the creation of well functioning supply chains. The alignment of actors also plays an important role in creating *legitimation* vis-à-vis policy makers, which is required for shaping the regulatory framework in favour of the emerging technologies. *Legitimation* relates to social acceptance and the compliance of the technologies with relevant institutions, and it is important that a new technology be considered safe and appropriate by society and users (Jacobsson & Lauber, 2006). Alignment between actors is also achieved by *codes and standards*. These have a key role to play for the technologies of firms to function together as a system (interoperability standards), and for their being approved for use in real-life settings (quality and safety standards), thus aligned to the requirements of the regulators. Firms use three different forms of stabilisation mechanisms to achieve alignment in the TIS: political networks, technology specific platforms, and codes and standards networks.

B. Validation of technology

A second set of stabilisation mechanisms deals with validation of technology. Technology in the formative phase is at the testing or prototype stage, and therefore requires validation before deployment in the marketplace. The technologies have uncertain costs (e.g. due to lack of manufacturing experience and scale economies), uncertain performance (e.g. never having been tested in real-life operation), and a lack of standards and regulation (e.g. standards and approval need to be developed). Thus, there is a need to test the technology in protected but real-life conditions. Validation means ensuring that the technology performs and its safety and quality are satisfactory. Technology validation therefore needs alignment with the development of codes and standards. *Knowledge search* help firms increase their understanding of a technology and reduces technological uncertainties. The firms search the environment for novelty in technology and science, which helps them in advancing their development process and validating the technology. A key factor is *demonstration projects*, which bring users' knowledge and expertise into technology development processes, and this results in interactive learning processes as well as institutional adaptation (Kemp, Schot, & Hoogma, 1998, p. 186). Validation of technology takes place in platforms of interaction where actors engage in learning processes, and with this, co-evolutionary processes between technology and institutions take place. Demonstration projects are such platforms of interaction. Two important mechanisms are explored for validation of technology: demonstration projects and knowledge search.

C. Market formation

Market formation is a crucial aspect of emerging innovation systems. In most cases, the technology does not have a market and the actors must then work towards creating one. Market networks play an important role for market formation in the formative phase. These are inter-organisational networks, which help actors in coordinating market formation, and include aspects of co-developing various related products and technologies. Market networks indicate that interaction between the different actors in the TIS is crucial for market formation, and the interaction helps reducing market uncertainty. The market formation process is highly complex and crucial in the formative phase, and it is not until small markets exist that the technological innovation system evolves beyond the formative phase. Hybridisation is a tool that firms can use to create or enter a market by coordinating a new technology with an existing technology, and thereby reducing uncertainty that relate to technology, market as well as institutions. Hybridisation is a phenomenon where a 'new' and 'old' technology co-exist in a hybrid technical design. Another way for markets to form is when governments create markets through regulation, as was the case for wind power in Germany (Bergek & Jacobsson, 2003). New technologies have a cost disadvantage compared to incumbent technologies, with two features obstructing market formation (Bergek et al., 2007, p. 20). First, emerging technologies such as renewable energy technologies might not have high performance in some dimension that the user is willing to pay for. Second, incumbent technologies are often subsidised.[32] Two stabilisation mechanisms will be explored and which relate to the process of market formation; market networks and hybridization.

4.7. Explaining the stabilisation mechanisms

4.7.1. Technology specific platform

Technology specific platform is a stabilisation mechanism relatively little treated in the innovation literature, but it has surfaced as a popular tool in emerging technological fields. A technology specific platform enables cooperation between firms and governments instead of government taking a leading role (Stiglitz & Wallstein, 1999), and is a soft form of governance (Greve, 2000). Accordingly, the *technology specific platform* is a mechanism that aligns private and public interests in a specific area and can lead to co-evolution within a TIS. In more practical terms, the concept of technology platforms has appeared as a strategy of the EU to address the Lisbon strategy on becoming a leading knowledge economy (EC, 2004). The particular role of the EU technological platforms is 'to define research and development priorities, timeframes and action plans on a number of strategically important issues where achieving Europe's future growth, competitiveness and sustainability objectives is dependent upon major research and technological advances in the medium to long term' (EC, 2004). These platforms are industry led and target areas with a high degree of industrial relevance. Kemp and Munch Andersen (2004, p. 10) argue that 'such platforms for specific innovation areas could become a powerful instrument in fostering the development of visions and cooperation among different actors in the relevant innovation system'. In the EU, part of the strategy with technology specific platforms is that they can include a public-private partnership in the form of a Joint Technology Initiative (JTI), where the EC and industry create a formal partnership with large devoted resources, based on equal cost sharing. Technology specific

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[32] For instance, according to the Intergovernmental Panel on Climate Change (IPCC), government subsidies in the global energy sector are in the order of US$250-300 billion per year, of which about 2-3% supports renewable energy.
<http://www.mnp.nl/ipcc/pages_media/FAR4docs/chapters/Ch4_Energy.pdf>, accessed 15 August 2007.

platforms thus are powerful instruments for the evolution of a technological innovation system.

4.7.2. Political networks

Political networks or technology-specific advocacy coalitions focus on shaping or changing the institutional framework.[33] Political networks coordinate the actions of different actors within the TIS to influence policy makers and other decision makers to support the TIS. They have been identified by several scholars as crucial for establishing stability in a TIS, for instance, Nelson (1995) and Jacobsson and Lauber (2006), where political networks were acknowledged as important for establishing *legitimation* of emerging TIS.

Legitimation is central for creating *trust* among decision makers that the specific technology is an answer to their perceived problem. In a situation where the new technology is in direct competition with an incumbent technology, political networks are necessary for legitimation of the new technology, in that incumbent actors have vested interests and want to protect their investment. The situation can then result in a battle between different technologies, making political networks necessary if the emerging technology is to gain influence among such decision makers as policy makers and large firms from user industries, and gain trust among consumers. Thus, legitimation is a key function of political networks in the formative phase of a TIS.

Political networks are necessary for creating *visions* and lobbying on behalf of the new technology, in particular 'to engage in wider political debates in order to gain influence over institutions and secure institutional alignment' (Jacobsson & Lauber, 2006, p. 259). Accordingly, they act as a key instrument for institutional change and constitute the place where joint visions of the role of that particular technology are developed. Jacobson and Lauber explain that 'the formation of political networks sharing a certain vision and the

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[33] In this thesis, I use the concept political network as equal to technology specific advocacy coalition, this means that I only use the concept of political network in relation to technology.

objective of shaping the institutional set up is an inherent part of this formative stage' (Jacobsson & Lauber, 2006, p. 259).

Another important factor is support from *prime movers*. These have been shown by Jacobsson and Johnson (2000) to be important in the market introduction phase. If the situation is one in which the markets are oligopolistic, so that market control lies in the hands of a few large actors, clear commitment from these actors is a key condition for the technology to reach a mass market (Nelson, 1995, p. 55). The process of legitimation is explained in terms of the actions of *industry associations*, which are key actors, as they lobby for regulation and for public support on behalf of the technology (Nelson, 1995, p. 55). Clearly, then, a political network is an important stabilisation mechanism for a TIS in the formative phase.

4.7.3. Codes and standards

Codes and standards are coordinated actions by a group with the intention of steering technology development, reducing variety and increasing specialisation. Standards are 'a set of technical specifications adhered to by a producer, either tacitly or as a result of a formal agreement' (David & Greenstein, 1990, p. 4). A standard is only a voluntary agreement, however. To be effective, it needs to have the force of law behind it; it must be adopted by a regulative agency and transformed into a code.

There are differences in both the *purpose* of the standard and the *origin* of the standard. The *purpose* of a standard has to do with reference, minimum quality, and interface or compatibility standards (David & Greenstein, 1990). Reference and minimum quality standards guarantee the characteristics of a product, while interface standards guarantee that a component fits into a larger system and that different technologies fit together, such as fuel and vehicle (David & Greenstein, 1990, p. 4). Standards, as such, might spur innovation, not only because it becomes possible to use the technology in real-life settings, but also because different organisations can innovate on the component level and inter-dependent technologies will fit together. Safety concerns are important deal with to ensure that users will feel comfortable with the technology and thus constitute a key concern for diffusion of a new technology.

With regard to their origin, standards emerge either spontaneously through market processes or through negotiation. Two forms exist for each instance. Standards created in the market are un-sponsored and sponsored, and they become chosen by market forces (David & Rothwell, 1996). These are *de facto standards*. In addition, voluntary standard-writing organisations like ISO can create standards, or governmental agencies that have some regulatory authority can mandate standards. These are *de jure standards*. ISO, IEC and the UN have working groups set up explicitly to develop global standards. In this thesis I focus on the latter.

Standards have proved to be important when rapid technological change makes the cost of aligning users such as consumers high (Christensen, Suarez, & Utterback, 1998; David & Greenstein, 1990; Metcalfe & Miles, 1994). According to Foray (1998, p. 82), in situations with high uncertainty about future technology, standardisation can 'intervene', 'making it possible to create temporarily stability, transient lock-in, giving agents the possibility of coordinating their activities in a context of fast change'. On the other hand, technological change can sometimes create uncertainty among users, be they firms, consumers or public organisations. Users want to avoid being early adopters of a technology that is later abandoned, an effect David calls 'angry orphans' (David, 1986; Foray, 1998). This effect sometimes makes it difficult to convince users to adopt the technology in the early phase, as they are uncertain that the standard will exist when technology improves.

4.7.4. Knowledge search

Knowledge search is the firm-specific actions to gather and internalise knowledge about for example technological and scientific advances, competitors' products, and opportunities in the emerging TIS. For emerging technologies, where the technological uncertainties are high, knowledge search is particularly important as a means to reduce uncertainties. Firms employ a range of knowledge search activities that include conducting internal knowledge development processes like R&D (Nelson & Winter, 1982) as well as screening the external environment and cooperating with other firms and research organisations. R&D is important in order for firms to be able to internalise external knowledge and stay in front of the technological development (Cohen & Levinthal, 1989; Tilton, 1971).

Firms have the opportunity to employ a range of tools to reduce technological uncertainty and thus help validate the technology. One form of knowledge search is patent analysis (Almeida, 1996; Jaffe & Trajtenberg, 2002). Patents can be an important source of information that is publicly available to firms. Scientific journals may play an important role for firms' technology development activities, due to relationships between science and technologies where firms incorporate scientific findings into their technology development (Grupp & Schmoch, 1992). Another form of knowledge search is attendance at conferences and fairs. Conferences can provide firms with knowledge based on novel research or, by connecting firms and researchers, can lead to cooperative agreements or R&D contracts (Maskell, Bathelt, & Malmberg, 2006).

Knowledge search can also include relationships between firms, such as user-producer interaction where firms specify problems and can jointly flesh out solutions (Lundvall, 1988; von Hippel, 1988). Further external relationships supporting knowledge search can take the form of sub-contracting of particular parts of the innovation process (Love & Roper, 2004), R&D programmes, and various forms of cooperative agreements and strategic alliances (Freeman, 1991; Hagedoorn, 1993, , 2002), joint ventures (Kogut, 1988) and public-private partnerships (Stiglitz & Wallstein, 1999).

4.7.5. Demonstration projects

Demonstration projects are coordinated actions by a group of actors to test and validate technology in a protected space. They are a key stabilisation mechanism in a TIS, making the actors able to coordinate technology development with institutions and the activities in political networks and technology platforms. Finally, they can be a key mechanism in preparing for market introduction.[34]

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[34] Importantly, the concept of niches from transition management is sometimes used synonymously with demonstration projects, such as in Geels (2002). I choose to use the term demonstration projects, since the concept of niche is also used in referring to niche

The rationale behind demonstration projects is that when the technology is mature enough for testing in real-life settings, but before technology can be employed by a user, the technology needs to be validated. Harborne et al. (2007) argue that demonstration projects can help in reducing the uncertainty of the technologies by testing and thus learning about the drivers and barriers that the new technology will face (Harborne, Hendry, & Brown, 2007). Kemp and colleagues (1998) have stated that it is important to develop a protected space for the development of promising technologies. Protected spaces typically take the form of demonstration projects, supported by industry or government, which target specific applications. These protected spaces are termed *niches*, and a key point about niches is that they bring the knowledge and expertise of users into technology development processes.

Niches, argues Geels (2002), are *incubation rooms*, and in them, the technology is shielded from mainstream market selection. Protection is needed due to poor price/performance ratio compared to existing technologies. Public subsidies are important for providing the necessary resources for the protected niches. Niches are understood as platforms for interaction in which actors engage in learning processes. Kemp et al. argue that 'apart from demonstrating the viability of the new technology and providing financial means for further development, niches helped to build constituency behind a new technology and set in motion interactive learning processes and institutional adaptations … that are all important for the wider diffusion and development of the new technology' (Kemp, Schot, & Hoogma, 1998, p. 184). Thus, demonstration projects enable co-evolution of technology and institutions and prepare for market introduction.

Niches are certainly a key concept in the transition management approach, used to explain important dynamics in emerging TIS. There is confusion in this literature, however, on the exact meaning of the notion of 'niches'. This is because 'niches' are referred to sometimes in the sense of technology, sometimes in the sense of markets, and

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markets, which becomes confusing. The difference between niche market and niche as a protected space is also discussed in this section.

sometimes in the sense of innovations, and confusion can arise when an accepted term is used in different ways. First, ‘niche’ is sometimes used in the context of technological niches, which relate to a specific technology (Geels, 2002) or to protected spaces (Kemp et al., 1998). Second, ‘niche’ is also used to refer to market niches, an accepted term for a small market where customers have an unusual demand; for instance, high-end products like Ferrari cars or specialist vehicles like wheelchairs constitute market niches for vehicles. Technological niches, being protected from market selection, acting as incubation rooms, are demonstration projects. The technological niche, then, is an area of demonstration where there is no market demand that fits with the current performance of the technology; technology demonstration projects are supported, however, because their learning effects can make the technology competitive in markets. This means that ‘protection of the niche comes from small networks of actors that are willing to invest in development of new technologies’ (Verbong & Geels, 2007), not from market selection. Niche markets, however, are places where the technology is selected, that is, market transactions.

Niches are quite important concepts in the study of how a TIS evolves, since they relate directly to different mechanisms and different ways of commercialising technology. An existing early market requires quite different strategies than a protected niche (in terms of performance requirements and potentials for revenues). It is therefore important to distinguish between these different concepts in an analysis of a technological innovation system.

Demonstration projects, pilot projects and field trials clearly play an important role for moving technology from the R&D phase to the pre-commercial or early commercial phase. This is a crucial phase, as the technology now repositions from the lab to a protected space and is tested in terms of reliability, durability and assessment of learning effects. Initial demonstrations may subsequently lead to a pre-commercial or supported commercial phase, in which the numbers increase and support comes from commercially oriented companies.

4.7.6. Market networks

Market networks are inter-organisational networks that have the purpose of coordinating market formation. This includes co-developing inter-dependent products or technologies, as well as firms agreeing on the geographical areas for deployment and the time for market deployment.

An important factor for market networks is the recognition of markets as social arenas and not as anonymous and distant relationships between buyers and sellers. Fligstein (2001), for example, explains that markets do not automatically arise from the meeting of supply and demand, but are created by the interaction between firms, as well as among firms and public authorities. Thus, markets for new technologies are dependent upon embedded relationships in the TIS or industry (Granovetter, 1985; Granovetter, McGuire, & Callon, 1998). Fligstein also recognises that social relations and rules must exist for markets to function, that is, the formation of market networks that include different stakeholders. Fligstein emphasises two social relations that can be used in understanding how markets work. First, there are actual relationships among producers, consumers, suppliers and governments in a given market: that is, market networks. Second, there are formal and informal rules about organising economic activity which provide the social conditions for economic exchange and allow for the production of new markets (Fligstein, 2001, pp. 10-11). Such formal rules are typically created by firms agreeing on a joint vision, including the specification of technology and how to deploy the technology.

The role of market networks is important for strategic analysis of niche and early markets. This is clear in the work of Cooper and Schendel (1976) and later Christensen (1997), which tells us that firms need a niche market or an early market in which learning effects can occur before mass markets are targeted. To do this, the firm must identify the buyers that are willing to and have the opportunity to pay the premium for these technologies or products. The benefit in terms of performance of the emerging technology therefore exceeds the additional cost. This requires a strategic view of markets and the actors within them. Adner and Levinthal (2001; , 2002) have a similar view, arguing that the key issue for firms developing emerging technologies is to find the right context for the technology and that technologies are commercialised in different applications as performance improves and fits with demand requirements.[35] For this purpose, market networks play a crucial role for meeting between suppliers, users, customers. Thus, they are important mechanisms for the stabilisation of markets in an emerging TIS.

Another aspect of markets networks relates to their importance in sectors or markets that are characterised by network effects. Network effects mean that there is a relationship between the number of users and the benefits of the technology (Katz & Shapiro, 1985; Liebowitz & Margolis, 1998). The benefits of using a technology thus increase when the number of other users increases. Types of network effects are defined by Unruh (2000, p. 822) as industry (or inter-industry) coordination, that is, creation of standards and design-specific supply relationships; network forces of private associations; and educational institutions developed in response to social and market needs of the expanding system. If there are strong network effects, complementary technologies must be developed simultaneously; market coordination becomes more complex, and 'markets networks' are the arenas where such discussions take place.

Instances of market networks created to solve network effects are currently occurring in the mobile telephony sector, where the mobile phone OEMs (original equipment manufacturers) are coordinating market control of an operating system for mobile phones. The actors are using their market position to close the mobile phone market to entrants from the computer and software industry. To do this, they have organised themselves and established *Symbian* as a platform for coordinating the market in relation to mobile phone operators (Ancarani & Venkatesh, 2003). This form of market network means that the creation of a joint standard for the operators is increasing the benefits to users as the switching costs between different mobile

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[35] One of their examples is the case of video recording technology, which was first deployed in the domain of broadcasters, then, as product/price improvements increased, was applied in the industrial and commercial domain, and finally was deployed in the mass consumer market. Another example is technologies like mobile phones, which have shown that dramatic cost reductions are possible within the scope of a single decade. From 1985 to 1995 the prices fell from approximately 5000 Euros to 100 Euros (much less if one includes the subsidies of mobile operators that basically made the phones free of charge for consumers).

phones and operators is minimised (same standard, same interface and usability), and is reducing market uncertainty for the actors involved as they protect themselves from new entrants. Network effects are thus, in many cases, dependent upon coordination between *prime movers* of the inter-related technologies.[36]

A key concept for market formation is the role and character of niche and early markets. There is confusion, however, in how niche markets are referred to in the literature; as a group of researchers pointed out in a recent conference paper, niche markets are used synonymously with early markets (Godfroij, Jeeninga, Menno, & Bunzeck, 2007). Niche market are quite different from early markets, however: niche markets are oriented towards specialised needs; early markets are focused on mainstream needs, but the price tolerance of users is higher than it is in the mass markets. For instance, the strategy group of the EU Hydrogen and Fuel Cell Technology Platform (HFP) makes a distinction between early markets and niche markets. According to them, 'early market' refers to a 'short term market for a specific product or application, which satisfies initial business objectives prior to commercialisation', while 'niche market' refers to a 'small area of trade within the economy, often involving specialised products. Markets of limited size concerned with specific applications for a given product' (HFP, 2005, p. 102). Early markets, then, would be created from a demonstration project that targets broader use, that is, mass markets, while niche markets are oriented to specialised use that is not targeting broader use.

Market networks signify interaction between users and producers of a specific technology. One particular tool that firms can use to establish interaction consists of *conferences, fairs and exhibitions*. These have been identified as important tools for firms in many sectors (Maskell, Bathelt, & Malmberg, 2006). At these events, companies meet other companies, and participation in such events helps firms identify the current market

[36] The introduction is coordinated in the form of demonstration projects or early market applications. If there is a situation in which the markets are oligopolistic, and thus market control is in the hands of a few large actors, clear commitment from these actors is a key condition for the technology to reach mass market. Inertia in the markets will hinder the escape from niche markets or demonstration projects.

frontier. Firms meet users of their technology and establish connections with the purpose of creating markets. Current thinking on temporary clusters indicates that the role of conferences, fairs and exhibitions is becoming increasingly important. Accordingly, they constitute an important part of the 'market network' stabilisation mechanism. Indeed, these events are clearly crucial for meeting suppliers, users and customers, and for getting ideas about where the technological evolution is heading. Thus, they constitute a means of inter-organisational interaction and can therefore be of substantial importance in establishing market networks.

4.7.7. Hybridisation

Geels (2002) identified *hybridisation* as an important stabilisation mechanism for a technological innovation system to gain ground. Hybridisation is a technology strategy to coordinate evolution of technology with the purpose of circumventing lock-in effects in specific sectors, and it refers to the process in which 'new' and 'old' technology hook up to form some kind of a hybrid technical design (Raven, 2007). Hybridisation in this sense means connecting the new technology to the existing one, in a form of symbiosis, and is a mechanism that affects market evolution. This builds on the assumption that market creation can occur through *technological add-on* and *hybridisation* (Geels, 2002, , 2005).

Technological add-on and hybridisation involve a firm's linking the new technology up with established technologies and solving particular bottlenecks that the incumbent technology can solve. One example is steam engines, which entered sailing ships as an auxiliary device and not for propulsion (Geels, 2002). Another instance of a successful hybridisation process is the introduction of gas turbines into the energy sector. The incumbent technology was steam turbines, and firms introduced gas turbines to solve peak demand requirements. After a period of experimentation, gas turbines took the dominant position from steam turbines, and finally, this led to the development of combined cycle power stations (Islas, 1997).

Thus, hybridisation means that in the formative phase, when new technologies link up with established technologies, these co-exist in a form of symbiosis (Geels, 2002). Similar arguments have been posed by

Pistorius and Utterback (1997), who analysed different forms of interaction between technologies. Their perspective is that technologies interact not only in terms of competition but that also they can have a positive effect on each other's growth. Thus, the new technology can first be in a symbiotic relationship with the incumbent technology, while this relationship might later shift to competition between the technologies.

4.8. Formulation of the research question

The objective of this thesis is to analyse how the stabilisation mechanisms affect the evolution of technology, markets and institutions. Thus, the overall research question in this thesis is:

W*hat kinds of stabilisation mechanisms are at play for the evolution of a technological innovation system in its formative phase?*

This question is highly central for understanding the co-evolution of a TIS in terms of stabilisation mechanisms and will be investigated in an embedded case analysis of two different cases, each consisting of four examples. I defined the stabilisation mechanisms as: (a) technology platform, (b) political networks, (c) codes and standards, (d) knowledge search, (e) demonstration projects, (f) market networks, and (g) hybridisation.

In order to investigate each stabilisation mechanism and its effect on the evolution of the TIS, I develop seven sub-questions in conjunction to the main research question. These relate to the three dimensions of the TIS that I examine and which I investigate in chapters 6, 7 and 8.

The questions for the process of institutional evolution are:

1. What role does the *technology specific platform* play in creating stability in the TIS, and what does the platform accomplish for the purpose of creating stability?
2. What types of *political networks* exist, and what is their role in creating stability in the formative phase of the TIS?
3. What types of *codes and standards* networks exist, and what effect do *codes and standards* have on the evolution of the TIS?

The questions for the process of technology are:

4. What kinds of *knowledge search* strategies do firms use to reduce technological uncertainty, and how is knowledge creation distributed in the value chain?
5. Which are the key *demonstration projects* in Europe for FC&H2, and how do they help in reducing technological uncertainty?

The questions for the process of market evolution are:

6. Which actors are involved in *market networks*? How are market networks created? In what ways do they impact market formation?
7. What is the role of hybridisation for market formation in the TIS, and in which applications does *hybridisation* affect the evolution of the market?

A second main research question relates to understanding the stabilisation mechanisms of the different firms and how these are related to firm strategy in the formative phase. This results in an analysis that goes more deeply into explaining various dynamics within the TIS in the formative phase, and specifies more clearly the extent to which its evolution is the result of spontaneous actions of individual actors or the result of more programmed coordination organised in platforms and formal networks. Thus the second main research question is:

In which situations does co-evolution of a TIS occur as the result of stabilisation mechanisms by the spontaneous actions performed by single or few actors, and in which situations does co-evolution result from more programmed coordination such as in technology platforms and formal networks?

It is crucial for the analysis to make solid arguments about which situations, in this case for FC&H2, the different stabilisation mechanisms are relevant to, for understanding co-evolution. Thus, I have further operationalised the criteria for analysis of how to assess these types of explanations, avoiding tautological explanations between the dependent and the independent variables. This is explored in the methods chapter in section 5.2.

4.9. The theoretical contributions of the thesis

This thesis will make six contributions to theory. First, this thesis focuses on the formative phase of a TIS and hence contributes an enhanced understanding of this phase by introducing *stabilisation mechanisms* for the co-evolution of technology, market and institutions. The formative phase is poorly understood in theory, as pointed out by several researchers (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2007; Malerba, 2004). I will improve this understanding by explaining the dynamics in the formative phase by the means of stabilisation mechanisms.

Second, I advance the understanding of various types of commercialisation strategies. Previous research has tended to look at differences between incumbents and newcomers (Christensen & Rosenbloom, 1995; Mitchell, 1989; Rothaermel, 2001) or in terms of first or late movers (Christensen, Suarez, & Utterback, 1998; Lieberman & Montgomery, 1988, , 1998). In terms of firm actions in early phases of an industry or an innovation system, I will further develop the concept of actor strategies by distinguishing between two forms, *coordinated* and *bottom-up* strategies. To strengthen the analysis of these strategies, I provide examples of what situations these two strategies are useful for in commercialisation; thus, the conclusions are empirically founded.

Third, the focus on actors also contributes a clearer picture of actors and their different actions in the innovation system, a weakness with the innovation systems approach as identified by Coriat and Weinstein (2002). According to them, too often in many institutionalist approaches the firm remains a 'passive', black box, 'acted' upon by the macro-social determinants in which it is inserted. Thus, there should be a clearer focus on agency and actor strategies.[37]

Fourth, previous research on hybridisation (Geels, 2002; Raven, 2007; Pistorius and Utterback, 1997) has identified technological hybridisation as an important factor for evolution of a TIS. I extend the theoretical

[37] This point also relates to the second contribution, the understanding of firm strategy in the formative phase.

understanding on hybridisation by developing a taxonomy including technological as well as institutional hybridisation.

Fifth, I further develop the understanding of how niche cumulation affect evolution of a TIS by specifying the situations that this phenomenon occur.

Sixth, this thesis is a study of FC&H2 that is unique relative to previous studies. Although there have been a few studies of FC&H2, none have analysed the evolution of the TIS and included both stationary and transport applications. For instance, Van den Hoed (2004) analysed the incumbent auto industry and its commitment to fuel cell vehicles, while Brown et al. (2007) studied the emergence of stationary applications. This thesis studies two cases with eight different examples within the same TIS. As a result, I provide a perspective on the complete innovation system, not some parts of the system.

5. Research design and methods

This chapter gives an account of the research design and methods used in the thesis. This study of the technological innovation system (TIS) of hydrogen and fuel cell technology in Europe focuses on the different mechanisms for creating stabilisation that the actors use in the formative phase of TIS. It thus takes a highly actor-oriented view of the evolution of the TIS. In order to conduct such an actor-oriented analysis of the processes of evolution of a TIS, I have developed a research design based on a case study approach. The objective of the dissertation is to conduct an analysis to generate propositions from the empirical material.

Section 5.1 discusses the objective of the study and argues for the choice of using a case study design. Section 5.2 presents the operationalisation of the research, and in section 5.3, I explain the aspects of embedded case studies. In section 5.4, I present the selection of cases, and I explore the sampling strategy in section 5.5. In section 5.6, I explain the data sources, and in section 5.7, I discuss the aspects of the data analysis. Finally, in section 5.8 I present a discussion on the reliability and validity of the research.

5.1. A case study based research design

The topic of this Ph.D. thesis is to understand what drives or determines early phases of the evolution of a TIS by employing a perspective on stabilisation mechanisms in the formative phase. The objective of this thesis is thus to test the model of stabilisation mechanisms that I created in the theory chapter and analyse how the stabilisation mechanisms affect evolution of technology, markets and institutions. The overall research question in this thesis is: *What kinds of stabilisation mechanisms are at play for the evolution of a technological innovation system in its formative phase?*

In order to investigate each stabilisation mechanism and its effect on the evolution of the TIS, I developed seven sub-questions in conjunction to the main research question, which I investigate in an embedded case analysis of two different cases, each consisting of four examples. These sub-questions explain the *impact* of the various stabilisation mechanisms on the *evolution* of the TIS. Thus, the stabilisation mechanisms are the independent variables and evolution of the TIS is the dependent variable. These relate to the three dimensions of the TIS I examine in chapters 6, 7 and 8.

The next step in the analysis takes place in chapter 9, where I conduct a comparative analysis measuring the importance of each stabilisation mechanism for evolution of the TIS. This analysis shows which stabilisation mechanisms firms use for the various applications and thus reveals the complexity involved in the evolution of the different examples. Chapter 9 also includes an analysis that goes more deeply into explaining various dynamics within the TIS in the formative phase. This analysis specifies more clearly the extent to which evolution is the result of spontaneous actions of individual actors or the result of more programmed coordination organised in platforms and formal networks. Thus, I also posed a second research question: *In which situations does co-evolution of a TIS occur as the result of stabilisation mechanisms by the spontaneous actions performed by single or few actors, and in which situations does co-evolution result from more programmed coordination such as in technology platforms and formal networks?*

In order to investigate research questions, I conduct an embedded case analysis to identify and cluster different strategies for co-evolution based on the characteristics of each example. This is determined in terms of two forms of complexity, technological complexity and market complexity. The first relates to the complexity of coordinating technology evolution, such as whether there are strong inter-dependencies to other technologies (network effects) and to competing technologies. The latter relates to the complexity of coordinating market introduction, i.e. to the organisation of the value chain and of links to user industries, as well as to the effect of institutions, like codes and standards. The result of this analysis is an understanding of different firm strategies in the formative phase.

The analysis in the thesis is based on the model of stabilisation mechanism that I developed in the theory chapter and their role in the formative phase, and I have chosen a case study based research design to accomplish this. Case studies, according to Yin (2003), are a suitable research strategy when studying a *contemporary phenomenon*, such as, in this thesis, understanding how particular stabilisation mechanisms function in concrete empirical situations.

First, to conduct such an analysis, I needed to grasp the connection of the empirical field in relation to the social, strategic and political issues that the firms deal with in the formative phase. According to Ragin, case-oriented research takes these aspects into consideration because 'they are concerned with actual events, with human agency and process' (Ragin, 1987). Thus, case studies provide an analysis understood in terms of the social and political context of the empirical field. The connection with the social, strategic and political issues is achieved by collecting firm specific data as well as participating directly in the process of creating a deployment strategy in the technology platforms. These primary data from firms, political networks and the technology platform provides a first hand account on the process of strategy making in the TIS.

Second, a crucial point for empirical analysis is to make solid arguments about which situations, in this case for fuel cells and hydrogen technology, the different stabilisation mechanisms are relevant in for understanding co-evolution. The case-oriented approach treats cases as whole entities and not as collections of parts, or as collections of scores on variables (Ragin, 1987). Yin (2003), in line with Ragin, states that an important feature of case studies is the 'incorporation of context' because many factors can have an impact on the results, not only the most obvious ones. These features of case-oriented research make it possible for researchers to interpret cases historically and to make statements about the qualitative changes in specific settings (Ragin, 1987). In this thesis, I explore the field of fuel cells and hydrogen technologies in Europe, and the dynamics in the industry in the formative phase. The timeframe of the analysis is five years, from 2002 until 2007; thus, I study a contemporary phenomenon, concerned with the social, strategic and political context of the actors involved, and a case-study approach, then, is clearly the most advantageous research strategy for this thesis.

A result of this case study is the development of propositions about how stabilisation mechanisms work in a TIS in the formative phase. Yin states that it is a goal of case studies to develop propositions about a specific phenomenon that can be tested later in similar situations (Yin, 2003); clearly the case study suits the objectives of the thesis. The propositions developed here can be tested in similar situations, i.e. in other TIS in the formative phase, thus leading to generalisation and theory development. I present the propositions in the conclusions chapter with suggestions for further research to strengthen the theoretical implications made in the thesis.

5.2. Operationalisation of the case study design

The theory chapter presented a theoretical perspective for analysing co-evolution of a technological innovation system in its formative phase along three different dimensions. The dependent variable in this thesis is co-evolution of technology, markets and institutions, and I have extracted seven mechanisms that I use as independent variables to investigate how, by whom, and when co-evolution takes place. It is important to add that co-evolution might not always take place, but is dependent upon the actions and interaction of actors and networks by means of different stabilisation mechanisms. As such, co-evolution is not a random process. The framework developed here with the seven stabilisation mechanisms thus makes it possible to construct propositions about in what situations, and how, co-evolution takes place.

The next step was to operationalise the set of stabilisation mechanisms into analytical tools for research. A challenge with qualitative analysis and case studies is to be able to make assessment criteria and to be certain that you measure what you are studying. In order to assess whether or not the stabilisation mechanisms are 'doing their job' I rely upon the actors' perception of what is and has been useful in the concrete development process. This includes concrete results in terms of project development, demonstration projects, support from policy makers and initial markets. In the following, I define the assessment criteria for the stabilisation mechanisms used in the thesis.

'Technology evolution' is assessed qualitatively by means of interviews and project reports. I have conducted interviews with firms and assess, first, the firm-specific modes of knowledge search and how the firms acquire competences. This is measured using an interview guide with a Likert scale to measure attitudes towards different knowledge sources.[38] Second, I analyse the types of relationships the firms establish to develop technology, the types of agreements they use, the objectives of the agreements, how they select their partners and which they choose. I distinguish between inter-firm relationships and relationships with universities and research centres. This is a measure of the types and role of learning networks, which situation a particular type of network is best suited to and when it is best to 'do it alone'. Furthermore, I identify and analyse the most successful 'demonstration projects' in Europe by interviewing involved firms and by analysing reports and web pages. I asses the purpose of the demonstration projects, how they did or did not fulfil the objectives and, most importantly, the results in terms of either continuation in larger projects or market deployment.

Since few products exist for consumers on the market, 'market evolution' needs to be analytically assessed differently than for mere size of market. I analyse the types of relationships the firms establish that were oriented towards creating a market. As part of the analysis, I develop a category of 'bottom up' and 'orchestrated' market formation processes, because some firms target and operate with immediate market opportunities while others target more long-term and strongly networked markets. I use this distinction to assess the dynamics of market evolution and analyse the different market development strategies of firms, how firms target different markets and the obstacles they perceive in this process, whether they have managed to come to the market with a product. Finally, I assess what types of applications develop first. These questions relate to the stabilisation mechanism of 'market networks', which I identify in terms of structure, function and organisation in the types of market relationships developed in two different applications, transport and stationary. Further, I look at the concept of 'hybridisation' to assess those applications and markets in which hybridisation plays a key role for evolution and those in which it has a small or no effect.

[38] This is further discussed in section 5.6.2

‘Evolution of institutions’ is assessed in terms of the ‘political networks’. It is not easy to assess how important they are for evolution of the technological innovation system, but situations in which such networks have led to the creation of market-development activities, negotiations or lobbying that result in the development of concrete policy tools or large-scale demonstrations, are examples of networks that have concrete and real impact. Codes and standards can be assessed in terms of standards that have been developed and whether they have been transformed into codes, i.e. supported by law.

The final step is to asses what determines co-evolution between the three dimensions. It has been argued that in order for the TIS to reach the next level, co-evolution of the three dimensions of technology, institutions and markets is required. What, then, are the situations in which these dimensions co-evolve? This requires assessing that the actions, in the form of stabilisation mechanisms, are resulting in technology, institutions and market becoming aligned. One example of this kind is the change from the EU’s FP6 programmes with their strong focus on R&D and demonstration, to the FP7 programmes indicates the technology platform and the Joint Technology Initiative (JTI) with larger demonstrations, including assessment of necessary regulative obstacles and market aspects becomes a vehicle for co-evolution.

5.3. Embedded case studies

The object of study in this thesis is the TIS for fuel cell and hydrogen technology in Europe. Furthermore, I compare two different embedded cases found in the TIS, stationary and transport applications, and use four different examples in each case study. As a result, I will find out how the different stabilisation mechanisms affect the outcome in two different applications.

By employing a case approach on two different applications that are in the same ‘technological innovation system’ and span many different industries, I explain how different contexts affect the strategies of firms and how co-evolution occurs in different settings. The approach of this thesis is therefore an ‘embedded case study’ (Yin, 2003), or a ‘within comparison’ (Ragin, 1987); that is, the comparison is between two different applications within the same TIS. The different cases and examples are displayed in Table 5.1.

Table 5.1: **Cases and examples for FC&H2 in Europe used in this thesis**

Cases	**Transport case**	**Stationary case**
Examples	1. Auxiliary Power Unit 2. Forklifts 3. Fleet vehicles 4. Consumer vehicles	5. By-product hydrogen 6. Telecom back-up 7. Micro CHP 8. Large-scale power production

The reason for choosing a design based on the analysis of two different cases within the same TIS is that this opens up the possibilities for a result that is realistic, holistic and representative. Realistic means that the analysis covers the entire TIS and not only parts of it. Through using two different applications as cases, and with four examples from each case, the study becomes highly representative of what actually goes on in the TIS. Previous research has tended to focus on one application of a 'technological innovation system', and not on the complete innovation system (Harborne, Hendry, & Brown, 2007; Hoed, 2004). As such, the analysis includes variation in understanding the different dynamics within a TIS.

5.4. Selection of the cases and the embedded examples

A strategic selection of cases means that the researcher has some knowledge about the different cases beforehand. First, the work with this thesis started with my master's degree in 2003 and through that, I had developed an understanding of the innovation system for FC&H2 in Norway. The results from this study showed that the EU level was thought to be the key level among the actors and suggested that the study continue at this level (Godoe & Nygaard, 2006). I therefore chose to study the EU-specific initiatives and the dynamics in the EU-wide innovation networks. Second, I participated in an OECD project on energy technology studying FC&H2 technology from February to October 2003, which gave me further insight into the field of FC&H2 and resulted in a report as well as two journal papers.[39] Third, I have

[39] (Godoe, Nerdrum, Rapmund, & Nygaard, 2003; Godoe & Nygaard, 2006; Klitkou, Nygaard, & Meyer, 2007).

also interacted with a diverse set of industry experts on the topic of FC&H2 technology. This experience provided me with insights into the different FC&H2 applications and was the key rationale for choosing the various examples to investigate the different mechanisms for evolution of the TIS. Based on this knowledge of the field, I decided to use two cases in the thesis, transport and stationary applications, and to exclude portable applications. My decision to exclude the portable application area was based on the fact that the European actors are not present in the whole value chain, and I wanted to compare across the whole value chain.

I decided two include within each case four different examples that are comparable in terms of the different stabilisation mechanisms. I tried further to create variation in the choice of application, so that I would have different firms with different strategies. Within the two application areas, then, I have examples of both stationary and transport applications, and these include examples that relate to niche markets, early markets and mass markets. The eight different examples create a broad understanding of the dynamics of technology, market and institutions in these two different applications of the TIS in the formative phase. Thus, I argue that I create a strong understanding of the technological innovation system.

In the transport area, I decided to focus, first, on consumer vehicles, as they constitute a potential mass market, and second, on fleet vehicles, as these receive a lot of attention in terms of demonstration projects. Third, I also included forklifts, which are a niche market targeted by a group of firms and make a good contrast to consumer vehicles. Another reason is that there are different firms targeting forklifts and consumer vehicles, and this makes comparison more attractive to pursue for the researcher. Finally, I chose to include auxiliary power units for caravans because this example has evolved rapidly within a short period.

For the examples of stationary applications, I selected, first, the small-scale stationary market, that is, micro CHP, since this example is the potentially largest market of the stationary applications. Second, the large-scale power production application is a technology that can replace existing energy production in large-scale power stations and thus constitutes a contrast to the micro CHP example. As such, these two application areas complement each other. Third, I discovered that some companies are exploring the use of by-product hydrogen from chemical factories for power production with fuel cells, to provide electricity to those factories. This was clearly a good case for studying how firms target immediate opportunities in niche markets. Finally, I chose to include back-up power for the telecom sector. I chose this example because it is an interesting example of firms in the industry identifying a new application area, and it has quite different market dynamics than the existing markets for small-scale fuel cells. An additional factor for choosing telecom back-up was that I had interacted with several firms targeting this area and gained first-hand insights into their market development plans and activities.

5.5. Creation of the sample

The total population of firms in Europe consists of more than 400 firms, and the majority of these are located in Germany, Italy, the UK, France, the Netherlands and Scandinavia. There are large differences among them in terms of how committed the firms are to developing FC&H2. For instance, many firms state that they are involved in FC&H2 development, but this might be an activity they have done in the past or a field that they are only 'monitoring'. It is therefore much more relevant for case study research to include only those firms that are actively involved in FC&H2 technology development, and as such, are directly involved in creating the TIS.

Thus, in this study, given the uneven commitment among firms and the differences in the possibilities of firms to affect the evolution of the TIS, sampling for proportionality is not the primary concern; the objective, rather, is to reach a targeted group of firms.[40] Since these technologies are highly complex and their commercialisation requires a certain amount of resources, they require a clear commitment from the actors. It is therefore not suitable for the research to normalise firms

[40] There are two forms of sampling procedures. One is to sample a proportionality of a total population, where firms are chosen using a random process. This is useful when trying to generalise from the sample and to a population, and is usually done in statistical analysis. This study employs the other, as described.

and pick a random selection for comparison, but more meaningful to identify the key actors. Thus, I chose purposeful sampling for the purpose of including the key actors in the field and strengthening the analysis.

5.5.1. Purposeful sampling

The sample of firms used in the thesis is based on what is called 'purposeful' or 'strategic sampling' (Patton, 2002), where the sample is created because of their characteristics. This is preferred, when a special type of firm is the target, in order to have a stronger theoretical sample. That is, if you want to study firms that are active in specific networks and platforms, you do not randomly choose from a full population of firms but try to identify those firms that participate in these networks and then use this as the basis for inclusion.

Purposeful sampling is recognised moreover to be important for creating theoretic generalisation, not statistic generalisation (De Vaus, 2001). This means that the goal is not generalisation towards a full European sample of all firms working with FC&H2. Rather, a generalisation about firms that have an innovation strategy and are central in the networks in the European sector is strengthened. This makes the external validity towards similar types of situations stronger than sampling on a random proportion of all FC&H2 firms could achieve.[41] Furthermore, by including the key actors the generalisation on the effect of the stabilisation mechanisms in the formative phase of a TIS is also strengthened.

5.5.2. Selection of the sample

This section explains how the selection of the sample was conducted. In this thesis, I focus on the European sector of FC&H2 with an in-depth study of the activities surrounding the European Hydrogen and Fuel Cell Technology Platform (HFP). The HFP is the common platform created by leading firms in Europe and is supported by the European Commission as well as many national governments.

[41] Such as for other emerging technological systems or FC&H2 activities outside Europe.

The criteria for inclusion in the sample are, *first*, to have a full coverage of the value chain, and *second*, that the firm have a cooperative strategy. By cooperative strategy, I mean that the firm has to participate in some form of platform, industry network or other cooperation with the goal of developing or commercialising FC&H2 technology. This means that if I could not find the firm through industry reports or keyword search on the Internet, the firm was not considered to have a 'cooperative strategy'. *Third*, I chose to include the most committed firms in the sample. This means that they should be active in a national or regional European network, or have a leading position in the industry. *Fourth*, I chose firms from the most active geographical regions. The firms selected were in Germany, Italy, the UK, Belgium and Scandinavia. Germany was chosen because this is where the major concentration of firms in Europe is located. Italy was chosen due to its activities in fuel cell and hydrogen technology and to the collaboration I set up with Bocconi University in Milan. Scandinavia was chosen due to the activities found there as well as its being my home region. I verified that the firms in the sample met the criteria and selected a group that creates a full coverage of the value chain in Europe.

I developed the sample of firms by using several database searches as well as a general web search. These were, first, the member list of the implementation panel of the HFP;[42] second, the member list of the European Joint Technology Initiative for hydrogen and fuel cells; and third, the online industry directory of the market intelligence organisation Fuel Cell Today.[43] Fourth, for the German firms, I used, in addition to the industry directory of Fuel Cell Today, the German Fuel Cells Initiative (IBZ).[44] This gave a good picture of the situation there and included firms in all parts of the value chain. In Italy, the internal database of the Italian Hydrogen Association was also used.[45] The resulting sample includes 38 firms from all parts of the value chain.

[42] <https://www.hfpeurope.org/hfp/participating_organisations>, accessed 2005-2006.
[43] <http://www.fuelcelltoday.com/online/industry-directory>, accessed 2005-2007.
[44] <http://www.initiative-brennstoffzelle.de/en/live/start/1.html>, accessed 2005-2006.
[45] <http://www.h2it.org/>, accessed 2005.

5.5.3. Characterisation of the firm sample

I have studied in detail 38 European firms with a sample consisting of 20 firms in Germany, 8 firms in Italy, 5 in Scandinavia, 2 in the UK and Belgium, and 1 in France. An overview of the firms is presented in Table 5.2.

This sample is biased towards Germany, because the major activities are taking place there. The German firms include the leading stationary companies, four of the six automobile original equipment manufacturers (OEMs) that have FC&H2 innovation programmes, and a large national programme. Germany's influence on the European scene is substantial, as in the creation of and work with the HFP.

The initial sample included 45 firms, but 7 firms were deleted from the sample due to unwillingness to participate in the study. The reasons these firms gave for not participating were time constraints, some had problems with confidentiality and therefore could not answer the questions, and finally, some did not respond to my request for an interview.

Table 5.2: **Overview of the sample according to application, position and sector**

	Sector	Application	Value chain	Focus	Focus 2	Size
1	Auto	Transport	End use	Consumer	APU	Large
2	Fuel Cell	Transport	Integrator	Consumer	Public	Medium
3	Auto	Transport	End use	Consumer	-	Large
4	Auto	Transport	End use	Consumer	Public	Large
5	Auto	Transport	End use	Consumer	-	Large
6	Fuel Cell	Transport	Integrator	By-product	Consumer	Medium
7	Thermal	Transport	Sub-system	Public	Fuel	Large
8	Fuel Cell	Transport	Integrator	Public	Forklift	Small
9	Electronics	Transport	Sub-system	Consumer	Public	Micro
10	Fuel Cell	Stationary	Integrator	Back-up	-	Small
11	Fuel Cell	Stationary	Sub-system	Distributed	-	Micro
12	Fuel Cell	Stationary	Integrator	APU	Portable	Medium
13	Material	Stationary	Component	Distributed	Portable	Medium
14	Fuel Cell	Stationary	End use	Energy prod	Back-up	Medium
15	Power gen	Stationary	Integrator	Energy prod	Distributed	Medium
16	Fuel Cell	Stationary	Integrator	Distributed	APU	Small
17	Power gen	Stationary	Integrator	Energy prod	APU	Large
18	Heating	Stationary	End use	Distributed	-	Large
19	Heating	Stationary	Integrator	Distributed	-	Small
20	Fuel Cell	All	Component	APU	Distributed	Small
21	Material	All	Materials	Consumer	Distributed	Micro
22	Material	All	Materials	Consumer	Portable	Small
23	Material	All	Materials	Consumer	Portable	Micro
24	Sensors	All	Sub-system	Consumer	Portable	Micro
25	Industrial gas	All	End use	Public	consumer	Medium
26	Material	All	Materials	Fuel	Portable	Small
27	Chemicals	All	Materials	Consumer	Portable	Large
28	Industrial gas	All	End use	Fuel	By-product	Medium
29	Oil	All	Integrator	Fuel	Back-up	Large
30	Oil	All	End use	Fuel	Energy prod	Large
31	Industrial gas	All	End use	Fuel	-	Large
32	Industrial gas	All	End use	Fuel	-	Large
33	Oil	All	End use	Fuel	-	Large
34	Industrial gas	All	Integrator	Fuel	Forklift	Large
35	Fuel Cell	All	Integrator	Forklift	Consumer	Micro
36	Political	All	Association	-		Micro
37	Political	All	Association	-	-	Large
38	Consulting	All	Association	-	-	Micro

First, in terms of position in the value chain, the sample includes most firms that are system integrators and most that are focused on 'end use' (12 each). Another 5 produce materials, 2 produce components and 4 develop sub-systems. In addition, there were interviews with 3 associations or organisations; these are political networks. The composition of the sample is presented in Table 5.3.

Table 5.3: **Value chain composition of the sample**

Value chain	**Number**
Materials	5
Component	2
Sub-system	4
Integrator	12
End use	12
Association	3
Total	**38**

Table 5.4: **Sizes of the firms in the sample**

Size	**Type**	**Sample**
<250	Large	15
>250	Medium	8
<50	Small	7
>10	Micro	8

Second, the 38 firms in the sample include micro, small, medium and large firms.[46] The largest share of firms is large firms, of which there are 15 in the sample, while the number of medium, small and micro firms is well balanced with 8, 7 and 8 firms respectively. The sample in relation to firm size is presented in Table 5.4.

Third, in terms of commitment and network activities, only a few of the 38 firms in the sample are not part of the HFP or the JTI, and have indirect relations to these industry groupings through close links as strategic partners. I should mention that the sample also includes micro, small and medium-sized enterprises (SMEs), a group of firms that does not have a strong presence in the HFP. They were drawn from national and regional platforms, as these include a greater number of SMEs.

Fourth, this sample includes the major stakeholders involved in innovation in FC&H2 technology, such as the European automakers (OEMs), fuel cell and hydrogen system integrators, energy companies,

[46] Based on the EU definition of SMEs, <http://ec.europa.eu/enterprise/enterprise_policy/sme_definition/index_en.htm>, accessed 12 August 2007.

and materials and component producers. This is presented in Table 5.5, which shows that the firms come from 12 different sectors. Thus, the variety of actors in the sample is high and as such not biased towards particular industry views. The largest share however, belongs to the fuel cell industry, that is, firms specialised in fuel cell-specific components and systems.

Table 5.5: **Sectors to which the firms belong**

Sector	#
Fuel Cell	10
Industrial gas	5
Material	5
Auto	4
Associations	3
Oil	3
Heating	2
Power generation	2
Chemicals	1
Electronics	1
Sensors	1
Thermal	1
Total	**38**

Table 5.6: **Focus of the firms in the sample**

Focus	Primary	Secondary	Total
Consumer vehicles	11	3	14
Fuel	8	1	9
Micro CHP	5	2	7
Large scale PP	3	3	6
Public transport	3	3	6
Lobbying	3	-	3
APU	2	3	5
Back up	1	2	3
Forklift	1	1	2
By-product	1	1	2
Total	**38**	**19**	**57**

The integration of hydrogen-related technologies belongs to the industrial gas companies and oil companies, while the chemicals and materials industries develop materials. The components belong to several industries, such as electronics, and components more specific to fuel cells belong to the fuel cell industry. Finally, the auto companies, the heating companies, and the power generation and the oil companies (fuel retailing) do end-use integration. These companies integrate fuel cells and hydrogen systems into specific applications.

Fifth, the sample consists of firms working on transport and stationary applications. Of the 38 firms, 19 target both applications, while 10 target stationary and 9 target transport applications. Thus, the sample is well balanced between the two applications.

Sixth, the focus of the various firms is an important factor to include, so that all the different sub-cases are part of the sample. The focus of the firms in the sample is presented in Table 5.6. In terms of the application focus of the firms in the sample, firms working on consumer vehicles and fuel constituted the largest grouping, but distributed energy and central energy production were also satisfactorily covered.

5.6. Data sources and data collection

This thesis relies on qualitative data to answer the research questions posed in the theory chapter. The data collected in the thesis to answer these questions consist of three types: participant observation, interviews, and documents. The data collection strategy is based on the use of several different sources of data and, as such, evidence is triangulated (Yin, 2003). Further, the use of multiple sources of evidence in the study is used to avoid researcher bias (Taylor & Bogdan, 1984), and it increases the validity of the research.

5.6.1. Participant observation

A key source of information came from participating in the finance and business development sub-group of the European Hydrogen and Fuel Cell Technology Platform (HFP) from February 2005 until it dissolved in March 2006. My role was to provide input to the various tasks of the group and I authored a paper on the dynamics of early markets for portable fuel cells (Nygaard, 2006).[47] The different groups of the platform create different documents regarding the strategy for implementation of the vision created by the high-level group in 2002. In particular, the objective of the working group was related both to finance and business development. In terms of business development the objectives were: [48]

- To identify early niche markets and near-term market opportunities related to hydrogen and fuel cells technologies and system solutions
- To evaluate needs and actions required for supporting a longer-term market development for hydrogen and fuel cells in the energy markets

[47] This paper is not used directly used in this thesis as its focus is on a different application, namely portable applications.
[48] Source: webpage for the Financing and Business Development Subgroup, <https://www.hfpeurope.org/hfp/fbd>, accessed 2006.

- To provide recommendations on activities and actions required for bridging the gap from product development to commercialisation

The working group presented the results of its activities at its concluding event in Brussels in March 2006, including a report and a set of recommendations. The topics the group dealt with later became part of the HFP Implementation Panel, Working Group on 'Cross-cutting Issues', which included some of the same members.

Participation observation is a method in which the researcher is actively involved in the activities of a group, and is a research strategy that is clearly useful when the objective is to gain close familiarity with and deep knowledge of a particular group of actors. The benefit of this method is the rather unusual opportunity to access a group that is otherwise unavailable for scientific investigation, consequently increasing the actual understanding of a process or phenomenon. A problem, according to Yin (2003), is the potential bias that participation can create, when, for instance, the researcher might take the same position as the group on a specific question. However, as I use multiple sources of evidence and triangulate this data with information from interviews and written documents, the sources of evidence are much broader than those the researcher of a single group would assemble, and thus I avoid a potential bias of this kind.

I participated in eight one-day meetings, a two-day workshop and a two-day assembly together with all the stakeholders in the Platform. In the meetings, the management of the HFP presented the perspective and work of the other working groups, as well the steering panels for the *strategic research agenda* and the *deployment strategy*. The experience from participation in these meetings yielded valuable insights into different problems that industry works with and suggestions for solving them. It was also an opportunity to meet and converse with key stakeholders, and I had an opportunity to come to know people who later acted as key informants with special insights into the industry as well as into my research.

5.6.2. Interviews

During the work with this thesis, I conducted 42 interviews with managers from 38 different firms and with industry experts from the various associations and industry networks. In addition to these interviews, I supervised a master's thesis project that included two case studies of regional projects.[49] As part of the data collection for the master's thesis, 12 interviews were conducted with stakeholders in these two regions. The interviews are the main source of information in this thesis, and the goal was to have a large sample representing all parts of the value chain and in each application area. Table 5.2 presents the set of actors that I interviewed in the research process.

The interviews lasted from about half an hour up to two hours, and I recorded and later transcribed these.[50] The interviews were performed face-to-face with one or two senior executives in each company or over the telephone.[51] I aimed at targeting people who were responsible for R&D and business development activities, as these have the best knowledge for responding to the topic of this thesis. I therefore targeted the people who had positions in the various strategic or business development groups in the HFP or in the national or regional initiatives. All the people I interviewed had a position that made them relevant for an interview.

During the interviews with the companies, I collected qualitative data that were both closed and open.[52] The closed questions in the interview guide were collected based on attitudes of the firms on a set of key issues. The factors explored in the interviews were:

- knowledge search tools and strategy
- acquisition of competences
- cooperation with firms

[49] Ingo Bunzeck, European Inter-University Association on Society, Science & Technology (ESST) M.A. project (2006).

[50] Names of companies and persons from the interviews are not used in the thesis, and I signed a confidentiality agreement with the companies stating that I would not reveal any confidential information or try to sell this to any third parties, as the interviews are conducted for pure research.

[51] At approximately half of the interviews Stefano Pogutz at Bocconi University also participated. The number of telephone interviews conducted were 10

[52] See the interview guide in the appendix for a full overview of the themes discussed during the interviews.

- cooperation with universities
- the role of networks and platforms

These factors were explored using a Likert scale from 1-7, where 1 is not important and 7 is very important. I used these as a means to measure opinions of firms on these issues. The results from these questions were later analysed to assess the importance of the different indicators in each theme. In relation to the different themes, the informants also explained why a factor was or was not important, thus providing context and explanation for the answer.

In addition to these closed questions, I also used open questions on several themes. This more explorative part of the interviews included topics like:

- the actual cooperation process
- the objectives of the different cooperations
- the potential and barrier for market development
- the critical barriers for the technology
- the role of policy makers
- the key actors in the industry
- technology platforms and industry networks

In total, the interviews provided me with rich information on all the various examples in both the cases I use in the thesis.

5.6.3. Documentary sources

The documentary sources consist of various policy documents, strategy documents, industry reports, company statements and websites. At the European level, the documents consist of reports and strategy documents produced mainly by the HFP strategy group and project reports from EU projects like Hy-ways, Hy-light and various demonstration projects. HFP also provides a newsletter for registered users of the extranet with updates about the work with the technology platform and the Joint Technology Initiative (JTI), as well as news about the European Commission's position and actions regarding FC&H2.

First, the key documents from the HFP that I have used are the *Deployment Strategy* (HFP, 2005) and the *Implementation Plan* (HFP, 2007), as well as the newsletter distributed by the European Hydrogen & Fuel Cell Technology Platform Secretariat to the registered users. The deployment strategy and implementation plan documents were created by two working groups consisting of key industry actors in the field of FC&H2. As such, they represent the industry view on the processes of deploying this technology in the marketplace. A few consultancy firms also support the industry group in developing these strategic documents. Since a group of leading industry actors creates these documents, the probability is high that the content of the documents actually represents the industry's perspective.

Second, the policy and strategy documents from national governments include the German Transport and Energy Strategy (NIP, 2007) and the strategy behind Hynor (Norway) and the Scandinavian Hydrogen partnership.[53] [54] These reports are key sources for analysing the different strategies in the various regions in Europe, as well as with the companies involved. For instance, the German strategy closely follows the EU strategy developed as part of the HFP and focuses on both stationary and transport applications. In Scandinavia, however, the actors focus on how they can build a large-scale demonstration for hydrogen vehicles in the transport sector.

Third, several of the EU projects on FC&H2 delivered quite detailed management and final reports. These reports provided me with information on how successful the projects were, the difficulties encountered and issues for further activities.

Fourth, another type of written source that has been useful is company-issued reports and materials. These exist in various forms, such as annual reports, newsletters and public statements, marketing materials, and material from exhibitions. I used this source, first, to get an overview of the company and its activities before the actual interview, and second, to have supplemental information on the firm. Finally, industry and consulting reports are also available to a considerable degree. The most comprehensive sources are 'Fuel Cell Today' and

[53] <http://www.hynor.no/pdf/engelsk-hynor-presentation.pdf>
[54] <http://www.scandinavianhydrogen.org/scandinavianhydrogen/project/SHHP_brochure.pdf>

'Fuel Cells Works', which send out weekly reports and updates about companies, technology market development and financial information.[55] These sources are valuable for seeing what actors are operating in different applications and regions, their various prototypes and key partnerships. Finally, reports from the International Energy Agency (IEA, 2000, , 2005) have been used as a source of information on the topics of challenges and prospects for FC&H2.

In the data collection process, I combined primary data from participant observation and interviews with secondary data in the form of relevant documents. It is important to be cautious about the content in secondary data such as company- and EU reports, as the rationale behind them might not fit with the purpose of the research. Triangulating with primary data sources, however, gives a much richer picture than using only secondary data. This research strategy enables a deeper understanding of the industry dynamics as well as helping to contextualise the different examples. I also gained a strong understanding of the strategic implications of developing technology, as well as of prototyping, demonstration of technology and market strategies.

5.7. Data analysis

Data analysis in qualitative studies is the process through which data are transformed into findings (Patton, 2002). Among other things, this process includes minimising the data and separating the trivial from the important. The theoretical framework and the research questions developed on the basis of the theoretical discussion shape the analysis. The data analysis should then be conducted in such a way that the data answer these questions in a satisfying way.

A specific characteristic of qualitative research is the fact that data collection and data analysis occur simultaneous, or their borders are at least blurred. Patton writes, '[I]n the course of fieldwork, ideas about directions for analysis will occur. Patterns take shape, possible themes spring to mind' (Patton, 2002). This means that during the course of the data collection process I wrote field notes and impressions from

[55] < http://www.fuelcellsworks.com/> and < http://www.fuelcelltoday.com/>

interviews and comments. These notes were valuable for the further analysis after the interviews were completed, and for asking the informants about impressions that I got during the data collection. However, too much focus on analysis should not be conducted while gathering data so that the researcher does not 'rush into premature conclusions' (Patton, 2002, p. 436). The goal should be to create a sound balance of analysis that will result neither in premature conclusions nor in losing insights forever.

The first sets of data I used are written sources in the form of industry reports. These gave me valuable information for the selection of cases. The primary data I collected from participant observation and interviews were the most important sources for analysis of stabilisation mechanisms. Participant observation provided me with data on the industry view and the perspective of various actors on all the examples used in the case analysis. These data were most relevant, however, for market development and policy issues, and for how the process of establishing the technology platform occurred. The data from interviews complement the participant observation. These focus on firm-specific perspectives on technology development, market development and the effect of institutions. By using both types of data, I was also able to triangulate between how a firm uses specific stabilisation mechanisms, and how the industry grouping at the HFP develops strategies for specific stabilisation mechanisms.

The interviews were taped and transcribed verbatim, that is, according exactly to what is said in the interview.[56] Verbatim data are considered to be the essential data for qualitative analysis (Patton, 2002). I transcribed the data personally because this is a good way to get to know the data beforehand and what they consist of. This gave me a

[56] The transcriptions were written in Word, which makes it easy to manage the data. Computer programs can be of great help to the researcher in organising and displaying data, but as Patton explains, '[T]he qualitative analysts doing content analysis must still decide what things go together to form a pattern, what constitutes a theme, what to name it and what meanings to extract from case studies' (Patton, 2002, p. 442). Computer programs make it possible to highlight, to cut and paste between documents, and to remove trivial statements and quotes. How the data are to be interpreted, however, the researcher must decide.

good picture of the type of data I had collected as well as insights into the kind of findings I could generate.

The interview transcripts needed to be reduced considerably, as the 38 interviews together consisted of more than 400 pages of transcription. Data reduction, where the redundant is removed and the essential points highlighted, makes the analysis much easier to manage for the researcher. In order to reduce the data, I organised them according to the different topics and themes discussed during the interview. I later compared these topics across the respondents according to similarities and patterns. I developed a document for each theme based on the important statements from the actors. The next step was gradually to remove the non-important parts and to highlight the different quotes I would use in the thesis, and with this, the amount of data become more manageable. I changed the actors into type of firm, i.e. OEM, system integrator, component developer, hydrogen distribution company, or industrial gas company. In addition, I compared the findings from the interviews to the documents I had collected as well as to written sources from companies and information from their websites. Together, the data collected gave a clear picture of the dynamics in the European innovation system and covered both application areas and all eight examples I focused on.

5.8. Discussion of validity and reliability of the study

This section discusses the important criteria for the design and implementation of research, namely the validity and reliability of the study. Validity and reliability are important criteria for assessing the extent to which the research results are scientific (de Vaus, 2001).

5.8.1. Reliability

Reliability refers to the extent to which the study is replicable. This means that if I were to do the study all over again, would I then reach the same results. De Vaus states that a 'reliable measure is one that gives the same reading when used on repeated occasions' (de Vaus, 2001, p. 30), which is key to having a reliable study. Threats to reliability can be poor wording of questions and asking questions of people who do not have an opinion on the matter or have insufficient knowledge, and answers can be affected by mood or the context in which they are asked (de Vaus, 2001, p. 31).

In order to create reliability in the study, first, I made a preliminary test of the interview guide with a manager from one firm, who was asked to assess the clarity of the questions and whether something was missing. The interview guide was thus tested for its usefulness for the analysis that I set out to do. Second, in terms of asking the questions of people with insufficient knowledge, the use of purposeful sampling assures that the firm is relevant for the study, and the person interviewed is in a position in the firm to deal with the topics discussed. I also sent the interview guide by email at least one week in advance, so the respondent had time to prepare for the interview.

Case studies have often been criticised for a tendency among researchers to allow their favourite cases to 'shape or at least colour their generalisation', something that can be a problem for the reliability of the case approach (Ragin, 1987). It is therefore crucial that the researchers are aware of such issues and not become blinded by their favourite examples. As a means of avoiding this form of bias, I used eight different examples from two different cases, thus incorporating a high level of variety; further, the data collection in this thesis included secondary documents as well as interviews and participant observation. Thus, I try to describe the TIS in the formative phase in terms of variety and differences, and not on the basis of the particularities of a single case.

5.8.2. Construct validity

Construct validity refers to how well the study actually measures what one set out to measure. Construct validity can be increased by creating concepts that are meaningful and by using multiple sources of evidence (Yin 1994, p. 34). First, I have used concepts commonly used in the analysis of emerging TIS and defined them thoroughly in the theory chapter. Further, I explain the criteria for how these concepts 'should be used' in the analysis of co-evolutionary processes in section 5.2.

In terms of sources of evidence, the data for this thesis consist of primary data from interviews with firms and different industry experts, such as people involved in technology-specific advocacy coalitions, and with members of working groups in technology platforms and industrial networks. Furthermore, in order not to represent a single firm perspective, I selected the firms from different parts of the value chain. These primary data complement the written materials like strategy reports from the HFP and different national and regional networks, progress and management reports from demonstration projects, and reports, newsletters and web pages from industry analysts and consultants. As such, the sources of evidence come from multiple sources. Based on these research methods, the construct validity of the thesis should be satisfactory.

5.8.3. Internal validity

Internal validity is the capacity of the research design to account for the causal conclusions stated in the thesis. This means that the causal relationships explain the conclusions drawn and that these are not the result of other factors. It is therefore important to rule out alternative explanations from the findings. It is impossible to rule out ambiguity in social science, but it can be minimised.

In order to increase the internal validity of the research, I have used multiple sources of evidence to avoid researcher bias and I have used data that include actors from all parts of the value chain. In addition, I sent a first draft of the thesis to all the persons I have interviewed as well as to two industry experts whom I know personally. Thus, I provided the actors with the opportunity to correct possible mistakes that I might have made in the research. I received five responses that gave valuable information for the correction and writing of the final version of the thesis. Furthermore, I discussed my major conclusions with the industry experts to assess whether I had mistaken the empirical field in any sense. All together, these measures that I have taken increase the validity of the research.

5.8.4. External validity

External validity relates to the transferability of studies and the extent to which research results can be transferred to situations with similar parameters, populations and characteristics. The external validity of case studies is enhanced by the strategic selection of cases rather than the statistical selection of cases (de Vaus, 2001, p. 238) and is established by theoretical replication. This means that the researcher needs to have sufficient knowledge of the cases beforehand in order to pick the right cases.

I sampled for the purpose of creating a theoretic generalisation, not a statistic generalisation (de Vaus, 2001). This means that the goal is not generalisation towards a full European sample of all firms working with FC&H2. Rather, a generalisation about firms that have an innovation strategy and that are central in the European sector is strengthened. This makes the external validity towards similar types of situations stronger than sampling on a random proportion of all FC&H2 firms could achieve.[57] The sample is thus believed to have a high external validity due to the sampling of actors in all parts of the value chain and in several different locations in Europe, each with a special industry structure and focus. Another method for increasing validity is the use of multiple sources of evidence, such as documents, expert opinions and interviews. Triangulation of data sources avoids single-stakeholder views by interviewing different stakeholders (Yin, 2003) and is something I used extensively in the research.

5.8.5. Generalisation of case studies

Case studies have been criticised as not being suitable for generalisation (de Vaus, 2001; Punch, 1998). Punch mentions two ways for creating generalisable results: by creating conceptualisations, or by developing propositions (Punch, 1998, p. 154). Conceptualisations mean that the researcher develops one or more concepts based on the case study. Propositions are made by linking factors from the case study to each other, and 'these can then be assessed for their applicability and transferability to other situations' (Punch, 1998, p. 155). Propositions thus become the output from the research, and 'developing abstract concepts and propositions raises the analysis above simple description, and in this way a case study can contribute potentially generalisable findings' (Ibid., p. 155). These generalisations are called theoretic or

[57] Such as for other emerging technological innovation systems or FC&H2 activities outside Europe.

analytic generalisations and are important for increasing a study's external validity. I stated at the beginning of this chapter that development of propositions is a key objective of this thesis. In the conclusions chapter I develop a set of propositions based on the findings in the thesis. These can then be tested in similar cases and lead to theory development. Therefore, the thesis will result in generalisable findings.

III. EMPIRICAL ANALYSIS

6. Alignment of actors

The aim of this chapter is to explain the process of the alignment of actors, and I explore this with three stabilisation mechanisms, 'technology-specific platform', 'political networks' and 'codes and standards. The actors use these stabilisation mechanisms to shape the regulatory framework, to create a joint vision and to seek institutional adaptations to a specific technology. The questions I set out to answer in the chapter are:

- What role does the *technology-specific platform* play in creating stability in the TIS, and what does the platform accomplish for the purpose of creating stability?
- What types of *political networks* exist, and what is their role in creating stability in the formative phase of the TIS?
- What types of *codes and standards* networks exist, and what effect do *codes and standards* have on the evolution of the TIS?

In section 6.1, I discuss technology platform, an important institutional creation by the EC based on the introduction of soft governance instruments in the form of partnerships between the EC and industry. In section 6.2, I discuss the various political networks in Europe and their role in the alignment of actors and in shaping the institutional framework. In section 6.3, I present the codes and standards networks and the process of code and standard development in the global networks, along with how these global networks relate to the European standardisation process. Finally, in section 6.4, I present the conclusions from the empirical analysis in this chapter.

6.1. Technology Platform

This section explores the European Hydrogen and Fuel Cell Technology Platform (HFP) and its role as a formal network involved in the co-evolution of technology, market and institutions in the formative phase. I first present the concept of technology platform, then I present the structure of the HFP, and then I asses the achievements and the role of the HFP in creating stability in the TIS, namely the creation of a joint vision, an implementation plan and the establishment of the Joint Technology Initiative (JTI).[58]

6.1.1. The concept of technology platform

A technology platform (TP) is a formally created network considered to have an important role for the evolution of the TIS in the formative phase. The TP is a multi-level instrument coordinating national, regional and industrial perspectives with a specific technology area of strategic importance to the European economy (EC, 2004). The EC employs a TP as a tool in many TISs, ranging across biomedicine, telecom, nanotechnology and energy. Thus, the TP is set up to establish coherence between the strategies and actions at the different levels by synthesising the perspectives of all the stakeholders involved in the development and commercialisation of the technology. An important role of the HFP mentioned by the firms is that besides making it possible for the industry to create a common platform, it also includes policy makers directly in strategy making. As one manager in an OEM explained:[59]

> 'This is an important issue for us, because we are heading towards some kind of standardisation with all the other OEMs and together with the government, so this is an important issue which takes place at a national or even European level. You have to define the interfaces, the quality of the fuel, or the safety regulations, and there is one other important factor: we hope to have some influence on strategic decisions concerning R&D. So that is why we take part in HFP, for example.'

[58] 'JTIs are used to create a single, Europe-wide and industrially-driven R&D and programme that will help EU industry to achieve world leadership. JTIs will combine a critical mass of national, EU and private resources within one coherent, flexible and efficient legal framework, <http://ec.europa.eu/information_society/research/priv_invest/jti/index_en.htm>, accessed 19 December 2007.

[59] The manager also mentions the national level, which is clearly important in Germany, where the national government has provided large resources and is very proactive. Importantly also, the German strategy is in line with the HFP strategy, and they are developed to create synergies between them.

The synthesis of perspectives of industry and policy makers involves the creation of a vision, a deployment strategy and a plan for implementation.

The progress of the HFP can be related to three important events: Vision (2003), Strategy (2005) and Implementation (2006). A final event was the adoption of the Joint Technology Initiative (JTI) on hydrogen and fuel cells by the EC in October 2007. First, the foundation of the HFP was based on the vision report 'Hydrogen Energy and Fuel Cells – A vision of our future' presented in June 2003 (EC, 2003). Second, the launch of the HFP took place in January 2004 and involved 36 main stakeholders. The HFP produced two key foundation documents, 'Strategic Research Agenda' and 'Deployment Strategy', which it endorsed in March 2005 at the Platform General Assembly. Third, the HFP group completed the implementation plan in December 2006, with the final endorsement from the HFP in January 2007. Finally, the EC adopted the proposal for a JTI in October 2007.

The background for the HFP is the potentially significant role of FC&H2 in Europe's future energy strategy. The actors involved in the HFP argue that these technologies are relevant to the future European energy system due to the benefits they hold for the EU strategy.

The goals identified by the EU are threefold: securing energy supply, reducing greenhouse gases and increasing EU competitiveness (EC, 2006b). The HFP actors lobby for the realisation of the HFP vision and deployment strategy by linking the HFP to the EU energy strategy. Thus, in terms of these three EC goals, the HFP group brings concrete suggestions for how FC&H2 technologies fit into the future energy strategy (Rovera, 2007).

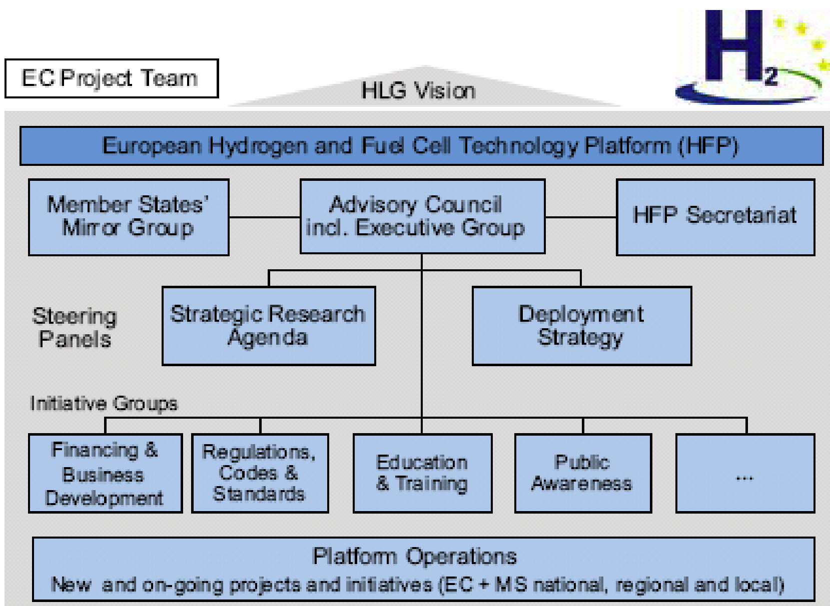
The first goal addresses 'security of EU energy supply', where the EU has set a target that 20% of energy use will come from renewable energies in 2020. Hydrogen's part in achieving this first goal concerns hydrogen produced from renewable sources, and its use has extended applications: hydrogen is a means to store excess energy, and fuel cells are energy-efficient end-use technologies. The second goal is the 'reduction of EU greenhouse gases' by 20% by 2020 (from 1990 levels).

FC&H2 technologies in energy applications, including transportation, have the potential of zero emissions. The third goal relates to EU competitiveness, namely that 'EU hydrogen and fuel cell technologies for Infrastructures, Vehicles and Power generation will enable, starting from 2020, a huge market potential with investments and job creation important for EU growth and competitiveness' (Rovera, 2007). Thus, the industry group claims that FC&H2 can strengthen European industry and simultaneously reach the goals of the energy strategy.

6.1.2. The structure of the HFP

The key aim of the HFP is to 'prepare and direct an effective strategy for developing and exploiting a hydrogen-oriented energy economy for the period up to 2050' (HFP, 2005). An advisory council guided the activity, while a deployment strategy steering panel was set up to identify the scale and scope of the programme. Figure 6.1 visualises the HFP structure from 2004 through March 2006.

Figure 6.1: **The structure of the HFP from 2004 to April 2006**

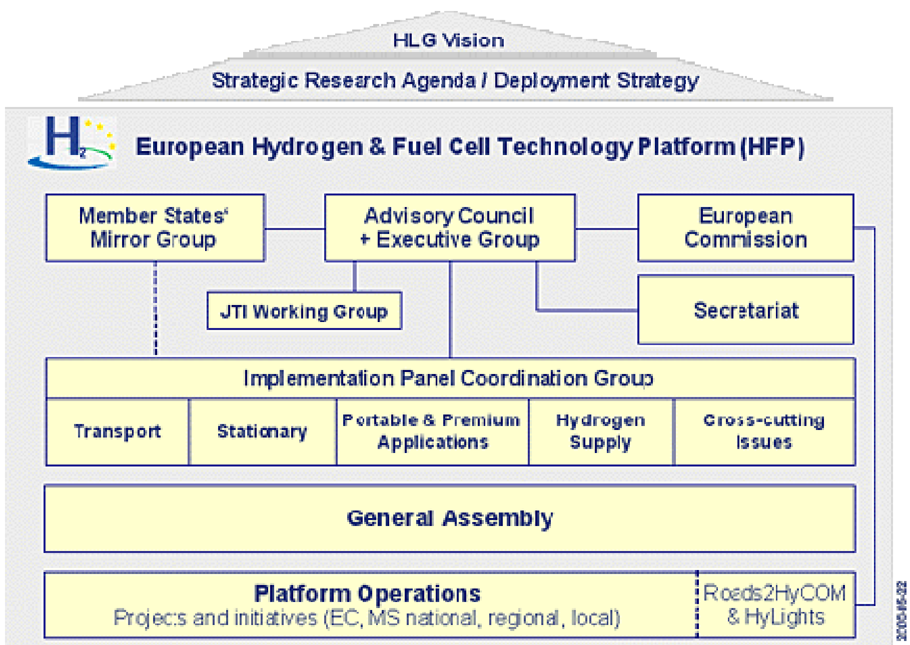


Source: HFP, 2006.

In addition, four initiative groups were established: Business Development and Finance; Regulations, Codes and Standards; Public Awareness; and Education and Training. These groups worked on their particular topics, organised the information and provided input to the implementation plan. Once their tasks were complete, the HFP dissolved these initiative groups as well as the steering panels for the strategic research agenda and the deployment strategy.

The HFP was restructured in 2006 with a focus on implementation of the strategy. The core activity took place in the implementation panel, which consisted of a coordination group as well as working groups on transport, stationary, portable and premium applications, hydrogen supply, and cross-cutting issues. Figure 6.2 shows the structure of the HFP with the various groups of the implementation panel.

Figure 6.2: **The structure of the HFP from April 2006 to present**



Source: HFP homepage.[60]

These were later dissolved when the implementation plan was completed in December 2006. Currently, only a few HFP bodies are active, that is, the Advisory Council, the Executive Group, the Member States Mirror Group and the Secretariat. The next phase is to realise the implementation plan with the Joint Technology Initiative.

[60] <https://www.hfpeurope.org/hfp/about_hfp>, accessed 22 April 2007.

6.1.3. Implementation plan

Key achievements to date from the HFP's work are the deployment strategy and the implementation plan, which develop the strategic vision as a snapshot of 2020 (HFP, 2005, , 2007). This means that these documents use a back-casting method, where a goal is defined for 2020 and then the resources and tools required to fulfil this goal are identified. This, then, constitutes a road map from 2007 to 2020.

The implementation panel consists of more than 100 stakeholders from industry, associations, government agencies, research, NGOs and the EC. The panel developed a programme in March 2007 for implementation of FC&H2 that comprises four Innovation and Development Actions (IDAs). The IDAs are a crucial part of the HFP because, as the group argues:

> 'they spell out the priorities for Europe and point to the technology which must be developed and acquired to foster hydrogen and fuel cell use in transport, stationary and portable applications by 2010-2015, and to achieve the 'Snapshot 2020' targets of the HFP. (HFP, 2007)

The total private-public resource requirements for the proposed programme amount to €7.4 billion for the 2007–2015 period, which is an 'achievable increase over current or already planned spending, both from public and from private sources' (Rovera, 2007). However, in the end, the actual support the EC decided to give the JTI for hydrogen and fuel cells was considerably lower. In fact, the proposed funding from the EU for the JTI is actually in the range of €450-500 million for 2007–2013. The industry grouping of the JTI will match this funding from the EC. The role of the European Parliament in the JTI decision process is that the parliament will have a voice in deciding the annual budget of the JTI.

Table 6.1 presents the funding for FC&H2 technology in the different framework programmes and for the JTI. There has been a rapid growth in resources for these technologies, doubling with each new programme. In the budget for FP7 (EC, 2007b), which totals €50 billion, Energy is slated to receive some 4% of the energy pot, for a total of €2.3 billion; of this, FC&H2 has only €94 million budgeted. In addition, however, the EC decided to adopt the JTI for hydrogen and fuel cell technologies on 10 October 2007 and to provide €470 million in support.[61] In all, then, the period 2007–2013 will involve a doubling from the previous period.

Table 6.1: **FP programmes for fuel cell and hydrogen R&D and demonstration**

FP	Size	Period
FP2	€8 M	1987–1990
FP3	€32 M	1991–1994
FP4	€58 M	1995–1998
FP5	€145 M	1999–2002
FP6	€300 M	2003–2006
FP7	€94M + JTI: €470	2007–2013

Source: (EC, 2006a).

The implementation plan for the JTI is organised into four main Innovation and Development Actions (IDAs) which target the period from 2007 until 2020 as the means to fulfil the snapshot developed by the Deployment Strategy Group. The IDAs suggest concrete demonstration projects to realise the vision of the HFP. The first IDA is hydrogen vehicles and refuelling stations, the second is sustainable hydrogen supply, the third is fuel cells for CHP and power generation, and the fourth is fuel cells for early markets.

In relation to the cases used in this thesis, IDA1 relates to the transport case, IDA2 relates to the applications for both stationary and transport, IDA3 to stationary, and IDA4 relates to both cases.

The target that the HFP group set for 2020 is to have 8-16 GW_e of energy produced by FC&H2 and from 400 000 to 1.8 million vehicles on the road. Also, 150 000 FC systems sold for micro CHP annually and 250 million micro fuel cell systems sold annually. To reach this target, the main objectives for the implementation plan are, before 2010, to create 13 demonstration sites for road vehicles including captive fleet, 200 vehicles, and 9 refuelling stations. Later this will be

[61] Press release: 'Commission promotes take-up of hydrogen cars and the development of hydrogen technologies'.
<http://europa.eu/rapid/pressReleasesAction.do?reference=IP/07/1468&format=HTML&aged=0&language=EN&guiLanguage=en>, accessed 17 October 2007.

expanded to include, in the period from 2010 to 2020, 30 demo sites with 3 000 vehicles and the cost of delivered hydrogen at the pump <€2.5/kg.[62]

The implementation panel of the HFP accepted the 'Snapshot 2020' from the deployment strategy as a reference market scenario for its implementation plan (HFP, 2007). The key assumptions of the implementation panel about the maturity of FC&H2 are presented in Table 6.2.

Table 6.2: **Key assumptions on FC&H2 applications for a 2020 scenario**

Year	**Stationary FC (CHP)**	**Road Transport**
EU H2/FC units sold per year projection 2020	100,000 to 200,000 per year (2-4 GWe)	0.4 million to 1.8 million
EU cumulative sales projections until 2020	400,000 to 800,000 (8-16 GWe)	1-5 million
EU Expected 2020 Market Status	Growth	Mass market roll-out
Average power FC system	<100 kW (Micro HP) >100 kW (industrial CHP)	80 kW
FC system cost target	2.000 €/kW (Micro) 1.000-1.500 €/kW (industrial CHP)	<100 €/kW (for 150.000 units per year)

Source: HFP, 2007.

The key assumptions are that the period from 2010 to 2020 is one in which the technology becomes validated as part of the IDAs and the large-scale demonstration projects of FP7. The transport applications, however, will take a long time to mature and will account for only a small percentage of the total vehicle fleet in 2020 (HFP, 2007). The target is to have EU-wide distribution of vehicles and infrastructure in 2020. The stationary applications of micro CHP and large-scale industrial power production are expected to have achieved substantial market penetration, with 400 000 to 800 000 installed systems as of 2020. In addition, the cost targets for transport are much stricter than those for stationary applications, meaning that the former is more reliant upon solving technological bottlenecks.

[62] Cost of hydrogen delivery at the pump (centralised and decentralised – excluding taxes).

6.1.4. Realising the 2020 vision

The next step towards realising the implementation plan and the 2020 vision is to develop concrete actions. In a communication to the EC and other involved stakeholders, the industrial grouping of the HFP identified six policy actions for realising the vision (Kohler, 2007). These policy actions enable *lead market pick-up*; thus they are key to enabling European actors to take the lead in developing FC&H2 technologies.

The first of these actions is the *Joint Technology Initiative* (JTI) proposal, which the HFP group argues should commence without further delay. The HFP group regards the JTI as the 'most effective instrument for concentrating industry effort & funding over the whole innovation chain' (Kohler, 2007). The JTI will be discussed in section 6.1.5.

The second action is to create *Lighthouse Demonstration Projects*, which, according to the industrial group, should include public procurement to enhance the progress of current demonstration projects towards commercialisation. The strategy of using Lighthouse Projects is a key part of the FP7. These are large-scale demonstration projects whose objective is to create a bridge from demonstration to early markets.[63]

The third action is *Public Procurement & Buyers' Pools*, which are instances of how early markets can be created as well as be applied to help build infrastructure and products. Public procurement is considered a major tool in 'providing market pull for early hydrogen and fuel cell products in demonstration projects and the early commercialisation phase' (Ibid., 2007). Another important factor for public procurement is the fact that public authorities are major consumers in Europe, spending some 16% of the EU's Gross Domestic Product (half of Germany's GDP).[64] Use of their purchasing power could facilitate the market introduction of hydrogen and fuel cell applications. One example the HFP group mentions is the memorandum of understanding (MoU) on Joint Public Procurement of Hydrogen Buses by European Cities and Regions. The

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[63] The various demonstration projects in Europe are discussed in chapter 7, Validation of technology.

[64] Answers from the HFP to the ETP questionnaire sent by the EC. <https://www.hfpeurope.org/uploads/1966/3100/HFP_ETP-questionnaire-240706_final_17NOV2006.pdf>, accessed 10 August 2007.

fourth action also relates to procurement, namely creating a *strategic procurement approach* targeting start-up firms in the pre-commercialisation phase. This action helps firms in a crucial phase to reduce market uncertainty and create an initial demand. This action should include FC&H2 in the current EC public procurement legislation.

The fifth action is to *remove regulatory barriers* by specifically harmonising 'Codes & Standards internationally'. For example, there is a need to develop EC regulation on hydrogen vehicles. This topic is discussed in section 6.2 on codes and standards.

Finally, the last policy action is to create *financing instruments*, such as specific approaches for SMEs. The HFP group argues that there is a need to rethink financing approaches for emerging technologies in Europe and argues that the financing instruments can be based on 'equity investments to address the specific needs of the independent private developers' (Kohler, 2007). This policy action helps to create stability in the TIS in terms of growth based on the formation of new firms, an imperative part of evolution for the TIS.

6.1.5. The Joint Technology Initiative

This section explains the most crucial part of realising the HFP strategy, namely the creation of the JTI, which enables the shift from strategy to implementation. A key achievement of the work of the HFP has been to establish a JTI in partnership with the EC. The idea is that in order to realise the ambitious goals of the HFP, the EC and industry need to coordinate their resources.

A conclusion on the basis of the perspectives of the HFP industrial grouping is that there is a need for the European programmes to be more industry oriented, with clear tools and actions for market development. The HFP actors identify the establishment of a JTI as the best way to achieve this and to enhance the potential for success in deploying these technologies in the future energy system. The EC, however, communicates that it can set up JTIs only in a very limited number of cases; importantly, though, 'the scope of an RTD (research and technological development) objective and the scale of the resources involved in a research effort could justify setting up long-term public-private partnerships in the form of Joint Technology Initiatives' (EC, 2007b). Realising a JTI, then, is highly competitive, and thus the JTI needs to be convincingly justified to the EC.

The HFP group argues that both the durable commitment and the strong political support necessary to realise the JTI do in fact exist for a public-private partnership on hydrogen and fuel cell technology. The HFP argues that as a partnership between the industry and the European Commission, the JTI will lead to coherent and industry-led research, technology development and demonstration activities. The JTI for FC&H2 will thus, according to the HFP actors, create clear targets, avoid duplication and fragmentation of investment, and leverage efforts in a more efficient way.

The purpose of the JTI will be 'to define and execute a target-oriented European programme of industrial research, technological development and demonstration on hydrogen and fuel cells in a coherently planned manner, to support the downstream, Europe-wide deployment of these technologies' (HFP, 2006).

Two particular issues are crucial for realising the JTI: first, the involvement of member states and, second, the involvement of SMEs. First, the HFP strategy points out that the different countries need to take an active part, and that 'without major contributions from Member States and Regions it will not be possible to achieve the common goals set by this Implementation Plan' (Ibid.). This might be a possible obstacle to realisation of the JTI, as the member states have not yet decided upon the budget. While some member states are very active, others are more reluctant to join. This also hampers the creation of the JTI, as the amounts various member states will contribute to the budget have not yet been determined. The financial involvement of member states, then, is an issue that needs more work. In the HyLights project, the different national perspectives are analysed and harmonised, and that will help in creating a more coherent frame for the participation of member states.[65]

[65] < www.hylights.org/>, accessed 12 December 2007.

Another important feature of the establishment of the JTI is the possibility to include SMEs. One important element in reducing technological uncertainty is to have many SMEs involved, working on particular bottlenecks with the technology. Thus, it is crucial to have SMEs participating in the JTI. Several actors with whom I discussed this mention that small firms lack the resources to participate in events like the HFP, and regard this as problematic. The goal of the HFP and the JTI is to include all stakeholders involved, not only large firms. One issue discussed extensively in the EU strategy developed by the HFP has therefore been the creation of incentives for SMEs to participate. The HFP group recognises the key role that SMEs play in the field, and states that the JTI can be a key tool for their involvement:

> The JTI is a suitable instrument to include both SMEs and large industrial companies in the process. This is a key issue as SMEs make valuable contributions to innovation in this area, but often have weak routes to market, whilst larger industrial companies benefit from the innovativeness of SMEs, and have the ability to take hydrogen and fuel cells into the mass markets at largest scale.[66]

Thus, the JTI can function as a bridge to create synergies between these two types of actors. Clearly, then, a paradox exists in the EU strategy for TPs: SMEs are to be involved, but they do not have the resources or receive the necessary support to participate. However, the JTI strategy will be a great step forward in realising the inclusion of SMEs. For example, on 28 March 2007, when the JTI industry grouping officially signed the foundation document, of those 45 companies that signed the agreement, 12 were small and micro companies. There is also the fact that when an OEM develops a highly modularised product like an automobile, it includes components from 15 to 20 suppliers, many of which are SMEs. Some component suppliers also mention that they receive information about the EU discussions through their relationships with larger firms with which they have supplier relationships. As such, many SMEs, though not participating directly in the HFP, are involved through their supplier networks.

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[66]<https://www.hfpeurope.org/uploads/1966/3100/HFP_ETP-questionnaire-240706_final_17NOV2006.pdf>, accessed 10 August 2007.

The JTI is thus the key tool for co-evolution within the TIS for FC&H2, with the focus on downstream technologies where the technologies have uncertainties in terms of market and institutions. By securing large resources and support for market introduction, the JTI will substantially reduce these uncertainties for the firms in the European TIS for FC&H2.

6.1.6. The political process of the JTI

On 28 March 2007, the JTI industry grouping officially signed the foundation document in which 45 companies joined forces to create a new international not-for-profit association as the first step in creating a European public-private partnership. This association, called the JTI Industry Grouping, is the key partner of the European Commission in creating the JTI for fuel cells and hydrogen.

The HFP Industry Grouping has on several occasions lobbied publicly with the EC for the establishment of the JTI. For instance, in a document from the EC discussing the potential for creating JTIs, four key criteria were outlined for assessing 'the readiness of JTIs', that is, how close they are to realisation. The criteria are *additionality*, *market failure*, *governance* and *the role of Member States*. The European Commission intends to submit those proposals for JTIs to the Council as soon as it is able to demonstrate that they meet these key criteria. The Roadmap for JTIs concludes that: "Based on the analysis to date, it appears that the JTI on Innovative Medicines and the JTI on Embedded Computing Systems are in a State of preparedness which could enable the Commission to adopt proposals for them in early spring 2007'" (EC, 2007e). While the proposed JTI for H2&FC does not yet fulfil these criteria according, the argumentation from the HFP Industry Grouping states that the JTI for FC&H2 does fulfil the EC criteria.

The HFP Industry Grouping has been successful in lobbying the EC for the JTI. It responded to the EC requirements as a 'single voice' on how the HFP's steps to create the JTI have been fulfilled, and on the fulfilment of the criteria as proof that the actors are highly committed to realising the potential of FC&H2. Furthermore, as the first of the energy-related European Technology Platforms, the HFP has moved closer to realising its targets. The EC report on energy research in the

FP7 discusses the role of JTIs and concludes that 'at present the most likely energy area where a JTI will be set up is fuel cells and hydrogen. If the concept proves successful, it may be extended into other areas' (EC, 2007b, p. 23). Thus, the HFP is the most advanced of the energy TPs.

In October 2007, the Commission adopted the specific proposal for a Joint Technology Initiative on fuel cells and hydrogen, based on Article 171 of the Treaty (EC, 2007c). Thus, the HFP, as the first energy-related TP, has achieved an important step towards realising a JTI. This is an indication that the JTI question is a serious matter for the actors involved, and thus the industry has established legitimation for the vision and a strategy to reach it.

To conclude this section, the key means to realising the vision of the HFP and thus enabling stability in the TIS, is to develop public-private partnerships (JTI) and to remove the uncertainties of institutions like codes and standards as well as other regulatory barriers for transport and stationary applications. The adoption of the JTI by the EC is undoubtedly a key source for creating stability for the TIS and enabling the growth of the system. Furthermore, the actions that the HFP suggests target the reduction of market uncertainty by developing tools for market introduction, that is, by creating partnerships in the form of large-scale demonstration projects (Lighthouse Projects) and public procurement. In addition, in terms of creating stability for actors in the industry, new financing instruments for SMEs are required for the purpose of expanding the TIS in terms of a supplier base for FC&H2. One conclusion is that the HFP strategy aligns the perspectives of the actors in the TIS behind a vision that is supported by concrete actions, thus enabling co-evolution of markets and institutions with FC&H2 technologies.

6.2. Political networks

Political networks or technology-specific advocacy coalitions are identified as important actors that can affect the evolution of institutions in the formative phase (Jacobsson & Lauber, 2006). Political networks are important for creating *legitimation*, and they relate to the process of convincing policy makers as well as *prime movers* from user industries that the technology is serious and has real opportunities to accomplish its potential. A related feature of political networks is that they are key actors in creating visions and lobbying on behalf of the new technology.

These forms of networks can be highly formalised, such as industry associations, or they can be informal networks between actors in a specific area, or large actors lobbying on their own. The importance these network forms play in an emerging TIS is not easy to assess, but it can be done by considering the view of the stakeholders, the creation of strategic visions, and whether the network has managed to obtain any financial support. Interest from politicians has also increased, but this relates to a general trend about concerns related to the environment, the energy supply and security. Thus, these are events, and not intentional actions from a firm or group.

In the next paragraphs, I will analyse some of the different political networks that exist for FC&H2 in Europe. I will discuss both formal and informal political networks, their specific role and achievement, and will indicate their potential impact on the evolution of the TIS.

6.2.1. Informal political networks

It is apparent that informal political networks spontaneously organised between firms are important. This understanding emerged during interviews with some of the key players in the field. Firms in the transportation applications initiated a political network that links vehicle production with hydrogen distribution. Thus, these networks consist of the prime movers in the transportation market, that is, the large multinational companies with substantial available resources that organise the value chain for vehicle production and hydrogen distribution. Policy makers, meanwhile, participate in the discussions through formal networks at the national level as well as the level of the EU.

The close links between OEMs and oil companies are an important factor that favoured the development of a national strategy in Germany. In the Clean Energy Partnership (CEP) project in Berlin, the major German automakers well as the major oil and energy companies in Europe are operating a demonstration project for vehicles.[67] What started as informal discussions among this group of firms led to the creation of a formal network, namely the Transport and Energy Strategy (TES) in Germany, which is supported by the German authorities as well. The actors developed a 'common understanding' on the challenge of fuel and vehicle production, such as how to make the steps from demonstration to larger demonstrations (Lighthouse Projects), and finally to market introduction.

The TES analysed five fuels in phase 1 of the project – natural gas including biogas, dimethyl ether, methanol, synthetic gasoline/diesel and hydrogen (Heuer, 2000) – and decided to focus on hydrogen as part of the German National Strategy. The TES group is, furthermore, the key actor behind the development of the ambitious German National Hydrogen and Fuel Cell Technology Innovation Programme (NIP), which has considerable public support in Germany. The budget for 2007 to 2013, in fact, is €500 million in public funding for fuel cell and hydrogen technologies, and the public funding is equally matched by private funding from industry (NIP, 2007). Thus, the German NIP budget is comparable to the total EU budget for the JTI in the same period.

This example shows how a group of influential actors sharing a similar vision, and capable of communicating its intentions to policy makers, can generate commitment from public and private actors and set up strategies with clear targets and large devoted resources. Clearly, the network's previous results and vision of the future create the necessary *legitimation* for policy makers to commit the huge amounts of resources that are indispensable for realising the potential of these applications.

[67] The Clean Energy Partnership is also discussed as a demonstration project in detail in chapter 7, Validation of technology.

6.2.2. Formal political networks

In the case of hydrogen, the key formal political network at the European level is the European Hydrogen Association (EHA), and for fuel cells, the key network is Fuel Cells Europe (FCEu). In addition, there are some national and some industry associations involved. This section presents the most important networks at the European level. A specific focus is devoted to the German Initiative for Fuel Cells (IBZ), which has been successful in creating legitimation and financial support at a high level.

The European Hydrogen Association

The European Hydrogen Association (EHA) is located in Brussels with the purpose of creating 'a strong presence of hydrogen in Brussels by informing policy makers of the contribution of hydrogen as an energy carrier to the creation of a secure, sustainable and innovative European energy and transport system'.[68] The EHA also has national members in Germany, France, Italy, Spain, Sweden, Norway and the Netherlands, as well as six companies working with hydrogen production or distribution.

A key role of EHA is to advocate for the position of hydrogen in the energy strategy of Europe. In this respect, EHA has had an impact on creating stability for hydrogen technology by discussing the role of hydrogen directly with the responsible EC policy makers. EHA advocates seeing hydrogen in a symbiotic, not competitive, relationship with renewables like wind and solar power. One example of this network's impact is a request for recommendations, made on 19 April 2007, by the European Commission at the Strategic Energy Technology Workshop organised by the EHA. In response, on 19 May the EHA submitted a two-page contribution to the European Commission on a possible concrete initiative to be included in the Strategic Energy Technology Plan.

EHA also works directly with the various European regions and includes them in discussions on the role of hydrogen in the future energy system of Europe. An example is a teleconference organised by

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[68] <http://www.h2euro.org/publications/press/docs2006/eha2006_001.html>, accessed 11 May 2007.

EHA in June 2007 with the different regions engaged in hydrogen activities. This conference also included the Directorate-General for Research (DG RTD) and the HFP. The objective was 'to define themes of common interest that could be jointly tackled at the regional level and the role of the EHA in facilitating meetings, exchange of best practice and general visibility of regional hydrogen activities'.[69] In this case, EHA played an important role in facilitating the flow of valuable information from the EC out to decision makers at the regional level, advocating local cluster building of hydrogen into the energy system.

Another important role of the EHA has been to provide information to the EC in the process of introducing hydrogen vehicles in the type-approval framework. The EC decided in October 2007 to create legislation for approving hydrogen vehicles (EC, 2007d).[70] The Commission would like to receive input from industry regarding the vehicle approval, and the European Hydrogen Association, in cooperation with Fuel Cell Europe, will facilitate this input. The topics are technical and relate to requirements of various hydrogen vehicles, such as the prioritisation of the subcategories for which regulation is needed, and which requirements would be similar for all vehicles and which would be different for the various types of vehicles.[71]

Another important role political networks play in the formative phase is to advocate for the technology vis-à-vis different technological alternatives. The proponents of other technologies might consider the two alternatives as competitors for the same scarce resources and thus view them as being in a competitive relationship. The EHA has experienced negative feedback from advocates of related energy technologies, such as renewables, when it has proposed sitting down and having a constructive dialogue on how they can jointly support the evolution of the various technologies by looking for synergies and positive outcomes. Advocates for the competing energy technologies

[69]<http://www.h2euro.org/publications/newsletter/newsletter.htm>, accessed 11 May 2007.
[70]<http://europa.eu/rapid/pressReleasesAction.do?reference=MEMO/07/405&format=HTML&aged=0&language=EN&guiLanguage=de>, accessed 15 December 2007.
[71] <http://www.h2euro.org/Index/Publications/newsletter/newsletter.htm#Roads>, accessed 30 November 2007.

are negative towards hydrogen, as they fear that more technologies will have to share the same amount of resources.

As it is for all emerging technologies that require political support, the means are scarce, and thus positioning occurs between them. This might lead to hostility instead of trying to focus on advancing the synergies between them.[72] An example of the impact on hydrogen, for instance, is the position taken by the European Forum for Renewable Energy Sources, a lobby group for the renewable energy actors. This group mentions the 'strong lobby for hydrogen' as a negative factor for the FP7 budget for Energy.[73] The EC allocates two-thirds of the energy budget to renewable energy and energy efficiency. According to the European Forum for Renewable Energy Sources, the use of hydrogen for transport applications should be covered as an alternative fuel proposed under the Transport heading, not under Energy, where it competes for the energy programme. However, the EHA later explained that it had managed to create a common platform with interest groups from the renewable sector and thus to focus on synergies, not on competition.

The impact of EHA in reducing the uncertainties for hydrogen is substantial. Several factors point to this. EHA has managed to provide an aligned industry perspective towards the EC. By interacting directly with the EC on the role of hydrogen in the EU energy strategy, EHA has managed to lobby for hydrogen with policy makers and provides direct input to the EC on the industry's view. This certainly reduces the industry's uncertainty on the position of the EC, and thus aligns the EC and the industry's perspective. EHA has also managed to establish positive relations with actors involved in complementary technologies.

Fuel Cell Europe

Fuel Cell Europe (FCEu) is an organisation formed in response to the concerns that Europe would not be ready for the commercial introduction of fuel cells in the same period as other regions of the world, in particular North America and Japan. The fear of European

[72] A situation of zero-sum game instead of a positive sum game.
[73] <http://www.inforse.org/europe/pdfs/S_BXL06_R&D-FP7_EUFORES_H.pdf>, accessed 15 September 2007.

industry was that without a competitive fuel cell industry, Europe would be at a serious competitive disadvantage economically as well as environmentally.

FCEu works as a lobby group in the EU, and a key task is to monitor the political climate in Brussels and elsewhere. In relation to this, a key role has been to provide input to the EC on the role of fuel cells in the EC's Strategic Energy Technologies (SET) programme. In addition, FCEu launched a lobbying campaign in 2007 and submitted a joint statement on the organisation's position on FP7.

More specifically, Fuel Cell Europe's current activities cover a wide field and include:[74]

- creating the power of a collective industry voice to represent industry interests to Parliaments, Governments and the European Commission;
- advocating for public funding, identifying regulatory barriers to fuel cell deployment and bringing pressure to bear for their effective resolution;
- facilitating for exchange of information on fuel cell research, development and operating experience;
- creating opportunities for members to participate in and represent industry interests at a high level;
- encouraging cooperation between national and regional fuel cell associations in Europe and other organisations with similar objectives.

One of the key achievements during 2006 was the release of a joint position paper on FP7 to the 54 Members of the European Parliament and a project proposal for EC funding in the Intelligent Energy Europe programme titled 'European Fuel Cell Application Road-show' (FCEu, 2006). In addition, FCEu met and held discussions with several key EC decision makers, such as the head of the unit on Energy conversion and distribution systems in the Energy Directorate and the Director-General for Energy and Transport (DG TREN).

[74] <http://www.fuelcelleurope.org/article_flat.fcm?subsite=479&articleid=571>, accessed 20 November 2007.

FCEu takes an active role in contacting the key decision makers and undertook a joint effort with EHA to target EC decision makers. In this activity, the two organisations brought some of their members to the new European Parliament building in Luxembourg, where they presented their applications for stationary power production.

FCEu also targets the regional level and has discussed directly with actors from the Pas-de-Calais region in France the issues for a regional strategy on hydrogen and fuel cells. In addition, the political network organised a conference with its industry members and regional actors to explore the opportunities for leveraging on fuel cells in a regional setting. The goal was to create strategies to 'accelerate the wide-scale deployment of fuel cells in Europe and reduce costs to the point of competitive viability'.[75]

The strategic priorities for FCEu during 2007 were to work for European advocacy, and the backbone of these strategic priorities consisted of five key activities:

- develop joint positions and present the interests and views of Fuel Cell Europe members on key European dossiers affecting fuel cells;
- participate in HFP panels to represent Fuel Cell Europe's small members;
- dinner debate with European Energy Foundation to discuss the role of fuel cells as clean energy technology options;
- visit of several advanced fuel cell production facilities with Members of the European Parliament;
- train start-up companies and established players at the European Investment Bank. (FCEu, 2006)

FCEu organises the key actors in the fuel cell industry and is active in demonstrating to policy makers, as well as to the user industries, that the technology plays a key role in the future energy system of Europe. The involvement of FCEu thus provides the industry in Europe with a collective voice at a high level, and creates stability for the European fuel cell industry through aligning the perspective of the actors and

[75] <http://www.fuelcelleurope.org/index.php?eventId=10>, accessed 20 November 2007.

communicating the actors' intention to EC decision makers. Thus, FCEu helps to create stability for the industry actors in the formative phase. It undoubtedly plays a key role in lobbying for fuel cells in the future energy technology programmes of the EC and in the establishments of early markets.

The German Initiative for Fuel Cells

The German Initiative for Fuel Cells or Initiative Brennstoffzelle (IBZ) is an industry organisation that gathers all the actors for micro fuel cell systems in Germany. The role of IBZ is to support the introduction of fuel cells into the market, and a key strategy of the organisation is a slow introduction based on 'careful preparation, and at the right time, using the right technology'.[76] Due to the many uncertainties of fuel cells, IBZ does not want to send immature technologies into the market, something that could damage the public image of the technologies. Rather, the actors have chosen to demonstrate the technology sufficiently, so that the technological uncertainty is reduced, before moving gradually into the market. One manager in a system integrator firm explains the reasons for this strategy:

> 'FC was very popular and one of the technologies that could solve the problems and there were very enthusiastic discussions in the public. And it was one aim that we agreed, all the manufacturers as well as energy distribution companies, that we need to more or less make a clear statement towards the public, regarding the market launch, the necessary R&D efforts in front of us, the success so far. And so on.'

An additional benefit of IBZ is that the energy industry is a partner in the network, so that there is direct cooperation between the producers of the systems and the user side.

In order to be able to reduce the uncertainties of fuel cells, the IBZ is active at all levels of development: devices and components, pilot projects and field tests, the construction of contracting models, and the creation of uniform norms and standards as well.

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[76] http://www.initiative-brennstoffzelle.de/en/live/start/18.html>, accessed 20 November 2007.

To achieve its goals, IBZ operates with two working groups. One works on public relations to inform all relevant actors about the current state and future perspectives of fuel cell technology. The other is a technical working group that organises joint projects, such as desulphurisation in fuel cells. The removal of sulphur from gas is a key technical challenge for the firms and an important factor for the fuel cells in micro CHP.

On a more general level, stakeholders mention the lobbying role of IBZ. One manager in a system integrator that focuses on micro CHP explained:

> 'What is also important is lobbying towards policy, for instance, for micro CHP, to get the right framework conditions and not the wrong one. So it is not really decided on the framework conditions for micro CHP, especially not if you are looking at Germany. We need a key decision from industry, that a key character of micro CHP is decentralised production of electricity – is really a target the nation wants to support or not. Because this is the field of the energy distribution companies and the biggest one in Europe is here in Germany.'

It is evident that the CHP market has many uncertainties and that the technology has not yet achieved legitimation in the eyes of policy makers. The manufacturers have organised themselves into a network, but the support from the energy/utility side is somewhat ambiguous, and in order to move the technology into to the market a clear strategy and decision from industry is required. One important role that IBZ plays in this regard is its involvement in the German national strategy for hydrogen and fuel cells, where IBZ leads the coordination group for stationary applications for domestic energy supply. The IBZ thus helps organise the actors' activities at all levels, and in doing so clearly plays an important part in creating stability for micro CHP solutions in the evolution of the TIS in relation to technology, market and institutions.

6.2.3. Political networks for transport applications

In the case of the transport applications, political networks have been very important for creating stability in the formative phase. The lobbying by powerful actors like the large automotive OEMs and oil companies created a sense of stability and trust on the part of policy makers, thus *legitimising* the strategy of the industry. This is most evident in Germany, where projects like the Clean Energy Partnership (CEP) and the national German Transport and Energy Strategy (TES) benefit from strong support from highly organised actors. In terms of resources, these actors have large budgets and can be a substantial factor for any emerging TIS moving to the next phase.

At this level, *size* is important, and due to the scale effects of infrastructure and vehicle development, SMEs have little impact on development. The creation of large national or European demonstration programmes needs the support of political networks to create the legitimation necessary for their realisation. Undoubtedly, this also affects the whole value chain positively, as OEMs hardly develop their vehicles or infrastructure in isolation as vertically integrated firms, but involve a large group of suppliers, thus including SMEs.

The role of the EU lobby groups helps to create stability in the sense that the hydrogen and fuel cell industry can lobby EC decision makers directly. However, the role of hydrogen in the EU energy strategy is still uncertain. There seems to be a perception of hydrogen as a remote alternative and not a near-term solution; thus the technology is not a real target of EU strategy at this point.

6.2.4. Political networks for stationary applications

This application area obviously relies on the work of political networks. The German IBZ plays a key role in enabling the German fuel cell manufacturers to speak with a single voice and cooperate on critical issues, including cooperation with the user side.

While the German Transport and Energy Strategy (TES) does include consideration of stationary applications, political networks seem to be stronger for transport than for stationary applications. The various political networks for transport create visions for market deployment and set up large demonstrations in conjunction with policy makers, but in the stationary markets, the political networks seem more weakly organised, particularly at the EU level, and there is a lack of commitment from the energy and utility actors. In the TES, there is no apparent commitment to the stationary markets at this point resembling its present commitment to the transport actors. There are uncertainties in this application area with regard to the large companies, that is, the energy and utility companies, and their interest in FC&H2. The most active and organised companies in the stationary sector are the fuel cell manufacturers and integrators, but they are not the actors representing the user side, and there are specific obstacles for market introduction, as access to the grid is highly regulated. Legitimation needs to be strengthened in order for the TIS to evolve in this application area.

To conclude this section, it is evident that political networks have reduced uncertainty for the actors and have created stability in the TIS by aligning the perspectives of actors in addressing policy makers, creating legitimation of the technology and, finally, receiving support at high levels. Clearly, these networks are decisive for the TIS to evolve to a growth phase.

6.3. Codes and standards networks

A code carries the force of law: a governmental organisation adopts a standard and turns it into a regulation. Standards, however, are voluntary agreements, and therefore in order to be effective they need support from legislative action. Codes and standards are important features of a TIS in the formative phase. Standards ensure that the quality and the aspects of a technology or a product are the same across markets. A standard thus refers to certain technical aspects of a technology that make sub-systems fit together, or to the fact that the product fulfils a specific performance with reference to the quality of the product.

The key actor in the creation of standards is the International Organization for Standardization (ISO), which coordinates the standardisation process in specific technological fields. An ISO standard can become a national standard as well, and thus reduce the need for the regulator to hold national consultations. As such, the ISO standard can be the basis for national technical regulations without causing unnecessary technical barriers to trade.[77]

The creation of common standards is an instrument that might be highly efficient for the innovation rate in any industry, as it ensures interoperability between various technologies that firms develop, but most important is the fact that the existence of common standards reduces the possibility that the companies involved will find later alternatives replacing their early technology investments. As such, standards provide companies that are willing to invest early in the technologies with a sense of stability, in that they ensure that the choice of technology will exist for a period, thus providing market stability.

Because a new technology poses new challenges for validation, it often needs specially tailored codes and standards, and this might slow down market diffusion. For hydrogen, codes and standards are clearly important since hydrogen has specific technical and physical features that make it a special case compared to other fuels used in the transport sector and as an energy carrier in the consumer markets. For instance, hydrogen has wide ignition limits, no visible flame, low calorific value and high flame velocity (HFP, 2005, p. 64). These factors certainly make it critically important to investigate and sort out safety issues for hydrogen in the transport sector. Another set of factors related to hydrogen is that it constitutes tightness problems with existing gas pipe materials and has a corrosive effects on metals, which can lead to leakages of hydrogen from the distribution pipelines (HFP, 2005, p. 64). These factors clearly need to be dealt with before the distribution infrastructure is built. Finally, hydrogen is classified as a chemical and not as a transport fuel and this makes practical demonstrations in real-life settings difficult. This section analyses what types of standards the industry is developing for hydrogen and fuel cells, the types of networks at work on establishing codes and standards, how they are defined, and finally, how important they are.

There are currently three options researched for hydrogen storage: compressed hydrogen, liquefied hydrogen and solid-state hydrogen. The

[77] <http://www.iso.org/iso/standards_development/governance_of_technical_work/standards_and_regulations.htm>, accessed 21 November 2007.

probability of co-existence between these three fuel alternatives is high, and it is not likely that only one alternative will prevail. Consider, for instance, the situation today, with 95- and 98-octane gasoline existing side by side with diesel and, more recently, bio-fuels. The situation with hydrogen as a transport fuel is currently that 92% of existing hydrogen stations deliver compressed hydrogen and 8% deliver liquid, but the liquid stations also deliver compressed hydrogen (Baker, 2005). In 1998-2005, the figure for compressed hydrogen was 70%, indicating that compressed hydrogen has been increasingly developed.

Demonstration projects do not use solid-state hydrogen, but several actors are researching the possibilities of using solid-state storage in the transport sector. This suggests that compressed hydrogen can be important and dominant in the future, but improvements in technology might favour other solutions in the long run. The standardisation moves towards 700 bar compressed hydrogen at 10.000 psi. This standard satisfies the driving range requirements for most applications (>400km), and will be valid for the next generation of vehicles (4 to 5 years).

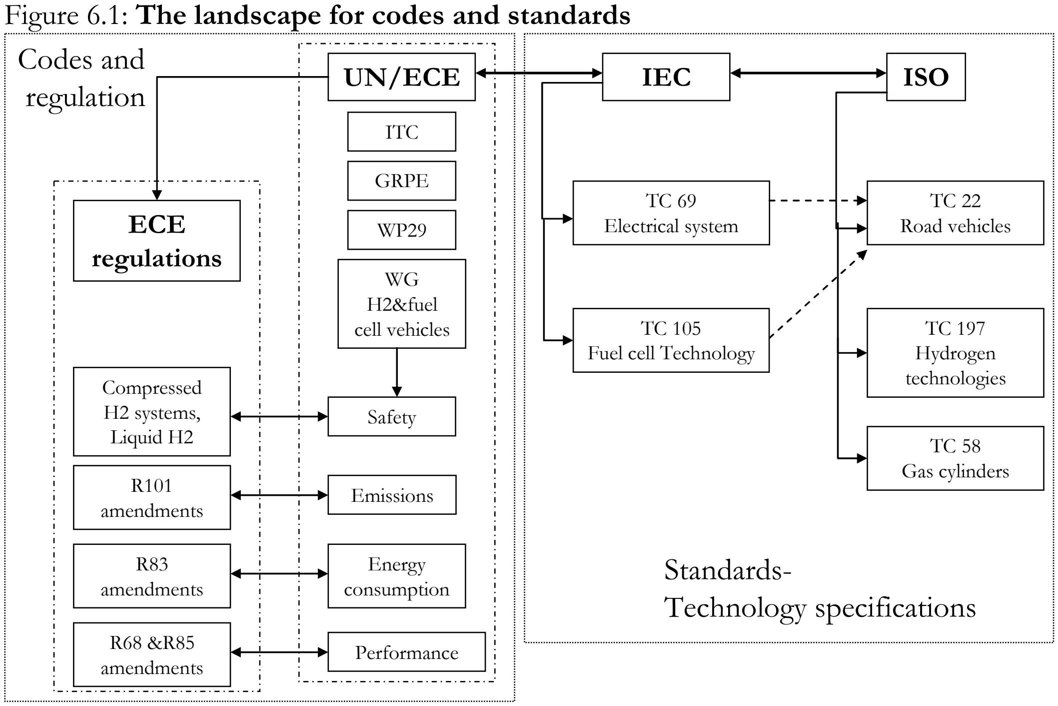
6.3.1. The international landscape for codes and standards

This section analyses the international development of C&S for FC&H2, and the role of the particular organisations involved. The landscape of codes and standards is vast, with many organisations drafting different aspects of these technologies. At both the national and international level, network organisations are conducting work on standards. Working groups at the ISO and the International Electrotechnical Commission (IEC) are active in developing international standards for hydrogen and fuel cells, for stationary applications and for vehicles. Another key organisation involved is the United Nations (UN), which is responsible for the implementation of standards in the different countries.

Figure 6.1 visualises the three key international organisations, ISO, IEC and the UN, and their relation to EU regulation. There is a division of labour between these three organisations in the formation process for C&S. This division is organised so that the ISO has different working groups developing standards for the different aspects of the vehicle, while the IEC has working groups on aspects that relate to fuel cells and electrical systems.

Finally, the UN acts as an international regulatory body, dealing with the regulative issues and harmonising them for the various member countries. The UN thus has projects on vehicle regulations, transport of dangerous goods, and a working group on gas in the sustainable energy division. However, the UN does not have the mandate to turn standards into codes; this is the responsibility of national governments and the European Union. The ISO standards are important, as strategy groups encourage national governments to use these in the national development of standards as well as in creating codes by law. The UN Economic Commission for Europe (ECE) is responsible for coordination between the UN and the EU.

Figure 6.1: **The landscape for codes and standards**



Source: Based on figure from the HFP Deployment Strategy (2005).

The scope of the ISO Technical Committee (TC) 197 on hydrogen technologies is to cover 'standardization in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen' (Dey, 2006). The TC 197 working group consists of 20 participating countries and is responsible for several standards (Dey, 2006). The TC 197 standards already cover the aspects of hydrogen technologies that relate to interoperability between the vehicle and the fuel system, aspects of the fuel, safety of handling and the use of hydrogen at airports.

The key working group for IEC in relation to FC&H2 technologies is TC 105 for fuel cell technologies. The scope of TC 105 is to prepare for international standards regarding fuel cell technologies for all fuel cell applications. This IEC working group has 15 participating countries and has published several standards, but the standardisation process for fuel cells requires more work, as the existing standards cover only a few aspects relating to actual use of the technologies.

In addition to these technical working groups, ISO also has working groups that discuss issues with regulation of codes and standards, such as the 'ISO Round Table on Global Harmonization of RCS for Gaseous Fuels and Vehicles'. The scope of the 'Round Table' is to 'cover the topic of global harmonization of regulations, codes and standards for gaseous fuels, infrastructure as well as road and offroad vehicles that use these fuels' (Dey, 2006). Participants in the round-table discussions are high-level policy makers from governments as well as global automotive, energy, infrastructure and other related companies. In addition, NGOs, the United Nations, and ISO/IEC are also participants. The Round Table's purpose is to get policy makers from governments and industry to:

1. understand the challenges facing harmonization of codes and standards;
2. support the harmonization effort more efficiently in the future so that globally harmonized regulations, codes and standards are ready at the same time as the market;
3. support the UNECE in the preparation of the Global Technical Regulation (Dey, 2006).

The role of the UN is to 'take the standards to the next level by writing regulations for how things should be implemented' (Harris, 2006). There is, then, a clear division of labour, where the ISO and IEC develop the technical requirements while the UN develops the regulations for implementation. The goal is that the UN will have created global technical regulations for hydrogen-powered vehicles by 2010.[78]

The role of these international organisations is imperative in reducing institutional uncertainty for FC&H2. Codes and standards are institutions that highly affect both the production of technology and interoperability, as well as the possibility of using the vehicles in practice. International harmonisation of C&S is crucial for reducing uncertainty since this facilitates the possibility of serial production under economically viable conditions. Different national standards would mean that production of vehicles would change according to the standards of each country, thus making vehicle production more complex. Natural gas vehicles are an example of the devastating effect of a lack of international standards. The situation was that different countries developed their own standards, these national standards became 'tools for development and it got too late for developing international standards' (Harris, 2006). The result was that if, for instance, you decided to cross the border from Germany to France with a natural gas-fuelled car, you either had to drive back to Germany to refuel or you had to carry spare connectors in the car (Harris, 2006). Thus, the importance of developing global standards concerns the need not only to enable serial production of vehicles and thus reduce the uncertainty facing OEMs, but also to enable the vehicles to be used in a number of countries.

6.3.2. Making codes – EU standard development

According to the 'New Approach' philosophy on Regulation, Codes and Standards (RCS), an ideal RCS landscape would include coordination between the ISO, IEC, the UN and the national governments (Van den Bossche, Van Mulders, Van Mierlo, Cheng, & Timmermans, 2007). The 'ideal situation' is one in which international standards exist on all appropriate technical matters, the regulations are globally accepted and refer to the standards, there is no overstandardisation or overregulation, and finally, no parallel or conflicting RCS work.

[78] A key activity is the 'Work Forum for Harmonization of Vehicle Regulations' (WP 29) work on Global Technical Regulations (GTR) for hydrogen and fuel cell vehicles (HFCV) and a GTR Roadmap under development.

In Europe the RCS development is in line with this reasoning, and in order to harmonise the RCS development several EU projects on codes and standards have been set up to monitor and identify the required activities. One such project is the 'HarmonHy project',[79] which was finalised in June 2006. This project has analysed the state of the art in RCS and identified in detail the needs for action in these activities. The project reduces the uncertainty of institutional creation for the actors in Europe by providing the decision makers in the EU with deep knowledge on the issues of RCS globally and how these can be implemented in Europe, at the EU level as well as in various countries. For example, the HFP strategy group used major recommendations from this project in drafting the implementation plan for the JTI. In particular, in the deployment strategy the HFP calls attention to the lack of a European hydrogen vehicle type approval, considered a substantial uncertainty for vehicle demonstration and deployment. It is only in a few countries that prototype hydrogen vehicles can be certified under a complex single vehicle type approval (HFP, 2005, p. 64). In other countries, hydrogen as a fuel is still banned. Thus, EU approval must be created so as to avoid problems with the large-scale demonstrations planned for FP7 and the JTI.

One result of the recognised role of harmonised RCS for FC&H2 is the need to move the approval procedure for hydrogen forward in Europe. This topic therefore has a prominent place in the JTI, thereby removing a key institutional uncertainty. The issues that concern RCS belong to the 'Strategic Support Services' within the JTI programme office, whose task is 'to strategically manage, coordinate and accelerate the RCS development process involving many diverse RCS bodies on national, European and international levels'.[80] Clearly, in securing harmony between regulations in different countries, the activities on RCS harmonisation play an important role for reducing uncertainty in the formative phase of the TIS.

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[79] <www.harmonhy.com>, accessed 24 August 2007.

[80]<https://www.hfpeurope.org/uploads/1966/3100/HFP_ETP-questionnaire-240706_final_17NOV2006.pdf>, accessed 2 February May 2007.

6.3.3. Codes and standards for the different applications

The results of the analysis show that codes and standards are important as a stabilisation mechanism only for some transport and stationary applications. Other applications do not rely on standards because the actors use technology already regulated by existing codes and standards.[81] In addition, firms use existing codes and standards for power production with fuel cells based on by-product hydrogen.

Codes and standards for transport applications

For the transport applications, codes and standards are crucial for the technology to be realised for consumer and fleet vehicles. It is required by law, in fact, that vehicles have approval for use on public roads. A key aspect for EU approval is the close alignment between the ISO/IEC work and the EU projects, which led to the creation of regulation of vehicles in Europe. The link between the EU approval procedure and the ISO takes place in the United Nations Economic Commission for Europe (ECE).

A feature of the standardisation process is the co-evolution of technology and regulation that occurs in the demonstration projects. The demonstration projects test and validate various technologies and in conjunction with the demonstration projects, the drafting of codes and standards occurs. Importantly, the EU demonstration projects carried out under Framework Programmes 5 and 6 clearly contributed to the development of codes and standards. Examples like the CUTE, CEP and Zero Regio projects have contributed technical data on real operation of the technology, thus providing the standardisation projects with key knowledge. In Germany standards are developed as part of the Transport and Energy Strategy (NIP, 2007), in Scandinavia the Scandinavian Hydrogen Highway Partnership is concerned with codes and standards, and in Italy standards for using hydrogen vehicles were obtained through the Zero Regio project. Thus, participation in EU projects is a key factor for establishing standards also at the national level.

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[81] This is what I call an institutional hybridisation and is discussed in chapter 8, Market formation.

For instance, the HFP states in a communication to the EC that regulation of the type-approval of hydrogen vehicles will enable the operation of hydrogen vehicles on public roads in all 25 EU member states.[82] The regulation builds on joint stakeholder activities carried out since 1999.

The next step is thus to make standards 'legal', that is, turn them into codes by law. A further action towards establishing harmonised RCS took place on 17 October 2007, when the EC proposed a vehicle approval for hydrogen vehicles. In this memo the EC states that the lack of a legislative framework clearly poses several uncertainties for the OEMS that target HFCV when they try to place the vehicles on the market. The EC recognises that the lack of harmonised RCS 'results in a fragmented internal market of hydrogen powered vehicles, as well as complicated and costly approval procedures, which discourages the introduction of this environmentally friendly technology'.[83] The EC states that the proposal it introduces will help these vehicles by reducing institutional uncertainty, since hydrogen vehicles 'will be treated the same way as conventional vehicles and a single approval will be sufficient for the entire European Union' (EC, 2007a).

However, the EC also states in the memo that some perceived safety issues exist around using hydrogen for vehicle propulsion, due to its differences from characteristics of conventional fuels. The EC will therefore ensure that the hydrogen vehicles put on the market in the EU are at least as safe as conventional vehicles. The European Parliament and the Council of Ministers are now considering this proposal.

Clearly, for the use of hydrogen in the transport sector, harmonised and global RCSs play a decisive role. The uncertainty in this application has now been considerably reduced due to the approval for hydrogen vehicles adopted by the EC.

[82]<https://www.hfpeurope.org/uploads/1966/3100/HFP_ETP-questionnaire-240706_final_17NOV2006.pdf>, accessed 2 February 2007.
[83]<http://europa.eu/rapid/pressReleasesAction.do?reference=MEMO/07/405&format=HTML&aged=0&language=EN&guiLanguage=de>, accessed 20 November 2007.

Codes and standards for stationary applications

In the case of stationary applications, codes and standards are important in order to have products on the market. For micro CHP, some standards exist for using natural gas, and for large industrial applications, standards exist for hydrogen use. Thus, for these two applications, the companies can use the already-existing standards.

In terms of regulative obstructions to commercialisation, because the pathway chosen for micro CHP and large-scale power production uses natural gas as fuel, the firms can handle and certify micro CHP units under the regime of the European Gas Appliance Directive (EU 90/396/EWG), which is a CE certified standard created for domestic heat appliances. The companies working with micro CHP identified the creation of this directive as a solution to a major uncertainty for mass-market introduction (Klinder, 2004). Another aspect of this application is that system owners can supply excess power to the grid, and when the owner needs additional power, the grid can supply this back to the house. There are uncertainties, however, due to the absence of regulation that would facilitate installation of micro generators into the grid, and around regulation of grid access for the systems with no extra administrative or cost burdens for micro CHP and domestic fuel cell gas heating appliances (Klinder, 2004). Thus, in order for the benefits of micro CHP systems to be realised, uncertainties about these regulative issues need to be resolved.

Further, firms emphasise the importance of global standards for the stationary applications. One manager in a system integrator firm explains that this is because of the nature of the markets: 'This is a very international market. Local markets and national markets are too small, it is important to have international customers. There are international collaborations, so we need international standards.' Thus, in order to have markets of the size that will justify mass production, globally harmonised RCS needs to be developed.

With regard to hydrogen, there is a need to establish codes and standards that permit the safe storage and use of hydrogen (HFP, 2005, p. 64). At present, hydrogen can be used only in industrial applications, such as an industrial by-product, so that challenges remain for the introduction of hydrogen into consumer applications.

To conclude this section, an important factor in creating stability for a TIS in the formative phase is that national standards follow the work of the international standardisation organisations. For Europe, this means that the work of ISO and IEC is coordinated with activities in the UN Economic Commission for Europe, and the EC approval framework.

6.4. Conclusions on alignment of actors

This chapter has explored the role of technology-specific platforms, codes and standards networks and political networks. First, the findings on the role of the *technology platform* for the evolution of the TIS show that the actors have been successful in establishing a vision, a strategy and an implementation plan that is one of the most developed of the 16 different TPs in Europe. The EC decided to adopt the JTI proposal and the European Parliament will make the decision about the realisation of the JTI for FC&H2 in early 2008. Thus, these achievements stabilise the uncertainties for the actors in the TIS by establishing support and concrete actions for the evolution of the TIS. The HFP is clearly important for coordinating the various actors, and the long-term focus of the HFP strategy makes it a crucial tool for co-evolution between technology, market and institutions, with concrete activities to enable these processes. It is clear that for transport as well as stationary applications there are uncertainties about the future deployment of FC&H2. The HFP strategy creates stability by establishing a supportive framework for large-scale demonstration and validation. This increases the possibilities for co-evolution of the technology with the market and for alignment with institutions.

Second, the analysis showed that several types of *political networks* exist, both formal and informal. The political networks have affected the evolution of the TIS by succeeding in creating the necessary legitimation in the eyes of policy makers as well as users, thus creating the required support for the emerging TIS. In terms of both stationary and transport applications, there are strong political networks in Europe, where the EHA and FCEu interact with the EC on important topics such as lobbying for positioning FC&H2 in the energy strategy of the EU. In Germany, the actors in the TES for transport and the IBZ for stationary have been crucial for realising the German national transport and energy strategy, which has received large financial support from the German government. Thus, the political networks have created stability in terms of aligning the perspectives of actors towards policy makers, creating legitimation of the technology and, finally, receiving support at high levels. Clearly, these networks are decisive for the TIS to evolve to a growth phase.

Third, the findings in the analysis show that the *codes and standards* networks reduce institutional uncertainty by aligning the EU standardisation process with the global activities of the ISO and the IEC. The step from standards to code, however, is crucial, as this implements the standard by law. It is also important not to develop standards too early, as this might lead to a negative lock-in to an inferior technology. The actors, then, should standardise at the time when they consider performance to be sufficient to meet customer demand. Therefore, standardisation should be coordinated in conjunction with demonstration projects, which is the case, in fact, in the large EU demonstration projects scheduled to be part of FP7 and the JTI. The EU standardisation work is in line with the ISO work and, as such, global standards develop in conjunction with the validation of the technology in Europe. The standardisation process is gradually moving forward and the EU has now suggested an approval for hydrogen vehicles, thus reducing this uncertainty. For the stationary applications, some standards exist for micro CHP using natural gas, and large-scale industrial applications have standards for hydrogen, so for these applications the standards already exist.

7. Validation of technology

The aim of this chapter is to explain how firms validate technology and prepare for market introduction. Before new technologies can be deployed in the market, they need to be validated. The key stabilisation mechanisms for technology validation and market preparation are the use of knowledge search and demonstration projects. The questions I will answer in this chapter are:

- What kind of *knowledge search* strategies do firms use to reduce technological uncertainty, and how do they distribute knowledge creation in the value chain?
- Which are the key *demonstration projects* in Europe for FC&H2, and how do they help in reducing technological uncertainty?

The chapter is organised as follows: in section 7.1, I present *knowledge search* and in section 7.2, I present the *demonstration projects* that are important for reducing technological uncertainty.

7.1. Knowledge search

This section investigates knowledge search as a stabilisation mechanism for firms in developing and validating technology. Knowledge creation in the hydrogen and fuel cell value chain includes knowledge in science, technology and the market, and to investigate this topic, I have separated this section into six parts. I start with discussing the firm perspective on knowledge search tools in 7.1.1, and in 7.1.2 I present the important role of inter-firm coordination for reducing technological uncertainty. In 7.1.4, I discuss cooperation for transport applications, and in 7.1.5, I discuss cooperation for stationary applications. Finally, I investigate knowledge creation and value chain position.

7.1.1. Knowledge search tools

This section analyses the knowledge search tools that firms use to reduce technological uncertainty. Firms can employ a broad range of tools in order to increase their knowledge base and thus improve their technological capabilities. This analysis builds on data collected at the firm level to identify attitudes towards the tools that they judge important for knowledge search. The respondents answered that the entire list of tools was relevant and that none of the tools were insignificant.[84] Some tools, however, are more central than others. A key result is that cooperation with other actors is the most crucial method in reducing technological uncertainty. The other knowledge search tools have value as well, but much less than entering into cooperative relationships.

First, according to the firms there are simply not many interesting technologies to license in the industry at this stage; hence *licensing* is not an option for firms to acquire knowledge. Firms do issue patents, however, and the actors expect licensing of patents to occur more frequently when serial production starts because then markets for component technologies will grow.

Second, there are few *mergers and acquisitions* (M&A) in this field. There is no real indication of the importance of M&A at this moment, but the actors expect acquisitions to become more important as the TIS matures.

Third, the firms did not perceive *university employment* as particularly important. A manager in a system integrator firm explains:

> 'It is very, very, rarely that you can find someone with similar knowledge of the most advanced technologies that you have. You have people working in labs and universities for sure, but the technology they work on is much more beyond ours. Employment from industry is more important. Pretty difficult, but you can find people with knowledge in the market.'

Thus, the gap between university and industry knowledge on system integration makes direct employment from university less relevant for system integrator firms. A manager in a materials firm had another view, explaining that the materials for fuel cells are dependent on scientific advances and, in particular, that they are deeply impacted by nanotechnology, in which universities have a strong knowledge base. Therefore, at the level of system integration, the industry is the key knowledge source, while in the upstream part of the value chain – in materials and components – universities are a key knowledge source.

[84] The list of knowledge search tools is found in Appendix A - Interview guide.

Thus, the interaction between the scientific community and industry is closer in the upstream area of the value chain.

Fourth, firms consider *patent analysis* to be a good source of technological knowledge, but with several shortcomings. Firms can use patents to explore the opportunity for technology improvement, and to check for a possible conflict. Patents can also help firms to develop an understanding of what other firms are doing and to know if there is anything that they are not allowed to do. Clearly, patents can be important for firms because they can provide insights into what the competitors are working on, and the direction they are going. A problem with patents, however, is that they can be hard to decipher if you are looking at a particular application. It is possible to identify the claims, but the patents can be so neutral that they do not provide valuable information for the application the firm is looking at.

Fifth, an interesting finding is the fact that the firms do not view *conferences* as an important tool for obtaining knowledge because they are not considered to be places where crucial knowledge is discussed. It is a general understanding among the firms that people do not reveal what they are really doing at conferences. A conference is a place where results are presented, not a place where you would get new ideas.

In conclusion, firms use a variety of knowledge sources, and in doing so, triangulate between them to develop a picture of the technological uncertainties and possible solutions. However, the most important tool for reducing technological uncertainty is *cooperative agreements*.

7.1.2. Cooperation to reduce technological uncertainty

This section explores the different forms of cooperation various actors emphasise to reduce technological uncertainties. Table 7.1 shows some typical examples of the external relationships the different types of actors use to develop FC&H2. I also analyse the types of agreements in terms of the forms of knowledge partners exchange in the agreements. These examples of relationships show that the agreements that are frequently used are cooperative agreements protected by a *non-disclosure agreement* between two firms, i.e. bilateral agreements. Most of the agreements relate to development of technology and consist of supplier agreements, R&D contracts and system production.

Table 7.1: **Examples of inter-firm relationships**

Type of firm	**Relationships with**	**Aim of agreement**	**Form of agreement**	**Type of knowledge exchanged**
OEM	Competitor	Co-develop strategic components	Joint venture	Technological - engineering
System integrator	OEM	Improve system performance	Cooperative agreement	Technological - engineering
System integrator	Component	Improve performance of component	Sub-contract of key component	Technological - scientific
System integrator	University	Modelling of performance of system	R&D contract	Technological - scientific
Materials	University	Fundamental characteristics of materials	R&D contract	Technological - scientific
Component	University	Improvement of production process	R&D programme	Technological - engineering
Fuel distributor	University	Modelling infrastructure development	R&D contract	Technological - scientific
Fuel distributor	OEM	Demonstration and market introduction	Cooperative agreement	Technology validation
Fuel distributor	Technology supplier	Build infrastructure	Cooperative agreement	Technological - engineering
OEM	Technology supplier	Create standard	Cooperative agreement	Technological
System integrator	Utility	Test technology- create a market	Cooperative agreement	Technology validation

Source: Analysis of interviews with companies.

The firms explain that cooperation with other firms is important on several grounds. First, the partners have complementary skills. A manager in a component supplier, for instance, explained that it industrialises basic research by transforming scientific knowledge into specific components for FC&H2. A key activity for this firm, then, is cooperation with firms that do basic research. Another actor adds that it is the different ways of thinking that make cooperation attractive, in particular with companies that 'have a really interesting technology looking for a different solution than you are'. In this way, the different skills of partners complement each other and create synergies.

Second, firms use cooperation because of its possibilities for reducing the lead time of first movers. Cooperative agreements are important tools for firms to share their resources and thus combine their knowledge with that of other organisations. In situations where a group of firms is behind a first mover, the firms can use cooperation to catch up. One example is the case of hybrid vehicles, where cooperation indeed was a successful strategy.[85] A manager in a European OEM explained that in this case, 'the European OEMs have a disadvantage compared with market leader Toyota, so it is the only way to catch up. You go through the way of cooperation.'

Third, the analysis made it clear that interaction at conferences and other events constitutes an important opportunity for awareness and for updates on the actors in the field. Importantly, it was also the case that many informal exchanges that start at conferences can lead to cooperative agreements in the form of a specific collaboration. Once trust is established, then, the actors share knowledge that is more important. A key part of cooperative agreements in this field, however, is the actors' requirement of protection under a non-disclosure agreement, or at least a 'memorandum of understanding' (MoU). Thus, informal exchange is less central to the knowledge exchange per se; it is formal cooperation, rather, that is crucial for the exchange of truly valuable knowledge. A firm's knowledge is significant enough to protect, and it is only when firms sign a non-disclosure agreement that they are willing to share truly valuable information. An interviewed manager elaborated on the importance of confidentiality agreements:

> 'If you start talking with another firm, you can have some casual meeting, networking and so on, but when you start talking more specifically, then you need to have a MoU at least … a type of

[85] The hybrid vehicles referred to here are not a FC&H2 technology but are related, and many FC&H2 vehicles are hybrids, combining either a hydrogen ICE with a battery or a fuel cell with a battery. The present example is the hybrid cooperation set up by three major automakers to take on competition with Toyota and, to a lesser extent, Honda.

> agreement that allows you to start talking. So we have many of them. You need to have them to start talking, basically.'

Thus, it is only once you have a contract signed that you start talking. Before that, the firms are unwilling to exchange strategically important information. The importance of a formal contract is experienced both in hydrogen firms and in the fuel cell side of technology development and is a way to protect investments in R&D. Trust is important, but more important is the protection of a signed contract.

A fourth finding in the analysis was that joint ventures can be a strong tool to create key knowledge on particular products. OEMs, for instance, use joint ventures as a mean to develop strategically important parts of fuel cell systems. Another example of a joint venture is between a chemical company that develops membranes and a materials company that develops catalysts. The joint venture was set up to do research on and develop 'Membrane Electrode Assemblies' (MEAs), thus creating synergies between the two companies' key knowledge areas.[86]

Fifth, an interviewed manager from a component producer explained that a focus on cooperation and building of partnerships is key in the industry at this point. He portrayed the decade from 2000 to 2010 as 'the strategic positioning decade' because, as he explained:

> 'The market or the value of the market is not what the revenues are or how many components you produce, it is more important how many potential strategic cooperations and partnerships are you able to close. This is the most important aspect I think between 2000 and 2010, and this is my understanding of this decade, I define it as 'strategic positioning'. I mean it is like playing chess, you have to bring all your figures to the right position, to the right customers, to deal with the right customers, to make the good cooperations, … it is nice to have this revenue but it is much more important if you are able to set up cooperation with one of the car manufacturers.'

[86] Press release 25 July 2006 <http://www.solvaypress.com/pressreleases/0,,44644-2-0,00.htm>

The industry is at a stage between R&D and market deployment, where the potential large markets will emerge within the next decade. In order to create stability in the TIS, the actors thus need to develop strong partnerships that enable knowledge sharing across the value chain.

7.1.3. Cooperation for transport applications

In this section I discuss how knowledge search takes place in the form of bilateral agreements for transport applications. In these kinds of applications, I found with regard to the cooperation patterns of OEMs, that more links are established with other firms and fewer with universities. Further, the technological relations are more engineering oriented, as these firms bring different components and sub-systems into a large product system. OEMs are the vehicle producers and establish links that are technological, political, and market related. The following section discusses how OEMs cooperate with suppliers and universities in order to facilitate technological innovation. Results show that for OEMs three types of cooperations are important:

- the large cooperations that are publicly announced in the press, which deal with strategic technology alliances with other OEMs
- the smaller supplier cooperations, which are not usually part of the strategic frame
- the infrastructure discussions with the oil companies

Vehicle development occurs more as a result of bilateral agreements than of the EU framework programmes (FP). The supplier agreements are based on vehicle integration, where one supplier is responsible for delivering the stack, another delivers all the stack-specific components needed in the vehicle, and the OEM does the integration, electrification, air conditioning, etc. The technological relations they establish are thus engineering related, as these firms bring different components and sub-systems into a large product system.

The discussions with the OEMs revealed that there is an entry barrier for becoming a component supplier, namely the possession of a clear understanding of the automotive development cycle. As one interviewed manager in an OEM explained:

‘One thing we require, which is part of the specific skills, is understanding of the automotive development cycle. That is why new companies have problems coming into the picture, because they are not familiar with the automotive development cycle, and for us it is crucial, we cannot have a supplier which starts delivering hardware and then does not fully understand the process of how we need, for instance, A sample, B sample, C sample, how we approach market maturity within the development cycle by specific timing, etc. We need to test the vehicles in summer operation, winter operation. We have hardware test, software test, and all this is a very fixed testing frame that we have for our vehicles, and our suppliers need to follow that cycle. It is very strict, and for new companies not understanding this mechanism, it is very difficult.’

As a result, therefore, innovation in existing suppliers is emphasised, making it difficult for newcomers to become suppliers. On the other hand, fuel cell system integrators exist as tier-1 suppliers, and these have many agreements with component firms. In fact, most OEMs use at least two suppliers for each component. The value chain therefore consists of a mix of traditional suppliers and newcomers. To illustrate the relationship between existing and new suppliers one manager explained:

‘We would look at that and try to assess that and I don’t want to say that we never take a new partner, but we know by experience that for a new partner it is difficult to understand our cycles and processes, because it is crucial from a financial point of view and from a timing point of view. We do depend on getting the right hardware at the right point in time during our development cycles and if we don’t get it, we are losing like half a year or a year in the cycle because we are losing that test cycle. This is important for us’

Many OEMs also develop their own systems, and as such, the system integration takes place internally. This is because the development of the fuel cell system is a key component in the vehicle and something that is strategically important for the OEM.[87] Some OEMs also

[87] Similar to the engine of a regular car, also a key component.

combine their own stack development with cooperation with specialised suppliers. In the Japanese sector, for instance, companies like Honda have shifted from operating with an externally made fuel cell system to using a proprietary system.

A final type of relationship is the link to universities. These have to do with basic science concerning materials and characteristics, but also with cooperation on certain issues, such as hydrogen storage in the vehicle. A manager from an OEM explained the relationship it had with universities:

> 'Yes, we cooperate with universities, but on very specific questions. Usually not on the strategic frame, but very specific questions like materials research, these kind of things, specific expertise on research and knowledge generation.'

Given that OEMs use universities only for the more fundamental tasks, relationships between OEMs and component producers are more common. For instance, it is always the case that an automotive supplier performs the production of components.

A further finding is that the shift from science to technology takes place for the most part in the component developers. These types of firms make use of external knowledge from materials developers and the scientific community to engineer their components. Producers of components and particularly of materials therefore establish more links – in number as well as intensity – to universities and research centres. This is because the strength of universities in this technological field is not in system knowledge but in specific scientific characteristics at more fundamental levels like the development of new materials, catalytic processes and polymers. The relationship between materials suppliers and universities is crucial for understanding the science-technology link in the field. As one manager in a membrane company explained:

> 'We give them [universities] ideas and hints, for instance how to alternate polymer structure to maybe modify membranes, and the characteristics of the membranes, and so the outcome is modified membranes and MEAs, and they do a lot of testing themselves. …

> they get a lot of information from us, on how if you want to move up on scale, what to look for in the step from a lab product of a small fleet of membranes to industrial scale.

Another part of this relationship is thus that the company performs development into industrial applications because universities do not have the tools and the technology for this process. It is also important to understand how industrial production occurs within the industry. A membrane producer clarified this relationship:

> 'There are many ways to produce a membrane on a small scale that would never have a chance on a bigger scale, and that do not have an economic value, because they cannot be reproduced. The cost is too high. We have to do this, while they look at the molecular stuff, basic research.'

A conclusion, therefore, is that in the development of the fundamental parts such as components and materials, I would say that universities play a leading role, but when the process starts to become more user-oriented the universities become less central in knowledge creation. Component developers often develop components for several industries, and their relationships are with many different types of system integrators and OEMs. Materials and component suppliers, therefore, have knowledge that is more generic, since their technology is used in different industries.

7.1.4. Cooperation for stationary applications

In terms of network relationships, the more strategic market cooperations take place between utilities, which control the market, and system manufacturers and heating companies, which produce and install the systems. The fuel cell systems that the system integrators develop are prototypes, and therefore not sold directly to the customer but operated within the framework of a contracting agreement. This means that the installer operates and monitors the system, and technicians specially trained by the fuel cell manufacturers are responsible for servicing and maintaining the prototypes. The fuel cell system is thus the property of the installer. In this business model, the customers only pay for the energy they actually use, and in that sense the arrangement resembles a leasing agreement more than a purchase. The key actors in the stationary application area are thus the system integrators and heating companies, and these establish links both to policy makers and to the market.

In terms of technology development, the system integrators establish cooperative relations upstream to suppliers and universities in order to facilitate innovation and thus reduce technological uncertainties. An interviewed manager in a system integrator firm working on MCFC technology for the energy markets stated that university research currently focuses on PEMFC and SOFC and not so much on MCFC. He stated that many universities used to conduct research into MCFC technology but had now shifted to PEM or SOFC. The manager commented:

> 'Unfortunately, molten carbonate is not really an issue in universities and national labs. It used to be a couple of years ago, but in the last ten years funding has declined because people think that the technology is mature already, but it isn't in fact. Therefore we go to conferences and we read research reports.'

The key objective for these relationships is to overcome the challenges of degradation and durability, and thereby to reduce the technological uncertainty of the systems. A key challenge is to increase the *durability* of the FC systems. Stationary systems are required to run continuously for thousands of hours at a constant load, and this is quite different from transportation applications, where the fuel cell system starts, stops and starts, with high frequency of change of loads.

One of the greatest technical challenges for stationary systems is degradation, 'whereby the chemical and mechanical processes the system has to perform gradually reduce the ability of the fuel cell stack to produce electricity'. For example, in several demonstration projects in Europe the systems have shown a dramatic decrease in performance; in one of these, a major energy company experienced the electrical output of the systems falling from 1 000 watts to 400 watts after an average of 4 500 hours of operation. Even so, the unit was capable of running for a maximum of more than 13 500 hours. Thus, a key challenge for the fuel cell developers is to maintain a high level of operating performance over a long period.

Companies working with system integration believe that further research will lead to a better understanding of the processes within the cell, helping further to reduce degradation and thus prolong service life. The actors expect important knowledge to come from using different materials and special coatings, or in a redesign of components.

The technological relations thus are both with engineering oriented towards system optimisation and also with basic science, like materials development, catalytic processes and nanotechnology. In order to reduce the uncertainties and create stability for the stationary systems, the system integrators develop close connections to materials developers, component suppliers and catalyst companies to access new knowledge for the purpose of reducing degradation while simultaneously increasing the durability of the fuel cell system.

7.1.5. Knowledge creation and value chain position

The way a firm builds up its network of cooperative relationships depends on its position in the value chain. Indeed, as regards differences in the value chain, I analyse here the types of relations the different actors positioned in the value chain establish, and the types of knowledge exchanged in these relationships. Figure 5.2 in chapter 5 illustrated the position of the firms in the value chain and the types of scientific, technological or market knowledge the firms acquire. This section will expand this understanding of knowledge search in the value chain, building on the findings in this chapter.

A general picture of knowledge creation in the value chain is that the closer the firm is to the end user, the more it employs engineering knowledge. In addition, the more the firm is oriented towards fundamental characteristics, materials, membranes and other components, the more scientific knowledge is used.

First, the firms located upstream in the value chain, that is, the companies developing materials, polymers, catalysts and membranes, operate within a broad spectrum of industries and act as knowledge providers to the producers of fuel cell stacks and systems, hydrogen storage tanks and dispensers. Membranes, for instance, are used in MEAs for PEM electrolysis and PEM fuel cells, as well as for separation processes applied in a range of industries such as the beverage industry, the pharmaceutical industry, the chemical industry, textiles, and drinking water treatment. The knowledge of membranes, then, is generic, while MEAs become customised for the different applications. Thus, these firms operate in a range of diverse industries, of which FC&H2 is one. One informant from a leading membrane producer explained this difference:

> 'If you concentrate on the membrane only, you cannot focus on one area only. If you do the MEA or the system, or any other component that is directed to the FC market, you can say, 'Well, I focus on the stationary.' If you do the membrane or polymer only, you have to be able to be partner to all MEA manufacturers. That means you have to have the product for stationary, portables and auto.'

Another aspect of the upstream side of the value chain is that the knowledge of the materials firms strongly relates to the science field. A result of the close science links is that these firms therefore establish more links to universities than do firms positioned downstream in the value chain. For hydrogen, knowledge in the upstream area relates to different forms of hydrogen storage and different forms of hydrogen production technology. The industry presently has a temporary agreement on using compressed hydrogen at 700 bars and on liquid hydrogen, but no definite technical standards have yet been decided on. Thus, research is being carried out on improving onboard storage of hydrogen in compressed, liquid and solid states. Because of the advanced knowledge required in hydrogen storage, companies working with storage technology also utilise close links to the scientific community.

Second, located in the centre of the value chain are firms such as MEA producers, stack developers and system integrators. The knowledge of these companies, compared with component and materials suppliers, is more related to application. For instance, at the level of MEAs, which are considered the heart of the PEM fuel cell, the knowledge becomes specialised for the different applications. Firms need a different MEA in a stationary fuel cell, a portable fuel cell, or a stack used in a car. In addition, some system producers tend to develop the stack and MEA in house, or combine their own stack development with procurement of MEAs from specialised producers. The technological knowledge of firms in this area is mainly engineering related, and thus they establish close links both upstream and downstream in this industry, but not so many to external industries.

Finally, the firms located downstream in the value chain are the OEMs, the oil and gas companies and energy companies. The OEMs are traditional car manufacturers; their knowledge is in the production of passenger cars and buses, and so they operate with product integration of a range of technologies. In the production of hydrogen fuel cell vehicles (HFCV), this means that the OEMs need to develop relations to new fields of knowledge to integrate this technology into their vehicles. They have knowledge about transportation markets, vehicle integration, sales and service networks, and strong brands. These assets are crucial for commercialisation of emerging technologies and can be vital for surviving technological transitions within an industry. For hydrogen, it is clear that the market knowledge resides mainly in oil companies, while the industrial gas companies and hydrogen technology firms develop the technical knowledge. Universities and research centres provide important knowledge to technology companies, and some OEMs' R&D departments are important for accelerating onboard storage technology.

The challenge for component suppliers is to manage relationships with different system integrators, often coming from different industries and having different requirements. Component suppliers therefore monitor and participate in a great variety of sectors. System integrators, on the other hand, monitor advances in industries and knowledge fields for components that can improve their product. With increasing modularity of products, OEMs and system integrators use more suppliers for each product, which also increases the number of cooperative agreements and thus affects the management of cooperative agreements in the value chain.

To conclude this section, it is clear that the use of alliances and other forms of knowledge exchange between firms is a challenging and crucial activity that takes place in all parts of the value chain. With the high degree of specialisation and interaction in the field, this clearly helps the firms establish a sense of control, in that the process of solving the uncertainties becomes manageable.

7.2. Demonstration projects

Another key stabilisation mechanism for technology validation and market preparation is the use of demonstration projects. These prepare for market introduction and are the key step from the laboratory stage to early or niche markets. In demonstration projects, the technology is normally at the prototype stage, where production costs are high and firms need learning experiences for validating the performance. Demonstrations are a protected space in which the technology can grow before it is ready for market deployment, and therefore a key stabilisation mechanism for validating performance in real-life settings.

'Lighthouse Projects' are a key element in the strategy of the EU actors in the FP7 programme. These are large-scale demonstration projects set up to bridge the gap between the R&D phase and broad commercial introduction of FC&H2 (HFP, 2005, p. 96). According to the HFP deployment strategy, the main objective of the Lighthouse Projects 'should be the development of all key technologies of a hydrogen economy to market maturity, and in parallel the advance of market acceptance, so that decisions on mass production can be taken' (HFP, 2005, p. 96). The Lighthouse Projects should, furthermore, enable synergies between transport and stationary applications. In this section, I present some of the most important demonstration projects in transport and stationary applications in Europe.

7.2.1. Demonstration projects for transport applications

Several demonstration projects are operative in Europe, and further Lighthouse Projects and demonstration projects are planned in relation to the deployment strategy of FP7. Each Lighthouse Project will be utilised in a region, and there is strong competition between different regions to host a Lighthouse Project.

A key European Union-supported demonstration project for hydrogen fuel cell buses is the CUTE project.[88] In addition, HyLights is a project that coordinates the hydrogen demonstration projects by monitoring and preparing for the Lighthouse Projects. Two other transport projects are also important. First, the Clean Energy Partnership (CEP) in Berlin has been crucial for the German national hydrogen and fuel cell strategy as well as for EU strategy development in the HFP. The CEP project will have a key role in the larger demonstrations that will take place in Europe. Second, a more recent project is HyNor in Norway, which later expanded into the Scandinavian Hydrogen Highway Partnership.

The transportation area also includes the examples of auxiliary power units for caravans and fuel cell forklifts. The former is a commercial technology in which the markets already exist and products are available for sale. The latter is currently moving from demonstration to market deployment in a few niche markets.[89]

Clean Urban Transport in Europe

The project Clean Urban Transport in Europe (CUTE) is a demonstration project for buses financed by the European Commission under Framework Programme 6, in which fuel cell buses were demonstrated for end users in nine European cities: Amsterdam (Netherlands), Barcelona (Spain), Hamburg (Germany), London (United Kingdom), Luxembourg, Madrid (Spain), Porto (Portugal), Stockholm (Sweden) and Stuttgart (Germany). The CUTE project is supported by the EU and has received €18.5 million in financial support; it is one of the largest projects that DG TREN (Directorate-General for Energy and Transport) of the European Commission has funded.

The goal of the actors involved in the CUTE project is to demonstrate that hydrogen is an efficient and environmentally friendly power source

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[88] Two other EU-supported projects are the Zero Regio project for cars and the HyChain for mini transport. I choose not to include these projects in the analysis but instead focus on the CEP project in Germany and the HyNor project in Norway for cars. This is because I assess these projects to be more important for the validation of technology and for market preparation.

[89] I will not, however, analyse demonstration of the auxiliary power units for caravans since this is a commercially available product, and thus the technology is already validated and has entered the market.

for future transportation in cities. The partners involved are ten fuel producers and hydrogen equipment suppliers and an OEM that delivers the buses. At the kick-off meeting in February 2002, the actors involved presented their goal, which was to prove that zero emission public transport is in fact possible today.

The performance of the bus is comparable to that of a conventional diesel driven bus and has a maximum speed of 80 km/h but with less noise and zero emission from the tailpipe. Furthermore, the bus can accommodate up to 70 passengers and operates like conventional buses, on the same routes and under the same tight time schedule for best comparative assessment of performance and costs.

CUTE has played an important role for the OEM and infrastructure partners, as this is the first project to simultaneously address the production of hydrogen, safety aspects of hydrogen refuelling in city centres, and driving the fuel cell buses in commercial operation in public transport systems.

The experience from CUTE made the different actors learn about such issues as fuelling performance and requirements, leakage of hydrogen from systems and storage tanks, and degradation of the systems and components (CUTE, 2006). More specifically, the final report (CUTE, 2006) showed that the lessons learned from the project were, first of all, that the electrolyser is reliable in general but has some problems on the level of material. In addition, operating unmanned filling stations with current technology is not a realistic option, but requires new technology. Finally, as regards the steam reformer technology, units currently are prototypes and have several problems. For instance, problems with material have caused prolonged downtimes, and part-load operation is not always as feasible as expected in terms of fuel quality (Grubel, 2005). The lesson for the further extension of the CUTE project was that the production and supply technology needs to be developed further.

Another key finding from the CUTE project for the demonstration of hydrogen vehicles is that more field testing is necessary for tests to allow for a definition of 'best practise'. First, the variety of regions, technology suppliers and hydrogen sources has resulted in different experiences, and this makes comparisons difficult. Second, more filling stations per region are needed, such as in the form of a 'cluster' to verify operating experience. Therefore, in the up-scaling of demonstrations in FP7 in the form of Lighthouse Projects, there will most likely be more concentration on efforts in the form of cluster building, more filling stations (similar, so they can be compared) and larger fleets.

The partners state in their presentation of CUTE, 'Thirty fuel-cell powered buses, running on locally produced and refilled hydrogen, should prove that today when ambitious political will and innovative technology are combined zero emission public transport is possible.' [90] However, the firms state that it is a requirement for market formation that the Lighthouse Projects be realised, and this requires political support. With the right policy framework, the firms can target early market utilisation that expands on experience from the Lighthouse Projects. As such, the Lighthouse Projects will act as a bridge to early markets as technology is validated and the markets are introduced to FC&H2 technology in daily operation.

This example is a key market preparation for the vehicle producers and the infrastructure companies, as the network effects are small. Since the use of buses is restricted to cities, few filling stations are required. The limited need for filling stations makes the infrastructure convenient to build up and creates stability for the actors in terms of reducing the uncertainty about infrastructure requirements. A further advantage with this application area is the possibility of establishing partnerships with the local bus companies. These are public users of the fuel cell buses and create stability in terms of the step to market deployment.

Clean Energy Partnership

The Clean Energy Partnership (CEP) is a consortium in Berlin consisting of ten major industrial companies in Europe and including automakers, energy companies, infrastructure companies and the public transportation company. The project started in 2004 and a goal of the first phase, which ran until November 2007, was to 'tap the

[90] <http://www.fuel-cell-bus-club.de/html/body_cute_kick_off__february_2002.html> Accessed 21 August 2007

technological potential of hydrogen as a source of energy, conducting tests with a view to suitability for routine use and system capability'.[91]

The CEP demonstration project consists of the hydrogen infrastructure of two hydrogen filling stations, a vehicle fleet, a hydrogen information centre and a service station for hydrogen vehicles. CEP is working with a total of three different hydrogen production methods as well as three different hydrogen propulsion systems. Thus, the project explores a variety of alternatives. The vehicle fleet consists of seventeen hydrogen vehicles and, as such, is 'the largest and most complex demonstration project for future-oriented hydrogen technology in the world'.[92]

The first station opened in 2004 and delivers gaseous hydrogen that is produced on site via electrolysis and stored in compressed form. At this station, the fuel distributor also delivers super-cooled liquid hydrogen by truck and stores it in a cryogenic tank. The vehicles use hydrogen both in modified internal combustion engines and with fuel cells. A second station opened in March 2006 as part of this project.

The CEP project partners include the German car manufacturers (OEMs) as well as the major energy and infrastructure companies in Europe. In fact, four leading automotive OEMs are involved, and five internationally leading oil and energy companies are the infrastructure partners in the project. Thus, this is a strong candidate for the Lighthouse Projects financed in FP7. Moreover, CEP is the key demonstration location in Germany and is connected to the German Transport and Energy Strategy (TES). The TES consortia plan to extend the demonstration to include several hundred vehicles along with the corresponding hydrogen infrastructure; this will result in further technological validation, demonstrating the technological advances required for commercialisation (NIP, 2007).

The German National Development Plan (NIP, 2007) is an outcome of the Transport and Energy Strategy (TES) and describes the steps for

[91] CEP homepage <http://www.cep-berlin.de/index_more.html> Accessed 20 August 2007
[92] CEP homepage <http://www.cep-berlin.de/index_more.html> Accessed 20 August 2007

the demonstration of hydrogen and fuel cells in the transport sector. This strategy states that the actors need only a small fleet to validate the vehicles, but that there is a need for a significantly larger number of vehicles to demonstrate and validate the infrastructure. The goal for the infrastructure is to 'achieve as high a capacity utilisation for test purposes as possible', in order to ensure customer acceptance (NIP, 2007, p. 9). Thus, the partners need to develop a large infrastructure that is costly to build and requires commitment of large resources. The resources devoted to transport applications in the German National Strategy are in fact immense, consisting of €1.144 billion for the period of 2007 to 2015. It is clear that the CEP project will be a pillar in this strategy, with the strong consortium behind it and the first-mover advantages already built up in the first period from 2004 to 2007.

The markets the firms are targeting are not niche markets but mass markets. Niche markets do not have the necessary size to justify devoting large resources to demonstration. An aim of this project is to identify early markets in which the partners can deploy vehicles to mass markets as a step-up process. The mass market for hydrogen HFCV is the key case for the transportation market and is characterised by inter-dependence between infrastructure development and vehicles. These network effects make it imperative to plan for coordination between the demonstration and the market networks that must be developed. CEP is an important project that helps to reduce technological as well as market uncertainty and thus closes the gap to markets by establishing links with fleet users.

The strategy of the companies is to expand the fleets in the next period to several hundred vehicles in a Lighthouse Project. Fleets of large executive vehicles will target key decision makers, and fleets of small vehicles for urban use will target delivery vans, postal services and other public and private actors whose daily operations occur within a limited area. This step is between demonstration and market deployment in early markets and it creates stability in terms of market uncertainty by interacting with the users. The demand profiles of the key early market users have been analysed as part of the EU HyLights project, which assists the actors in the demonstration projects in the EU with market knowledge, among other things.

The strong partnership between the infrastructure and the vehicle sides has created stability for the large-scale demonstration of vehicles by legitimising FC&H2 for policy makers in Germany as well as at the level of the EU.[93] This combination of powerful actors, or 'prime movers', that are able to provide vehicles and infrastructure and, most important, have the required resources for long-term commitment, is essential for creating stability in this phase of the TIS.

HyNor

A group of firms in Scandinavia has high ambitions to validate hydrogen as a fuel in the transport sector. One important issue has been decisive, namely the limited access to HFCV in this region. This has led to a particular focus on infrastructure among the actors.

In Norway, the HyNor network employed a hybridisation strategy, acquiring 15 hybrid ICE vehicles that have been converted to run on hydrogen instead of gasoline. This enables the HyNor project to learn about market use and to test hydrogen filling infrastructure in real-life operation, and it increases public awareness of the opportunities for introducing hydrogen into the transport sector. This partnership focuses on learning about hydrogen refuelling and infrastructure requirements, and not so much on the vehicle side, because these actors are mainly hydrogen suppliers and infrastructure companies as well as users, including transportation companies and other fleet operators. This particular focus on the part of the actors fits well with the industry structure in Norway, which is dominated by energy companies.

In November 2007, the HyNor partners also signed a MoU with the Japanese OEM Mazda, which will deliver 30 hydrogen-fuelled ICE vehicles to the partnership in Norway. In the future, the partners plan also to have electric vehicles that use a hydrogen fuel cell system in a hybrid configuration with batteries. These vehicles are produced in Norway using a fuel cell system delivered by a Danish fuel cell system integrator. The electric vehicle uses the hydrogen fuel cell to recharge the batteries to achieve considerably longer distances than by using

[93] CEP also functions as a political network and has strongly contributed to the German National Plan for hydrogen and fuel cells (NIP, 2007).

batteries alone. The hydrogen fuel cell is thus not directly powering the vehicle but only recharging the battery as needed. This makes the size of the fuel cell quite small; in fact, it reduces the fuel cell to 25% of what is required in a normal FCV. Furthermore, this hybrid configuration increases the lifetime of the fuel cell since it is not in constant use, and reduces the uncertainty about the durability of the fuel cell systems. In a significantly supportive action, the Norwegian government made hydrogen vehicles tax-free in 2006.[94] In addition, policy makers in Norway introduced exemptions from road toll, vehicle tax, fuel tax, and parking fees. The vehicle tax is Norway is a large share of the total cost of the vehicle and this exemption can therefore contribute substantially to the demonstration and deployment of hydrogen vehicles.[95]

The HyNor project has the advantage of strong infrastructure and fuel partners and has managed to create legitimation in relation to policy makers as well as Japanese OEMs. This legitimation allowed the partnership to remove a substantial uncertainty in the demonstration of hydrogen in the transport sector, namely the limited access to vehicles. HyNor is also a partner in the Scandinavian Hydrogen Highway Project, which applied to be a host for a demonstration in the FP7 Lighthouse Projects. Competition for this will be keen, but the region seems to have developed first-mover advantages matched only by CEP in Berlin.

Forklift demonstrations

There are several demonstration projects for forklift applications where firms are preparing for market introduction. One notable example is a project at an airport in Germany where several companies, including a fuel cell system integrator, a hydrogen supplier, a forklift producer and a logistics company, are demonstrating a prototype in daily operation at the airport. The demonstration is a real-life demonstration where 'the forklift truck was simply refuelled like any petrol vehicle at the nearby hydrogen filling station in just a few minutes'. The benefit the fuel cell system offers is that the fuel cell replaces the battery in the electric forklift truck, providing the same performance but without the need for

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[94] value added tax (VAT) when the vehicle is purchased

[95]<http://www.hyways.de/docs/deliverables/WP3/HyWays_Norwegian_Vision_Hydrogen_Chains_NOV2006.pdf> Accessed 28 August 2007

the 8-hour link-up to a charging station. This is a crucial factor for users, as the forklifts are now capable of being in continuous operation.

The demonstration included a hybrid system between fuel cells and super- capacitors in which the fuel cell system provides a nominal output of 18 kW and the ultra capacitors serve as energy storage devices. The ultra capacitors also act as an electric energy storage device which uses the vehicle's braking energy to provide a peak performance of 38 kW in situations where this is required. The partners highlight that 'this ensures that the forklift truck is able to deliver the same dynamics during operation as its battery-powered counterparts'. In terms of design, the size of the system is identical to that of a conventional battery, so it is easy to retrofit with no additional adaptation required.

The project, which led to further contracts for several industrial vehicles with fuel cells, has aimed at continued development of fuel cell hybrid solutions, with a new storage configuration. A similar project is operated in Denmark, where a system integrator first produced a hydrogen fuel cell truck prototype in 2004 and started pilot testing 7 trucks in 2006. The project resulted in up-scaling to larger demonstrations in the range of 50 to 100 systems and later, for niche market deployment.

The technology uncertainties are low and the benefits of the technology fit well with the application. Users can benefit early on from the opportunities without large technical improvements. Thus, this is an example of how a firm can create a fast route from a demonstration project to a niche market.

Lighthouse Projects and regional competition

The Lighthouse Projects targeted for FP7 are crucial to creating stability for the TIS. One fact emerged during the analysis of the various transportation demonstration projects for fleet and consumer vehicles, however, that relates to regional competition: there is intense competition between regions to become so-called 'Lighthouse regions' in the FP7 programme. Cities such as London and Berlin, and regions like Northern Italy and Scandinavia, to mention some, are competing to host the large-scale Lighthouse Projects for FC&H2.

A result of the CUTE project is that, in terms of vehicles, only a few vehicles are enough to extract important lessons from prototypes, but to be able to learn about daily operation of the infrastructure, there needs to be a critical mass (CUTE, 2006; HFP, 2005, p. 97). Another factor is that an initial population of 10 000 vehicles is needed up until 2015 when mass-market rollout is expected. Those first 10 000 vehicles will result from the Lighthouse Projects proposed by the Joint Technology Initiative (HyWays, 2006). The firms involved will need a cluster of filling stations and vehicles to be able to learn about daily operation. Thus, the future Lighthouse Projects in FP7 will be different from the CUTE project, with an emphasis on large clusters of vehicles instead of demonstration spread over many different sites.

One condition of the FP7 programme is that an already-existing infrastructure is required, and this creates a form of entry barrier for new regions wishing to participate in the programme. Another factor is that the leading companies tend to favour regions that provide high visibility for their technology, thus excluding less profiled regions across Europe. Finally, there is a lack of infrastructure and hydrogen cars, which can be problematic for the development of a regional initiative. These demonstrations might be too resource intensive for a small region, and local actors may have too little impact to attract the large actors.

The regions for the Lighthouse Projects in Europe are still not decided, but several already have demonstration sites with existing infrastructure, which clearly is advantageous. The actors involved in the CEP project in Berlin already decided to increase this demonstration as part of the German National Innovation Programme (NIP, 2007), making it an obvious candidate. Scandinavia has emerged as a credible candidate with the building up of infrastructure and with support from the Nordic Council as well as from national governments. The key factors for creating a Lighthouse Project therefore are that the various regional initiatives need partnerships with powerful actors and support from local or national policy makers in order to be strong enough in terms of financial and knowledge resources.

7.2.2. Demonstration projects for stationary applications

There are several demonstration projects for stationary applications in Europe that are being utilised for distributed energy as well as for large-scale power production. And there are currently several demonstrations of telecom back-up systems and of by-product hydrogen, the latter based on expensive but commercially available PEMFC systems. In Europe, one manufacturer already has a product for telecom back-up systems on the market, while several firms are on the brink of shifting from technology validation to market introduction. One example is a consortium, led by a Danish system integrator, which includes several owners of telecom base stations, base station producers and energy companies. The consortium ordered more than 300 systems and the status currently is field demonstrations. The shift to market deployment will be manageable since the key users are involved in the project, and thus the market uncertainties are low.[96]

Virtual Fuel Cell Power Plant

Several companies are active in the small-scale application area demonstrating technology for distributed energy and micro CHP. One notable example is the large EU-supported programme, the Virtual Fuel Cell Power Plant (VFCPP), which is led by a heating company in Europe.[97]

VFCPP is a group of interconnected decentralised residential micro CHPs using fuel cell technology, installed in multi-family houses, small enterprises and public facilities, and this project tests and connects 31 CHP units in Germany, the Netherlands and Spain. The CHP systems provide heating, cooling and electricity production, and they are centrally controlled. The VFCPP contributes to meeting peak energy demand in the public electricity grid. The key actors involved are the German heating company and a fuel cell system integrator from North America. The project also includes several other energy companies from Germany, Holland, Belgium and Spain.

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[96] I do not present these examples as demonstration projects due their market availability. In this section I focus on some of the demonstration projects used in Europe for micro CHP and large-scale power production.

[97] <http://www.initiative-brennstoffzelle.de/en/live/pilotprojekte/vfcpp/liste.html> Accessed 18 August 2007

The project, co-funded by the European Commission under the fifth Framework Programme,[98] tested the third-generation systems over a 40-month period from 2002 to 2005. The objective of the project was to demonstrate an application of fuel cell technology and thus to transform laboratory technology into an everyday technology. The focus was therefore on demonstrating reliability and sturdiness in domestic and small-business CHP installations, to validate the performance and prepare for market introduction.

The PEM fuel cell system provided 4.6kW and used natural gas as the energy source. A significant success of this technology is the high fuel efficiencies of up to 90% and the electrical efficiencies greater than 30%. The consortium accumulated 138 000 running hours of the low-temperature PEM micro CHP systems and produced nearly 400 000 kWh of electricity.

The purpose of this project was to determine if fuel cell heating units connected to the public power grid can be a suitable means of optimising power generation in the grid, and if they will work together as if they were a single, large power plant. If so, the future of combined heat and power generation would not only make a substantial contribution to environmental protection, but would also reduce the burden on public power grids. From the field tests, the companies gained valuable knowledge that helps them reduce technological uncertainty and further develop the units.

In terms of success, the project fulfilled the expectations of the consortium, and no system had to shut down during the project. The project manager explained that they kept the budget and the timeline, and it was possible for them to follow the load profile of a utility very exactly.

The project identified three major barriers in the development of a product for the residential mass market (VFCPP, 2006). First, cost needs to be reduced to increase the technology's economic viability;

[98] <http://www.initiative-brennstoffzelle.de/en/live/pilotprojekte/vfcpp/partner/liste.html> Accessed 18 August 2007

second, the system must be simplified to improve reliability; and third, the temperature of the heat output must be increased to become compatible with existing heating systems and to provide opportunities for tri-generation.

One major result of the project has been to focus development efforts on high-temperature PEM fuel cells in order to overcome the barriers with the technology (VFCPP, 2006). At the end of 2006, a new transatlantic consortium of seven European and two U.S. companies was set up to create a new project based on high-temperature PEMFC technology. The project uses a simplified system design that reduces the system's complexity. This system is based on a new high-temperature membrane that makes it possible to increase the operating temperature. This important innovation makes it easier for the firms to link the fuel cell heating unit with existing heating systems, thus reducing the complexity of system installation.

As a stabilisation mechanism, the project helped the actors reduce the uncertainty of technology by identifying the barriers of the technology. Crucial factors were the introduction of a new high-temperature membrane to solve these barriers, the close links with the end-user partners to reduce market uncertainty, and the fact that the firms validated technology directly with customers.

Micro CHP

An example of a demonstration project for micro CHP is the activity of a Swiss company that has been very active in this application area for a long time. The company focuses its efforts on SOFC technology and started doing R&D related to fuel cells in 1988. It produced its first fuel cell stack between 1991 and 1993. The next step was field testing, which ran from 1994 to 1996, and since 2001 the company has been producing pre-series phase systems and is now moving the technology from demonstrations to market preparation.

The objectives in the pre-series phase are to validate and prove the technology but also to assess and prepare the market through analysing consumer behaviour. This requires the realisation of the necessary partnerships with the energy market. A key part, moreover, was to analyse 'proof of concept' and to establish service, support and training, first, so that the technology can meet the criteria for support and service that users need, and second, so that users get to know the benefits of the technology.

The company delivered 110 pre-production systems to partners in Germany, Austria, France, the Netherlands and Switzerland. Market partners are major energy suppliers and local installers. The installations in Europe consisted of 50 single-family homes, 10 multi-family homes, 5 laboratories and 32 public buildings. The fuel cell system is, like most domestic energy systems, fired by natural gas, which is easily available in these areas. The reformation technology converts the primary fuel into a hydrogen-rich gas, and due to the high operating temperatures, conversion occurs in the cell, thus removing the need for an external reformer. The high operating temperature is a key advantage of the SOFC technology; as stated by the company, 'It is here that the strengths of the SOFC concept come in to play.' The high temperature makes the SOFC technology much more resistant to impurities in the hydrogen. (For a PEMFC, 'even very low proportions of carbon monoxide in the fuel gas or sulphur impurities can badly affect performance.') Clearly, SOFC is a technology well suited to micro CHP based on natural gas.

The system integrator and its end-use partners have more than 1.5 million operating hours' experience in the phase of field tests. This is a key opportunity that has demonstrated 'the everyday practicality of fuel cell systems of the predecessor generation' and has provided necessary information for the next generation. Even so, a lot of development is required before market maturity.

The uncertainties relate in particular to system durability. A key problem with stationary SOFC fuel cells reported by several manufacturers is degradation of the system. Since the system requires performance that is equal to or better than existing technology, firms need to solve this barrier before market introduction. A major challenge facing engineers is thus to enhance the service life of the stacks. The stacks are subject to extreme stresses due to the great thermal variations that occur when the system runs up to operating temperature and back down again. This can result in mechanical, chemical and physical changes to the materials used and might lead to degradation that would have a negative impact on the performance and service life of the fuel cell.

The testing of such a large number of installations in customers' hands provides key market as well as technical information. The continuation of partnerships with many of the energy companies has clearly provided stability around market uncertainty and enables co-evolution between technology validation and the market preparation.

Large-scale applications for power production

The large-scale applications for power production involve installations in the several megawatts class across Europe. The technology includes both MCFC and SOFC, either alone or in hybrid configurations with gas turbines.

The MCFC demonstrations achieve considerable electric efficiencies of more than 40% and have the benefit of being able to run on sewage gas, residual gases or biogas to generate energy. The use of these fuels means that the energy production is CO_2 neutral and enables the extraction of useful energy from waste. Another advantage, which comes from operating a CHP system close to consumers, is the minimisation of loss during transmission. This increases the overall efficiency and emits increasingly lower levels of pollutants such as NO_x and SO_2. MCFC is believed to be a mature technology compared to SOFC. Currently, there are demonstrations using biogas, one of which is the EU-supported BICEPS project, which will run from 2006 to 2009.

One leading company in Europe has successfully installed 17 high-temperature fuel cells in Europe that generate 245-kW electricity and 180-kW heat. The MCFC is superior to conventional piston engine gensets because of its high electricity efficiency, which surpasses traditional technologies. A further benefit is the almost soundless operation that makes it especially popular for inner city use. The fuel cell systems have demonstrated close to 300 000 hours of operation, and are technically ready for market introduction.

The demonstrations operate in partnerships between system integrators and energy companies that clearly have an interest in the technology, but cost is an uncertainty at the moment. The particular role of the energy companies is that they have the distribution network, and as one manager stated:

> 'They know what would be suitable for a fuel cell installation. And they are interested, but of course they have a problem with the price. The cost of our applications is still too high for wider applications.'

Thus, the companies need to achieve cost reductions. The costs related to this technology come from several factors. One is low volume, but also that the technology is not validated. Therefore, to be on the safe side, the system integrator needs to build a certain amount of extra margin into the components, and this increases their size. A manager in a system integrator firm explained this:

> 'We have not been able to optimise the components with regard to costs, so there are still some safety numbers in our design. For instance, if you make a piece from sheet metal you can use 1 inch or 2 inch. As long as you don't know what you need, you take the 2 inch, and it is more expensive.'

Another issue is that the even though the technology is capable of long periods of operation, more demonstration is needed to reduce the system complexity, thus also reducing the cost. One manager explained that the firm needs more field experience because, due to uncertainty about the technology, it uses more control units and instruments than might be necessary, since 'the more experience you have, the more comfortable you feel when you change components'. Clearly, both optimising the system and its components and reducing the complexity of the system can be achieved through demonstration of the technology. Demonstration projects thus create stability for the actors and help in reducing technological uncertainty.

7.3. Conclusions for validation of technology

This chapter has explored the role of knowledge search and demonstration projects in creating stability for technological evolution. The analysis of *knowledge search* revealed, first, that the firms in the FC&H2 industry in Europe emphasise cooperation as the most important source for knowledge search, and thus for reducing technological uncertainty. This is because the knowledge base of FC&H2 is very complex, and the firms specialise either in narrow parts of the technology or in system integration.

Second, it is clear that all actors have an important role in creating stability. For example, the materials developers have a strong scientific base, which is important in solving particular uncertainties for specific components of the fuel cell systems. The types of knowledge these actors provide to the TIS are highly crucial in reducing technological uncertainty and relate to increasing performance by, for example, replacing noble metals in catalysts or developing new and improved components. These firms are thus crucial for the evolution of technology and for realising the shift from prototyping into larger demonstration units and, finally, into commercial production. The system integrators and the OEMs, on the other hand, play a key role in handling uncertainties about system design and performance as well as integration into end-use products. Thus, the value chain includes, upstream, a range of actors that are functioning as knowledge providers to a broad range of industries, of which fuel cells and hydrogen are one; and downstream, specialised fuel cell firms that integrate knowledge from materials and components into systems; and finally, the OEMs and energy companies that develop complete products for end-user markets.

Third, an additional finding is that the cooperation pattern of firms shows that the TIS is internationally oriented, with key emphasis on cooperation across firms and geographical borders. Firms create links to other knowledge fields like materials science, chemical processes, catalysts and advanced electronics to create stability for the TIS.

Fourth, in terms of particular cooperation between the actors, an interesting finding is that the firms require, at minimum, that a MoU be signed for starting technological discussions, meaning that formal agreements are necessary. The supplier industry creates important knowledge, and it is essential to establish links to system integrators or directly with OEMs in the value chain. This will create the necessary funding for demonstration and lead to first-mover advantages. In addition, it is evident that acquisitions will occur more frequently when the markets start to grow, probably sometime after 2010. Establishing links to the right actors is therefore crucial for obtaining first-mover advantages.

For the *demonstration projects,* I discovered, first, that they are important for both transport and stationary applications. They are located in a local setting like a city or a region, and results from this study show that in order to develop a successful demonstration and be able to expand the demonstration, it is important to have support from main actors such as OEMs and fuel companies. This is because access to vehicles and infrastructure is a key point, since their availability is limited and costs are high.

Second, in terms of creating stability for technological evolution from transport demonstrations, both the CUTE and CEP projects provided useful knowledge to the partners, and the firms identified particular bottlenecks. In the next generation of buses, for instance, the OEMs will change the drive system so it runs directly on electric propulsion. The key role of these demonstration projects is thus to bridge the gap to early markets by using fleet vehicles in larger demonstrations. Fleet vehicles require less complex coordination, so this is a way to find the path of least resistance and involves gradual upgrading of infrastructure.

Third, the most important demonstration projects for stationary applications are operating in Germany. These examples are characterised by network effects and thus need support on a large scale to reduce technological uncertainty. The demonstration projects have provided the system integrators with knowledge about the practical use of the technology, which has resulted in improved and simplified systems. The firms will work further on these technical uncertainties as the demonstration projects continue in the next phase, with continuing cooperation with end-use integrators.

8. Market formation

The aim of this chapter is to analyse the evolution of markets for transport and stationary applications. Importantly, FC&H2 is in the formative phase, and as such not yet commercialised. However, some forms have introduced FC&H2 products for niche and early markets.

The chapter explains the market formation process in terms of the stabilisation mechanisms *market network*s and *hybridisation.* The questions I answer in this chapter are:

- Which actors are involved in *market networks*? How are market networks created? In what ways do they impact market formation?
- What is the role of hybridisation for market formation in the TIS, and in which applications does *hybridisation* affect the evolution of the market?

I present the market networks for transport and stationary applications in section 8.1, while section 8.2 discusses the role of hybridisation for market evolution.

8.1. Market networks

The topics for this section are how firms develop market networks and what types of actors participate in these networks. In these networks, firms formulate ideas about how to create deployment strategies and how to develop early market applications. This section will present six different examples of market networks:

- fleet and consumer vehicles
- auxiliary power units for caravans
- forklifts
- micro CHP and large-scale power production
- telecom back-up
- by-product hydrogen

8.1.1. Market networks for fleet and consumer vehicles

This section explains the role of market networks for consumer and fleet vehicles, and I discuss four issues. First, I investigate the role of 'prime movers' for the creation of stability in the market formation process. Second, I examine the impact of the formal EU projects HyWays and HyLights, which investigate the implementation of the HFP strategy. Third, I explain the critical coordination between fuel and vehicle, a key uncertainty for evolution of the TIS. The fourth section explains the market entry strategies of the prime movers and the differences among these actors. Finally, I discuss conferences, fairs and events as tools firms can use to create stability and build initial markets.

The role of prime movers

The prime movers are important actors with the ability to have an impact in the evolution of the TIS. For the transport applications (fleet vehicles and consumer vehicles), the prime movers are the automotive OEMs and the oil companies. These actors are responsible for vehicle production and fuel retailing, i.e. the downstream area of the value chain. Entry into this area of application requires access to large resources and coordination with regulations (vehicle and fuel approval), as well as a large support structure for vehicle maintenance. The fuel infrastructure is equally challenging, requiring large investments to reach a satisfactory level for users. The process of creating stability for this example thus requires coordination between supply and demand, as well as proper policy support. Clearly, the issue of building infrastructure and vehicles is a key uncertainty for the OEMs and the infrastructure developers.

The analysis shows that in order to create stability in the TIS, these prime movers have internal discussions relating to how to introduce new technologies into the transportation sector. These discussions start at the bilateral level and continue in formal projects like the HFP and in the German national strategy group. The results of the analysis show furthermore that there is a core group in Europe that includes about eight key actors, and this group strongly influences the strategy process.

The discussion in chapter 7 on validating technology showed that demonstration projects have a key role to play in creating stability for the TIS. However, the firms need to create an overlap from demonstration to early market introduction by interacting directly with users under market conditions, and this requires the building of market networks. Demonstration projects can introduce the user to the technology in a specific controlled setting, while market networks expand the demonstration projects by interacting directly with users. This makes it possible for the firms to acquire knowledge about the performance of the technology and the demand requirements of users. This then creates a bridge to the early markets. A key issue is thus to make the transition from a demonstration project to an early market. An informant from an OEM, deeply involved in the process, explained this step as the most important and by far the most difficult:

> 'The step from demonstration project or even larger demonstration project to a first commercial customer is the most important step, because that is when you need the infrastructure to be in place. So these are all the discussions we have on the more strategic level with infrastructure partners. These discussions also do take place here in Germany, for instance in the TES, Transport and Energy Strategy. Energy companies, car companies, authorities, it is also part of the discussions in Brussels – in the HFP platform. But the more detailed discussions are more on the bilateral level, because that is where you exchange confidential information.'

Clearly, the key relationships in the market networks are between OEMs, fuel suppliers, infrastructure providers and actors dealing with regulation. Important discussions take place in the HFP and in the German national strategy.[99] The key relationships, however, are those between the OEMs and oil companies at the bilateral level where strategic discussions on market formation take place between firms. As such, the discussions between the OEMs and oil companies are crucial for creating stability in terms of market formation. One manager in an

[99] The German national strategy is clearly a key factor in creating stability for firms in the TIS. This strategy has devoted major resources to R&D and deployment of vehicles, as well as supportive framework conditions for the industry to commercialise FC&H2 technology in the transport sector (NIP, 2007).

OEM further elaborated on the important relationship it had with the oil companies:

> 'We are discussing with them the next steps together, as to where we should operate our vehicles and where should infrastructure be ready, so building up these local networks is really important and something we do. But then how do you come from local networks to area-wide coverage, because any local network would still be part of a demonstration project or very controlled fleet operation. Ultimately the goal is of course to sell the cars in showrooms. When the customer steps into the showroom and sees the fuel cell vehicle he of course needs to be convinced that the performance of the car is good, probably even better than a regular car today, but then of course when I drive the car out of here, where do I refuel the car? So this is why the step from demonstration project or even larger demonstration project to a first commercial customer, this is the most important step, because that is when you need the infrastructure to be in place.'

Thus, demonstration projects are utilised by the firms in a market preparation phase and for technological learning, but the real issue lies in coordinating the step from demonstration to market. The problem is to coordinate infrastructure and vehicles. Since there is no infrastructure, there is no need to build a HFCV, and since no HFCV exists, there is no need to build an infrastructure. Vehicle development needs to be coordinated with the fuel side, and the mechanism for doing this is coordination through market networks. Close coordination between the actors for supply and demand thus reduces market uncertainty. The important issue of how to enable market coordination was emphasised by one manager in an OEM, who explained in detail the cooperation between the OEMs and the oil companies:

> 'Those cooperations, it's not about money, it's not about knowledge, it's not about us building cars and them drilling for oil, it's really for a good understanding, to create a common understanding of what we need to do together. We cannot introduce fuel cell vehicles into the market if the infrastructure is not ready. You would not introduce an infrastructure if there are

> no cars, so what we argue is that we do this together. And to do this we have to be motivated.'

The strategic discussions between the fuelling side and the vehicle side are clearly important for the market formation process. In discussing this with several informants, it became clear that matching the fuel supply with the vehicle side is not always an easy task, as the perspectives of the prime movers might be different. One interviewed manager in an oil company explained that the OEMs spend a lot of money on R&D for commercialising the vehicles and they push the energy industry to do the same. The issue, then, is for the infrastructure companies to 'to match the number of vehicles with the number of stations'. The challenge is thus to time the development of vehicles with that of infrastructure, and this relates to the size of the infrastructure and to the geographical areas for infrastructure development. Ideally, the size of the infrastructure should match the number of vehicles and be located in an area where maintenance support is available.

In order to reduce market uncertainty for HFCVs, the actors have initiated discussions to coordinate and align perspectives on supply and demand. These discussions also involve policy makers, to ensure that they develop the proper policy framework in line with the industry strategy. These strategic discussions leading to the alignment of actors clearly help to reduce market uncertainty.

Market coordination in EU projects

This section discusses in more detail how market coordination takes place in order to plan the required steps from demonstration to market. The key actors that develop market strategies for HFCVs stress two EU projects as having an important role in coordinating market preparations and linking demonstrations to early market deployment. These are the two EU-supported projects HyWays and HyLights. Information from these projects helps the actors estimate the size of the markets, the number of vehicles and filling stations that the cluster of users needs and what their performance criteria are for adopting the vehicles. One manager in an OEM highlights their importance and states that these projects are 'looking at the wider use of hydrogen and what kind of let's say strategic prerequisites have to be found and met'. The identification of demand requirements for early users is an important issue for market preparation, as the status of the demand for hydrogen consumer vehicles is unknown.

The OEMs do not have the necessary insights into what customers want, for instance whether they are willing to accept a performance gap in relation to a conventional vehicle. In order to make an assessment of the demand for HFCV, the HyLights project is conducting an estimation of the requirements of early users and the expected demand for vehicles. The project measures the minimal technical performance requirements that stakeholders have for hydrogen vehicles and collects data by conducting interviews with selected stakeholders in several European countries. The aim of the project is to determine the required vehicle performance level through a set of pre-selected technical indicators and qualitative information.

In the HyLights project, the researchers cluster the various stakeholders according to the companies' different target groups. These target groups for early markets are: (a) governments, (b) postal delivery, (c) energy companies, and (d) public transport. These users, then, are the large fleet operators, the governmental fleet managers, public transport operators and energy companies. This research is a key preparation for the next generation of vehicles, and these are the first vehicles to be in customers' hands. Therefore, the OEMs need to assess the demand profiles of the companies to be able to deliver a satisfactory product. This strategy relates to the fleet vehicles, as this is a 'cluster of vehicles' requiring minimal infrastructure development, in contrast to the consumer market, which requires a massive infrastructure. The firms involved can then expand the clusters at a later stage and connect infrastructure clusters with other clusters along highways.

The estimation of demand by early market users is an important tool for the end-use integrators in planning for the market introduction of vehicles. These projects thus help to build stability for the actors in terms of providing crucial information on early market demand. This is essential knowledge, required for scaling up from demonstration to larger demonstration and thus to market introduction. When demand requirements are analysed, market uncertainty is reduced for firms, thus creating stability for the actors involved.

Coordinating hydrogen supply for vehicles

One of the crucial aspects for stabilisation of the market for fleet and consumer vehicles is to coordinate the supply of hydrogen with the vehicles. Any user expects to have a satisfactory fuel supply that is similar to that of gasoline and diesel today. There are strong network effects on this market, so that the benefits of using a technology increase when the number of users increases. Hydrogen vehicles, as well as all other forms of vehicles, are networked products, i.e. several products are inter-dependent. This makes industry coordination of infrastructure and fuel supply crucial for success. This section investigates how the actors for HFCV coordinate fuel supply.

Most of the demonstration hydrogen filling stations operate under the brand of one of the major oil companies. The industrial gas companies and specialised hydrogen technology suppliers deliver the necessary technology and the hydrogen. The key relationship here is then between the retail function and the production function. The situation for hydrogen distribution thus seems to be one in which the incumbent actors, that is, oil companies, are leveraging on their capabilities in consumer retailing, marketing and end-user distribution channels, as well their existing infrastructure with existing gas stations. This enables them to create a transition from being a petroleum-based to being a hydrogen-based transportation system (or more likely a combination of different fuels).

The newcomers in hydrogen distribution are the industrial gas companies, which have existing production capabilities in industrial hydrogen but no experience in consumer retailing of hydrogen. The industrial gas companies have the skills to provide the product from production to distribution, and the oil companies provide end-user retailing, marketing and brand names. The industrial gas companies have a vital role in setting up the initial infrastructure based on the existing pipelines. These companies already have a large infrastructure that also includes hydrogen, and these companies can easily supply the first applications with the existing hydrogen. In scaling up from the initial test markets to larger markets, however, there will be a need for additional facilities. As a manager in an industrial gas company explains:

> 'Of course when these become markets, not with thousands of cars, but tens of thousands or millions, additional hydrogen production facilities need to be built. And also hydrogen needs to become a sustainable energy, so future cars, let's say when consumers drive cars by the millions, hydrogen cannot come from natural gas only.'

Clearly, then, issues about how to develop the larger infrastructure as well as the decision about the production method of hydrogen need to be decided upon for stabilisation of markets. The question of the production of hydrogen is highly crucial, and the stakeholders identify a clear role for policy makers in taking this decision. Another critical topic is to create consumer products from hydrogen, and one informant from an oil company clarified:

> 'The change from industrial to private use: that is one of the key challenges for hydrogen technology. I think sometimes too much emphasis is put on production, or compression, or purification. You really need to look at the end. Can we develop sensible, competitive or sexy products, using this technology?'

One question in the industry has been whether some of the technology suppliers will move downstream and build up retail experience in order to enter the market in an early phase through their own brands. However, there is no indication that the industrial gas companies will move into retailing of fuels. The companies see themselves as technology suppliers. Thus, in the market for fuelling hydrogen to HFCV it is evident that oil companies and industrial gas companies have complementary roles, where the oil companies specialise in retailing while the industrial gas companies act as gas or technology providers. Furthermore, there are already-existing relationships between gas companies and OEMs, because the automotive companies use hydrogen in their production process. Thus, there are stable and ongoing interactions with clearly defined roles for the hydrogen value chain from production to consumers, and the close relationship and division of labour between the various actors creates stability and helps to reduce market uncertainty. However, there is a clear role in the future for policy makers in deciding upon the production of hydrogen for large markets, ideally based on renewable sources to capture the environmental benefits of the technology.

Market entry strategies for fleet and consumer vehicles

Another result that emerged from the research is that in terms of market entry, different perspectives exist between the OEMs and the oil companies on first-mover advantages and the effect of being a late mover. Since competition in the auto industry is global, based on technology, with high development costs and sinking margins, the question of how much emphasis they should put on developing new technologies like hydrogen and fuel cells is a key strategic discussion for the firms. The same goes for the fuel distributors, though the situation seems to be different for them. One manager from an oil company explained this difference in first-mover strategies:

> 'The OEMs think more about competitiveness among themselves, that if they are left behind, they might not be able to catch up. Others have gone into the market. From our side, obviously, is hydrogen for transport big enough? Should we be doing it? Or is it too early, should we stop and see how the vehicles develop and then catch up later?'

This comment makes a point in that OEMs and fuel suppliers perceive strategic positioning in hydrogen for consumer markets differently, a late entrance being less risky for fuel producers than for vehicle producers. In the automotive industry, first-mover advantages in new technological areas are positive and can certainly lead to competitive advantages. One recent example is the case of hybrid vehicles, where Toyota commercialised these before any competitor had a similar product on the market. Toyota experienced a positive response from the market that led to increased sales. Spill-over effects into the ordinary car market are also most probably present, since Toyota is perceived as an innovative and green company (Austin, Rosinski, Sauer, & Duc, 2003). Time of entry with new technologies in the market and being a first mover are thus important considerations in this field.

The oil companies regularly evaluate the situation of new fuels. They asses the situation for fuels, trying to get a picture of what is going on and whether new opportunities are emerging. The questions they ask seek to assess the probability and size of markets for hydrogen as a transport fuel. One informant in an oil company explained how it perceives the strategic importance of hydrogen for transport markets:

> 'We ask should we be very proactive, continue at the same rate, or do nothing? So this is our strategy. If we do a lot, it's risky. If we don't do anything it's also risky, because hydrogen could be a fuel like gasoline and diesel 25 years from now.'

The same uncertainties regarding entry and markets are also present among the fuel producers. However, one difference exists; these actors control an already-existing infrastructure for gasoline and diesel, which can be used for new types of fuels. The issue thus becomes assessing the competing alternatives in fuel:

> 'We are evaluating hydrogen as a possible fuel, but we don't say that hydrogen is the fuel for transport. We are not there yet, so we evaluate hydrogen as one option we have in the long run. In the short run we have bio-fuels, cleaner fuels, compressed natural gas and liquid natural gas … and hydrogen is one of the options.'

From the fuelling side, then, variety generation is still an important activity, and it is considered to be too early for standardisation into hydrogen as a fuel. A manager in an oil company explains the considerations this firm has to make concerning the various fuels:

> 'Potentially this could affect our company, which is to make fuels; hydrogen is a fuel so that is why it is important for us. It's not for now but for the future, but what do you do? How do you stage the development? Do you go slowly, or don't you do anything and jump in later, then you lose maybe? Where is the value for our company to play in this game?'

A conclusion is that on both the fuel side and the vehicle side, companies create strategic options in FC&H2 technology, but both types of firms also operate with other competing technologies, such as bio-fuel, natural gas and cleaner gasoline. As one manager explains, 'With hydrogen, our strategy for now is that hydrogen has a potential as one of the future potential options. This is how you should capture it.' Thus, there is a clear difference between hydrogen as the sole fuel and as one of several alternatives. However, both the OEMs and the hydrogen distributors have made commitments to hydrogen as a fuel, though their perspectives on being a first mover might be slightly different.

Leveraging on Olympic Games to reduce market uncertainty for fleet vehicles

Olympic Games are important events that firms use to create long-term visibility and support for the long-term transportation sector. This phenomenon started in Turin in 2006, with the exposition of a HFCV and several fuel cell hydrogen scooters, and it will continue in Beijing in 2008 as the first 'Green Olympics', with the intention to 'strengthen public awareness of environmental protection and promote the development and application of new technologies'.[100] As part of the 2008 Green Olympics, a hydrogen filling station is set up to fuel the vehicles demonstrated. The idea of a green Olympics continues in the Vancouver Olympics in 2010, where a group of actors plans a hydrogen highway and the testing of several vehicles. In relation to this event, a fuel cell system integrator received an order for fuel cell engines to power up to 20 fuel cell buses for the 2010 Olympics in Whistler, British Columbia.

In Europe, the London 2012 Olympics also constitutes a continuation of the ideas that started with the 2006 Turin Olympics. Several key actors in the FC&H2 area have established the London Hydrogen Partnership, and these actors more clearly target using this event as a direct tool for market formation. The actors plan to use the procurement from the Olympic Games to lay the foundation for the market for hydrogen vehicles to emerge. An important issue for market formation is to reach the first users so that the OEMs have the volume

[100] <http://www.solarcities.org/beijingolympics.htm>, accessed 18 June 2007.

needed to start mass production and thus to reduce costs. The commitment from the OEMs, however, requires stability in the early market to reduce market uncertainty. The partnership writes in a position paper that:

> The scale-up of production will only occur once sufficient end users and associated refuelling infrastructure are in place or firmly committed. It is highly likely that there will be sectors of the Olympics fleet which fit with manufacturer's ability to produce commercial hydrogen vehicles in 2012 (notably urban buses, light buggy type vehicles and passenger cars). If carefully managed, the procurement of vehicles for the London Olympic Games has the potential to act as a part of the process of unlocking of this scale-up vs. demand vs. fuelling infrastructure situation. The lasting legacy of a commitment to hydrogen vehicle deployment at the Games could be the initiation of the commercial phase of hydrogen vehicle technology.[101]

Clearly, the actors in the partnership intend to use the Olympic Games to support the build-up of infrastructure for fleet vehicles, which can sustain the early markets for OEMs and fuel suppliers. Thus, the early markets is stabilised through market networks created in conjunction with the Olympic Games, where the OEMs get the demand they need to ramp up production. A further effect of these events is that they have an important role for establishing the legitimacy of the technologies, as their visibility at Olympic Games is immense.

The analysis in section 8.1.1 indicates that the strategic discussions between the actors align their perspectives, helping to reduce market uncertainty. The key step for the companies is to be able to create initial markets for their technology and to do that, the coordination of fuel and vehicles must be in line with the strategies of the various actors.

8.1.2. Market networks for auxiliary power units for caravans

In this section, I discuss the market networks for auxiliary power units for caravans. I use the examples of some of the key system integrators

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[101] <http://www.fuelcellmarkets.com/article_default_view.fcm?articleid=13978&subsite=1676>, accessed 12 August 2007.

in Europe and show how they build up market networks for their technology and the issues involved.

Market formation with real products

First, a key element the firms consider is to establish credibility in user markets for creating 'real products'. Thus, they mention the need for real products to obtain contracts with the user markets. The system integrator firm states that in its view, a big problem in the fuel cell industry is that

> 'firms start building fancy prototypes which they financially cannot translate into a sellable product. So that is what where of our corporation energy goes, to make the technology as it is commercial.'

This comment points to the key strategic focus of this firm, that it sees the opportunities of the technology today, the limits and opportunities, and then finds the market in which it can leverage on these opportunities. This is quite a different strategy than finding a technology to replace an internal combustion engine or a gas boiler and improving it to a stage where competition is possible. Thus, the firm focuses strongly on the commercial aspects and targets niche markets in the applications where fuel cells can deliver real value for the users.

This conclusion has led this firm to target applications with additional performance and similar costs. A manager explains that any technology that is to replace an existing energy technology needs to be in the same price range, because it is not realistic to expect that a new technology will be successful when it is ten times as expensive as the older one.

One company in particular has been very successful in targeting the user markets for auxiliary power units. The strategy of this particular company is to find immediate market opportunities. In discussing its market strategy, the company stated that its approach was to create a 'unique selling point' (USP) for the user, where fuel cells are a real, competitive product the market. A manager in this firm explains how its product gives value to its customers:

> 'The applications that we are active in have a real USP. Just an example, the caravans, they are limited to one or two days at the camp, and they have solar systems which don't work at night, they don't work in bad weather, so it is not a very reliable energy source. And then they have generators that don't make you very popular with your neighbours, they smell, they make a lot of noise, and there is nothing else. Now there is the fuel cell, and that is why we are so successful, because we generate a real USP.'

The firms use the benefits of the DMFC to convince users about the technology. To develop a market for fuel cell products, the firms need to identify areas and applications where the technology offers the users clear benefits. In this sense, the auxiliary power units based on the DMFC offer benefits to caravan users in several ways. One interviewed manager highlighted that the main benefit to the user is not economic and not the environment but freedom, 'freedom not to have to go to a campsite to get electric power for the caravan'. Thus, the fuel cell product gives added value to the user in the form of an experience of freedom.

A manager in a first-mover firm in this field of fuel cells explains that its market strategy is to enter into cooperation with producers of those systems that are being used and that it aims 'to really produce that product in a way that makes sense for fuel cells, A, technology-wise and B, commercially'. Thus, this firm tries to maximise the fit of fuel cells in the markets it can reach first by having a realistic view of where it is able to make money and by finding the right partners.

Second, another finding in this application area is that the key actors are frequently not present in technology-specific platforms and industry networks, such as the HFP, but focus instead on creating links directly to the user industries. These firms establish market networks to integrate the auxiliary power unit applications directly with the users. When explaining this relationship, a manager said:

> 'They are our OEM. So fuel cells have become their product to the outside world, basically. But technology from us is inside, and that is basically how we see what will happen in many markets in the future,

> because we are more like a battery supplier, we supply energy, not the whole application, but the energy that makes the application possible, so it is always smart to team up with application experts.'

Clearly, the approach of this firm is to utilise the market knowledge of the various application experts and establish long-term relationships. Such firms minimise market uncertainty by targeting markets that are a good fit with their technology.

Entry strategies for the leisure market – leveraging on events

For the auxiliary power unit applications, conferences and fairs are important for establishing the market networks. This is because a basic feature of this area is that the firms employ existing technological knowledge in new market contexts. Results from the interviews show that the firms that target the auxiliary power units market operate with a strategy to move directly to where the market context fits with the performance of the technology today. These firms present their technology by attending user industry conferences, fair and events. For instance, there are specific caravanning conferences and fairs, where fuel cell system integrators show off their technology.[102] A manager in a system integrator elaborates the firm's particular view on conferences and fairs:

> 'We did that more in the past. Now that we are becoming more commercial our energy goes more into business networks, and into the networks of our customers, and that is a very interesting shift that we are noticing. Because before, we were interviewed for entrepreneurial excellence and start up, etc., so people would be excited about the idea, and we were participating in fairs showing prototypes like everybody else does. But now we feel that when we go to fairs we go to commercial fairs and we go there with a product, and we rather tend to present our prototype one-on-one so we know that they actually meet the expectations of specific partners, and commercial success is much more important than image was when we started. And that's something that we are noticing very strongly, and that is the

[102] In addition, these firms have a broad market-oriented focus and visit police fairs, military fairs, sailboat fairs, etc.

> classic stage between a technology developer and a commercially successfully company.'

This shift from technology-oriented networks to market networks means that the firm shifts from participating at conferences and fairs that are specific to fuel cells and hydrogen, to user-oriented fairs. A manager confirms this and explains:

> 'Yes, we would go to Fuel Cell Expo in Japan, but we did not go this year, we did not go to the Hannover fair this year, now instead we will be on several caravanning fairs, on sailboat fairs, we will be on police fairs, several military technology fairs, we went to Milipol in Paris this year. So we see the focus is shifting.'

This is quite interesting, since the shift towards user-oriented conferences and fairs creates visibility for fuel cell products and reduces market uncertainty for the firms as they create market networks directly with users.

Market identification

The analysis of the market strategy of these firms shows that they have a strategy of moving from one market to the next market; as one states, 'It is a niche market, caravanning, and we are highly successful, and it works as a door opener into other technologies and markets.' Clearly, firms use niche cumulation as they move from one niche to another, and in doing so, gradually increase the size of the company. Having success in one market creates legitimacy in relation to other user markets, that their fuel cell products actually function well and generate benefits for their users. However, these firms tend to avoid applications with network externalities, as this requires more coordination towards infrastructure partners and policy makers. Clearly, the stabilisation mechanism of 'market networks' reduces market uncertainty by convincing the users of the benefits of the technology as well as by being price competitive towards the incumbent technologies.

8.1.3. Market networks for forklifts

The firms initiate the market for hydrogen fuel cell forklifts by using market networks between users and producers. The most important links are those between system integrators and the user markets in which the technology operates under market conditions. This fact makes the time from demonstration to market short; in some cases, such as the auxiliary power units for leisure vehicles, the technology is already market driven, while the forklifts are in the stage of moving from demonstration to market deployment. The fact that the application is market driven also leads to a low degree of coordination with policy makers.

Forklifts are a niche market, but niche markets do not necessarily mean that their size is small: 'The niche markets for us are huge, they are specialised trains for buses, trucks, forklifts, etc'. The market for batteries for forklifts has been estimated by companies to be about €1 billion, and thus companies see opportunities to capture a share of this market.

The hydrogen fuel cell forklifts offer clear benefits for the user and do not require market support. Several firms are currently beta testing the technology, which is now moving rapidly towards the marketplace. An analyst specialised in fuel cell applications explained why these applications have become so popular for system integrators:

> Why PEM fuel cells are being targeted into this space is easy to understand. In an enclosed environment a vehicle cannot give off emissions. Currently battery technology, which requires a lot of storage capacity and change over time, is the incumbent. PEM fuel cells, with their ability to be refuelled in minutes, high speed performance and zero emissions profiles are a clear competitor to the battery technology. This can be seen by the growing list of companies either trailing or ordering fuel cell powered forklifts. (Adamson, 2006)

The effect of these market opportunities is that system integrators developing fuel cell systems for transport applications suddenly have a more short-term market to target. It can also mean that large companies involved in the materials handling industry will acquire small, specialised firms for fuel cell and hydrogen technology in order to access key knowledge and technology as a way to shorten the road to market. Accordingly, there is a considerable increase in numbers of fuel cell-powered forklifts in the last two years as beta testing is being completed by several companies which are scaling up for production. Thus, the expectation for this market niche is rapid growth before 2010.

A key factor that makes fuel cells attractive in this market niche is that the infrastructure requirements are quite manageable for firms, and one fuel supply point can refuel several forklifts. There are therefore clear benefits from deploying fuel cells in this market niche, and 'companies working in the fuel cell field have noticed this opportunity and are moving fast' (Hugh, Todd, & Butler, 2007).

I will present the market network building of two leading European system integrators involved in hydrogen fuel cell forklifts to illustrate this example. The first is one of Germany's leading fuel cell system integrators, already offering fuel cells for various vehicles. At the present time, the fuel cell system integrator is stepping up its activities in terms of commercialisation, for example through the expansion of its production facilities and a move to a larger site. A manager in this firm explains, 'We've completed the step from the testing laboratory to real, practical situations. With our technology, automated and inexpensive production is now possible.' Clearly, the difficult road beyond prototyping and demonstration has begun.

Several firms have demonstration projects ready to take the step into market introduction. The most notable is a project at an airport in Germany where several companies, including a fuel cells system integrator, a hydrogen supplier, a forklift producer and a logistics company, have demonstrated a prototype in daily operation. This successful project leads to further contracts for several industrial vehicles with fuel cells and to continued development of fuel cell hybrid solutions, with a new storage configuration.

A similar project is in operation in Denmark, where a system integrator first produced an H_2 fuel cell truck prototype in 2004 and started pilot testing 7 trucks in 2006. This further led to scaling up to larger demonstrations in the range of 50 to 100 systems, and awaits early markets.

It is clear that that the step from demonstration of one or a few units to market introduction is very uncertain, but in this area, given the particular benefits of fuel cells and the ease of handling infrastructure, the actors have little market uncertainty. This is an example of how fast the route from a demonstration project to an early market can be when a firm gains stability in terms of technology (manufacturing cost) and market uncertainty by interacting directly with the users. The firms thus get a sense of control in the market, which leads to stable market conditions.

8.1.4. Market networks for micro CHP and large-scale power production

This section explains the market networks for micro CHP and large-scale power production. These applications share certain similarities and uncertainties, and thus I analyse them together. The latter is a technology that targets replacement of the existing large-scale power technologies, while micro CHP means that energy is produced on site in small businesses and multi-family or single-family homes. Energy production is thus decentralised or distributed, which means that the business model of centralised power production is disrupted, or at least that variety is created in terms of power production.

In the distributed energy business model, the consumers produces their own electricity and heat, based on natural gas, or in the future possibly also from hydrogen. The shift means that consumers provide their own electricity from natural gas from their energy companies. With a traditional gas boiler, the consumer would buy natural gas for heating and electricity separately, from centrally located power plants. The consumer can also sell surplus electricity back to the grid if the right framework conditions are in place, such as feed-in laws to the grid. The micro CHP system thus has several advantages to offer consumers.

Furthermore, the market for natural gas fuelled wall-hung heating appliances is large. The yearly sales amount to over 2 million appliances, and clearly a future market exists for fuel cells for domestic co-generation. Several European firms are active in the micro CHP field and large demonstrations have been set up, in large part in Germany. The fuel cells the system integrators use are PEMFC and SOFC.

PEMFCs are generally more developed than SOFCs, which exist in beta field demonstrations around Europe. While Europe is considered to lead the market in SOFC system development, it has a weaker position in PEM system development. For instance, many of the PEMFC systems demonstrated in Europe are North American.

Market uncertainty

A key barrier identified with power production is the potential for inertia in the market. The market is controlled to a large extent by a few actors, and as one manager explains, 'These companies could use their market monopoly to keep renewable technologies out of the market to protect their own investment.' For instance, companies with vested interests in Europe might not be interested in competing technologies, as these will devalue their investment. The company strategies are thus to make partnerships based not on direct competition but on creating synergies. As one manager clarifies, 'We would like to persuade them to have existing technologies plus new technologies, and we believe governments will help drive this.' Thus, micro CHP is not in direct competition with incumbent energy technologies, but more an additional energy source.

Market building networks

For both the micro CHP and the centralised power production markets there are many alliances and projects between fuel cell system integrators, gas distributors and utility companies. The key actors in the micro CHP area are the fuel cell system integrators, the heating and power companies, and finally the energy and utility companies, which own the rights to distribute energy. Some of the largest gas distributors and energy companies in Europe are pursuing distributed energy, but a problem has been the lack of clear commitment, such as participating in the proposed Joint Technology Initiative (JTI), which has a clear majority of fuel cells system integrators and less interest in actual market introduction. Some of the energy companies in Europe also have signalled their interest in transport applications and not stationary power production.

In terms of market cooperation, the fuel cell system integrators involved in the micro CHP example regard cooperation with utilities as important on the market side. EU projects like the Virtual Fuel Cell Power Plant have made great advances and besides that, system integrators currently have approximately 15 agreements with utilities and distribution firms. These cooperative relationships are with local utilities in Germany and utilities in seven countries in Europe and aim at providing fuel cell systems in different buildings. A manager in a system integrator explains the division of labour in the market formation process and the role of the utilities and distribution companies:

> 'They are responsible to select the buildings, make the contracts with the owners, and so on. Selling the heat and power. This is a very important partnership. Because the energy distribution companies play an important role, or could play an important role, in the market for micro CHP.'

As such, the cooperative relationships with the utilities and energy companies are crucial for stabilising the market uncertainty for the system integrators.

Regulative uncertainty

One uncertainty for market introduction that several system integrators mentioned is the problem of grid access for new technologies. This can be related to the regulation of the electric grid and the fact that only a few actors are allowed to supply energy to the grid. In terms of de-regulation and grid access, the energy sector is comparable to the telecom sector, because the fuel cell system integrators need to have what they call 'fair access' to the public electricity grid. A manager described experiences from Germany with other CHP technologies where people purchased a product, such as an engine installed for about €15 000. The customers then received a letter from the energy distribution company saying that it needed to install a centre so it could shut down the system via radio control when it had a problem in the grid. Thus, due to grid regulation, the energy production is not distributed to the customers. The firms explained that another problem regarding security and safety was the intensely discussed issue of overload of the grid. As one informant explains:

> 'When too much electricity in the grid is given, for instance from wind turbines, and because of German legislation there is a ranking of shut down of systems in the grid. And the renewables have priority before micro CHP, for instance. So there is really a discussion here if the utilities have to have access or the micro CHP systems producing 1kW of electricity and I think this is not technology related but policy related.'

The situation for large-scale centralised power production is similar to that of the micro CHP. Both applications are reliant upon establishing relationships with the energy distribution companies that control the market interface. Similar statements coming from large-scale centralised power production clearly point to the fuzzy regulation of energy markets in Europe. To exemplify, a manager in a system integrator focusing on large-scale applications explains:

> 'We want distributed energy, but for that to happen the market needs to be de-regulated. For in Europe it's a mix of regulation, de-regulation, and the UK, it's the easiest market to operate in. In the US, which will be our initial market, that's where we think the utilities and power companies will be able to make their decisions about where they can buy products from.'

The manager states in addition that fair access to the grid for new technologies means that consumers get the freedom to use the technology they want to use to produce their energy. Thus, an implication is that firms perceive that, 'many ideas are around, but de-regulation has to happen first.' Clearly, the fuzzy regulative situation with new technologies that do not enjoy grid access is a serious uncertainty for the market formation of micro CHP as well as for fuel cells in large-scale applications. A related uncertainty is the lack of knowledge among consumers about the possibilities for micro CHP. In houses which have a natural gas fired heating boiler, people can install a CHP system instead. The CHP system, in addition to producing heat, will also produce electricity. However, according to several system integrators and end-use integrators in the field, consumers' knowledge about this possibility is limited, thus creating additional market uncertainty.

Market networks with policy makers

One instrument that can reduce market uncertainties is to create market networks that also establish links to policy makers. Policy makers are the actors able to de-regulate the market and provide the right framework conditions for new energy technologies. One informant explained this process:

> 'What is also important is lobbying towards policy, for instance for micro CHP, to get the right framework conditions and not the wrong one. So it is not really decided if the framework conditions for micro CHP, especially not if you are looking at Germany. We need a key decision from industry, that a key character of micro CHP is decentralised production of electricity – is really a target the nation wants to support or not. Because this is the field of the energy distribution companies and the biggest one of Europe is here in Germany.'

Most firms actually highlight the important role of policy makers in relation, first, to de-regulation and grid access and, second, to encouraging environmentally friendly technologies: 'We also believe the government will help in not only de-regulating the market but also actually providing incentives for greener, cleaner and environmentally friendly technologies.'

In order for this market to evolve, clear strategies and commitment are required. The strategic discussions between the fuelling side and the fuel cell system side take place in industrial networks, where the German Initiative for Fuel Cells (IBZ) and HFP clearly play an important role for stabilisation of market uncertainty.

In discussions about this with several informants, it became clear that matching the supply with demand is not always an easy task. As one respondent said:

> 'The question you are targeting is really open, if the energy distribution as a whole or a significant share of the industry will really contribute and support, that is an open question for me, there are utilities that we cooperate with yes, and a lot of companies contribute in the different platforms. But the decisions to support this in a big scale have not come yet. So at the moment it is open.'

Evidently, there are no easy answers on the commitment from the user industry in this market. The key strategies for firms approaching the large-scale power production market are, first, to get the technology working and, second, into the marketplace. According to key actors in this field, the market 'already exists'. The key uncertainty, however, is a matter of getting the technology working and solving the technological bottlenecks. So basically, when the technology performance is sufficient and costs are feasible, the market can be approached. This is because the business model of large-scale production is a continuity of the centralised power production in which the companies sell electricity to consumers; the model thus fits into the existing energy regime and is not a change to a distributed production regime where the consumer produces electricity and heat from the natural gas infrastructure.

The market coordination happens between fuel cell system integrators, energy distributors and local installers, and is organised in the form of EU projects and national or regional projects. Given this, business development is less the result of bilateral agreements and is more formalised in networks including governments. This is a result of the institutional complexity of codes and standards, and not least, market regulation. The market formation process base relies on the technology's soon being able to provide customer benefits, with public support. The applications that target direct replacement of an incumbent technology are reliant on strong policy support as well as technological breakthrough.

8.1.5. Market networks for telecom back-up

The telecom market is now actually a small early market in which several firms are selling products to customers. The installed systems are based on PEMFC technology and run on hydrogen. The potential market is quite large and increasing rapidly. At present, units are being sold and installed on the market, with mass production scheduled before 2010 by several system integrators. Its technological maturity and performance make the technology competitive at the present stage in some applications. Cost sensitivity is not a problem, as back-up solutions for the telecom market have high prices (~€1 000/kW). Because the telecom back-up market has high cost acceptance and a need for limited infrastructure, 'this product group is a good way to create business opportunities and at the same time avoid network externalities like the complexity of hydrogen infrastructure'. The user firms, moreover, are satisfied with the performance of the fuel cells at the present stage. Thus the business proposition that fuel cells offer in this market is increased performance at a lower or at least similar price.

In a paper discussing this market application, a North American fuel cell system integrator explains the advantages of fuel cells, that is, *cost* and *reliability*, as well as the particularities of this market application for fuel cells:

> Telecom service providers are a demanding bunch, and reliability is up there with price as a 'must-have' for any new technology. In this respect, remote-monitoring functionality built into the fuel-cell systems provides an additional level of confidence, automatically monitoring the status of key indicators such as system usage, start/stop, voltage, loading, fuel status and environmental conditions. (Ernst & Nerschook, 2004)

Thus, the telecom sector is used to adopting new technologies and making use of IT systems to increase functionality. The alliances between telecom firms and fuel cell system integrators have been very successful in identifying and responding to market needs and technological possibilities, as is evident in the fast route from initial testing to market deployment.

The key stabilisation mechanism in the telecom back-up market is to establish strong market networks with the user industry. Results show that several fuel cell system integrators have entered into strategic alliances with manufacturers of complementary technology, and with users and suppliers of telecom equipment. Two different market strategies of leading actors in Europe are presented here in order to analyse the market networks of the telecom back-up example. The first is the market approach of a German system integrator, considered an industry leader, that leverages on bilateral agreements on the market side and system integrator capabilities on the technology side. The second is the approach of an EU-based consortium consisting of firms from the telecom sector as well as the fuel cell and hydrogen sectors.

The first company I use as an example is a German system integrator, which is a market leader in the telecom back-up market. The company started serial production in April 2007 after having validated its technology in various field tests with international mobile-network providers since 2004. The serial production is a response in order to keep pace with the growing demand it experiences from the telecom back-up market.

The company develops market networks with end-user partners, some of which are the major telecom firms in Western Europe, Asia and Africa. As a manager explains, 'We are working together with power suppliers but also we are working together with MNOs, from Germany, South Africa, and telecom firms. These are our key partners.' The company operates with more than twenty firms as partners, and has little focus on basic R&D, acting rather as a system integrator. Market development is explained to be a result of the following:

> 'For our product it is high viability compared to a battery system, and high cost reduction compared to batteries, and to remove batteries because of toxic materials inside batteries, and to have higher back-up time, that is the interest. Power and energy, and easy to scale up with the hydrogen bottle.'

Thus, the company is able to offer the users environmental benefits as well as improved performance.

One market uncertainty relates to the development of a logistics system for replacing the hydrogen bottles that provide power to the back-up system. The need to refill the back-up system is dependent on the stability of the energy system in the country. For instance, in Germany the grid has few blackouts and requires the instalment of few bottles, while in Portugal the grid loss time is close to 600 hours for one year. Since each bottle lasts for 8 hours of back-up power, the firm needs to refill the bottles quite often in countries like Portugal. Thus, the more unstable the national grid, the more advanced the logistics system the firm must develop for replacing the bottles. A key relationship for market formation is therefore in hydrogen technology, where the system integrator collaborates with a major European industrial gas company. This collaboration ensures European-wide logistics coverage and refuelling of the hydrogen bottles. Thus, the partnership solved the uncertainty about logistics for Europe.

Another market uncertainty for the firm is to achieve cost reduction. The system integrator firm highlights:

> 'We have a product but we did not reach our target costs and we know we can reach them if we sell 5 000 units per year. The problem is that not everyone wants a fuel cell system for €14 000 but maybe for €3 000.'

This firm is one of the first with a product on the market, and even though the price still is high, the firm does manage to sell the system to early users. The market then gradually expands as the technology matures. The firm does not view this barrier as particularly problematic, because as the manager explains, 'It is not so much. It is 5 times. Compared to fuel cell for autos, the price difference between ICE and FC is much larger.' Clearly, the cost issue is not a source of market instability for this example.

The other example is a consortium that includes a Danish system integrator in conjunction with several major telecom base station owners, base station producers and energy companies. The consortium targets the European market for UPS in the telecom sector and uses a fuel cell system provided by a North American producer. The users have shown their commitment to fuel cells in this example by placing orders for some 300–400 systems.

The current stage of maturity is field demonstrations, but as the company states, 'We provide backup power solutions available for sale today to customers who see the compelling value proposition fuel cell technology provides to the telecommunications market.' Thus, the market already exists. The close links between the system integrator and both the base station users and producers show the commitment of these users to seriously implementing fuel cell systems into the telecom sector. Thus, the market networks are operating well and secure stability for fuel cell system integrators and end-use integrators.

Leveraging on conferences and fairs

A key stabilisation mechanism for the market formation processes of this application is 'conferences and fairs'. The actors pursuing this market strategy do not participate in technology-specific platforms and industry networks such as the HFP, but focus on creating links directly to the user industries. The firms tend to attend or present their technology at user industry conferences, fair and events. For instance, there are specific telecom conferences, where fuel cell producers show off their technology: 'We are more focused on the application, we don't participate in the fuel cell activities but more for telecom platforms.'[103] Another informant confirmed this view on conferences and explained: 'We go directly to the application areas, user conferences to establish links with users and are not active on the fuel cell milieu in that sense.' The basic feature of the applications for telecom back-up solutions is thus simply that of existing technological knowledge applied in new markets. The key for reducing market uncertainty is to develop market networks to telecom base station owners, which the firm approaches at telecom-specific conferences and fairs.

8.1.6. Market networks for by-product hydrogen

Several system integrators in Europe target the use of by-product hydrogen as a niche market for large-scale stationary fuel cells. One of the key features of this market is the size of the system, because, as one manager explains, 'The sale of one plant is like a thousand portable systems.' As a consequence of the size of one system, the firms need few agreements with users to generate substantial revenues. The market networks that these system integrators establish are with the large

[103] This example is similar to the approach taken towards the leisure market, and with the police and military fairs that are also visited by the firms that have a strong user-market-oriented focus.

companies that produce chemicals and have hydrogen as a by-product in their factories. These chemical firms can use the hydrogen directly, employing it to produce electricity for the factory. Since the chemical production processes are energy intensive and hydrogen is a residual from the production, the stationary fuel cells can create synergies between these factors and reduce the total production costs. Since producing electricity from hydrogen also is emission free, it reduces nearby pollution from the electricity production.

This section presents the market strategy of a leading system integrator for using by-product hydrogen in chlor-alkali factories. The key advantage of this firm relates to the fact that legitimacy is crucial for gaining access to the users. This requires a belief on the part of the potential user of the fuel cells that the system integrator has the skills not to disrupt factory production. A manager in the system integrator explains:

> 'We provide the core competence. We have agreements with the two biggest chlor-alkali producers. We can provide the expertise to integrate this inside a chemical plant. Because if you go to a chemical plant as a fuel cell producer they say, ok, your technology is fine, but stay away from my plant because I need to work and cannot stop production.'

This example shows that the management in factories might have concerns about possible problems in their production process when the fuel cell system is being installed. Since the factories run continuously, factory management wants no disruption to the process. Being able to maintain production is thus a serious barrier for installing fuel cell systems. This particular fuel cell system integrator is in fact part of a larger industrial corporation that also constructs chlor-alkali plants and as such, uses that corporation's market networks to enable discussion with the chlor-alkali plant owners. Having already-established cooperative relations enables trust between the partners, and the system integrator uses this trust to leverage into the hydrogen market.

The manager explains that if the chlor-alkali plant owner then agrees, this agreement is based on the fact of the trust from previous cooperation with the corporation that possesses competence in factory construction: 'OK. I trusted you because you know how to do it. So this is what we are doing.' The complementarities between the fuel cell division and the plant manufacturer are vital for success in the market. The manager explains the division of labour between them:

> 'We provide the module and they are the main contractor to the customer providing the system, including the fuel cell to balance the plant. They have the customer base, the channel to the market and most important very good technological capabilities, because now they are one of the three big players in the production of chlor-alkali plants.'

The system integrator firm explains, further, how it uses this market as a bridge to other markets and what its interest is in this particular application:

> 'So why are we in the chlor-alkali plant? Because we have an immediate market today, but in the intermediate to long term we can use the same system, and link to, for instance, hydrogen coming from renewables.'

Thus, it can use the platform to accumulate in different niche applications and expand its activities. The key mechanism for market formation is the alliances the fuel cell system integrators create with the chemical companies. Furthermore, entry barriers exist in the form of the likelihood that chlor-alkali plant owners will choose a system integrator with which they have a previous relationship. Thus, it is easier to enter the market via a mother corporation than to do so as a start-up firm.

8.1.7. Forms of conferences, fairs and events

Market networks are a key stabilisation mechanism in many market formation processes. In the analysis of the two case studies, it became apparent that for several of the examples, 'conferences and fairs' play an important role in facilitating market networks. There are several reasons for this importance. One is the industry-specific role that helps establish the supply chains and, as such, is technologically oriented. Another has to do with establishing links to user markets in which demand and supply of new technologies find novel use. These events might be the turning point, as a novel technology might find the right market context for utilising the technology-to-be. For stationary and transport applications, then, conferences and fairs have an important function for market evolution. Some firms use conferences, fairs and events as a specific form of market network, and key for them in building initial markets for their technology. This section analyses the various forms of conferences, fairs and events that the firms examined in this thesis use. The analysis of conferences and fairs shows, in fact, that they serve quite different purposes for firms in the various market applications. For example, the actors working with forklifts were not using conferences and fairs as a market development activity in the same way as the actors for the auxiliary power unit applications in the leisure market. I present three different types of conferences and fairs that emerged from the analysis in Table 8.1.

Table 8.1: **Forms of events, conferences and fairs**

Type	Purpose	Example	Perspective	Goal
Fuel cell specific	Supply chain	Fuel Cell Expo	Long term	Tech. learning
Public event	Initial demand	Olympic Games	Med. term	Visibility
User specific	Build market	Milipol	Short term	Market entrance

Source: Analysis of firm interviews.

First, the fuel cell-specific conferences and fairs are important for firms to develop technological supply chains. The time horizon is long term, with the firm's goal being to enable technological learning. Here materials firms and component suppliers meet the system integrators and OEMs involved in all applications areas. The applications are all fuel cell and hydrogen technologies and involve relations that include technology development. Second, firms use public events like the Olympic Games to create an initial demand for their technologies. In relation to these types of events, the organiser employs new, promising technologies to show the world their possibility. Thus, they constitute an initial demand for the firms and create visibility for the firms, for their technology and for the proactive conduct of the organisers. The time horizon is typically medium term, with the target of increasing the initial demand by enabling market networks with local early users. The applications are fleet vehicles (as a step towards consumer vehicles), as well as small-scale stationary units for powering niche products in relation to the event (as a step towards micro CHP). Finally, the user-specific conferences are organised around particular product groups such as for sailboats, caravans, materials handling and telecom, as well as for public users like the military and the police. The purpose of these events for the system integrators is to build a market instantly. The events provides them with an opportunity to present the benefits of their technology directly to users, and thus to enter the user markets. The perspective is short term, with direct market entrance. The applications are leisure market APUs for caravans and sailing boats, forklifts, and all types of military and police applications.

8.2. Hybridisation

The topic of this section is how firms use hybridisation as a stabilisation mechanism to enter into markets in the formative phase of a TIS. Hybridisation relates to the combination of two or more different things and is aimed at achieving a particular objective or goal.[104] Hybridisation for FC&H2 technologies occurs in several ways, such as combining battery and fuel cells in a vehicle to improve performance or using existing codes and standards for new purposes, such as for new technologies.

In this section I present the role of hybridisation for the various applications. Hybridisation plays an important role for some examples of FC&H2, more precisely, for fleet and consumer vehicles, which I present in section 8.2.1. The niche transport applications of forklifts and auxiliary power units for the leisure market I present together in section 8.2.2, as these share similar characteristics. In 8.2.3, I discuss hybridisation in the micro CHP example, and in section 8.2.4 I investigate how actors use hybridisation for the examples of by-product hydrogen and telecom back-up. Finally, in section 8.2.5 I elaborate the findings from this analysis and present a new taxonomy of hybridisation.

[104] <http://en.wikipedia.org/wiki/Hybrid_%28disambiguation%29>, accessed 11 December 2007.

8.2.1. Hybridisation for fleet and consumer vehicles

The role of hybridisation for fleet and consumer vehicles is limited to the vehicle side. The industry has decided to pursue hydrogen as the sole fuel in connection to HFCV, and not methanol, a solution that the OEMs explored in the late 1990s.[105] A manager in an OEM explained that the industry decision to focus on hydrogen came about as a result of the California Fuel Cell Partnership.[106]

Only one OEM operates with a hybridisation strategy using gasoline, reforming this to hydrogen in the vehicle. This strategy is developed to avoid the effects of infrastructure needs on the network and still have high efficiency and reduced emission of climate gases. The other OEMs are doubtful if this is the right strategy because they experience gasoline reforming as inefficient and because it does not reduce oil dependence, which is one of the key motives for using hydrogen as a fuel in the transport sector.

There is also experimentation with hybridisation on the vehicle side that includes using batteries and super-capacitors to enhance performance of the vehicle as a means to reducing the requirements of the FC stack,[107] thus leading to lower costs and higher performance by the vehicle. This hybridisation strategy was first developed by Honda in Japan, which used an imported FC stack at the time and experienced better performance than the European OEMs. As a result, the other OEMs adopted this hybridisation strategy.

A further development of fuel cell hybrids was released in June 2007, where a so-called plug-in fuel cell hybrid was unveiled that combines battery and fuel cells. While the OEMs use super-capacitors to increase the performance of the FCV, this latest prototype uses the battery to

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[105] The industry also works, of course, with other fuels such as bio-fuels and natural gas, but not in connection with fuel cell vehicles. I also include hydrogen ICEs among hydrogen vehicles.

[106] < http://www.cafcp.org/index.html>, accessed 12 October 2007.

[107] Super-capacitors or ultra caps are frequently used in fuel cell vehicles to provide additional performance. These are electrochemical devices with a very high energy density and have a variety of commercial applications, such as in 'energy smoothing' and momentary-load devices. The benefits they have include an ability to reload energy quickly, and this make them attractive for regenerative braking applications where energy from braking is stored and used for propulsion of the vehicle.

power the vehicle and the fuel cell to recharge the battery. This hybrid strategy has the advantage of zero emissions and long distance due to the refuelling capabilities of the fuel cell, which a battery electric vehicle lacks.

Clearly, OEMs are increasingly using hybridisation as an important tool to create synergies between battery technology and fuel cell technology. This hybrid solution has several advantages over the electric vehicle and the HFCV. First, it offers less cost in connection with the fuel cells, since the fuel cell system, which only recharges the batteries, can be quite small. Second, the hybrid solution is also a more flexible energy solution since the user can also recharge the battery directly by plugging into the electric grid.[108] Third, this hybrid system does not use the fuel cells directly for propulsion, but at constant load to recharge the batteries. The limited use of the fuel cell, and only at constant load, enhances the lifespan of the fuel cell.

Hybridisation can clearly be a firm strategy that helps new technologies come into use by solving existing problems recognised by the industry. With regard to using hybrid technologies to make use of the existing gasoline infrastructure and thus avoid the externalities of setting up a new hydrogen infrastructure, while this makes it possible to solve the short-term problems of infrastructure, it does not affect or help in the long-term problems of oil dependence. This is why few actors are targeting this solution. The hybridisation approach on the propulsion side makes the requirements of the fuel cell system easier to attain, and the problems around high cost and durability become smaller. However, they do not solve the network effects; this requires other means, those of strong policy support and regulation.

8.2.2. Hybridisation for niche transport applications

For the forklift and the auxiliary power unit examples, this research shows that firms use hybridisation as a stabilisation mechanism for market formation. In the forklift example, system integrators use

[108] In theory, with new so-called regenerative fuel cells, which also have hydrogen storage capability, the user can refill the hydrogen tank directly at home from the grid. So when there is a surplus of energy in the grid, this energy can be used to refill FCH vehicles.

hybridisation by connecting fuel cells with other energy devices, while the auxiliary power units use either a reformer for hydrogen or DMFCs, fuel cells that can run directly on methanol, thus avoiding the market uncertainty related to the institutional and technological complexity of hydrogen.

For auxiliary power unit applications, the technology offers high benefits at an acceptable price, and the actors can avoid infrastructure development and new codes and standards by employing methanol or propane, fuels that are already certified and have the necessary codes and standards in place.

Many of the new forklift systems include hybrid designs in which fuel cells are operated in conjunction with super-capacitors, and analysts expect these numbers to increase substantially over the next couple of years (Hugh, Todd, & Butler, 2007). In a hybrid system for forklifts, the fuel cell covers only the basic load while the electrical storage element such as super-capacitors provides additional energy for peak load operation. The energy storage device first stores the energy recovered from braking and makes it available when higher performance is needed, for example when accelerating. This increases the available performance for the forklift and reduces fuel consumption as well. Indeed, a result of the hybrid configuration is that it requires only 50% of the present energy costs.

Furthermore, the more the vehicle is required to stop and start, the greater the potential savings are in a hybrid system. One manager highlighted that compared to conventional combustion engines or fuel cells, hybrid products offer a lower total cost of ownership, due to the greater efficiency in this system. A manager in a system integrator firm that has commercialised fuel cells for caravans based on DMFC systems explained the important issues for establishing an initial infrastructure:

> 'Logistics have to grow with the technology … but with hydrogen you need an infrastructure, with methanol you need an infrastructure, and you need to invest in that, maybe oil companies will have a big chance in doing that, establish an ethanol or methanol infrastructure at this point in time, while they are still getting money in from their old

> technology. But it is a difficult process because they feel this is a competitive technology … that is a critical factor, to get the infrastructure, it works now for methanol but it is a heavy investment and we would wish to have a partner that would do that.'

This firm developed its own infrastructure for supplying hydrogen to caravans by making agreements directly with camping sites. At camping sites across Europe, caravan users could buy a bottle of methanol that fitted directly into the fuel cell system. Thus, this infrastructure was sufficient for creating the niche market. Since there are already existing codes and standards for methanol, the firm did not need to wait for hydrogen codes and standards, but could use the new technology in combination with existing institutions. The firm thus enabled a hybrid relationship between the old regulation of methanol and a new technology, a relationship characterised as institutional hybridisation. Eventually, when codes and standards are ready for hydrogen in consumer markets, the system integrator can switch to hydrogen-fuelled systems, providing zero-emission technology.

Hybridisation for the transport applications, then, is a key stabilisation mechanism that enables firms to bring technologies to the market at an earlier stage than they could if they targeted a 'pure' hydrogen solution.

8.2.3. Hybridisation for micro CHP

First, for the micro CHP example, the actors expect natural gas fuelled SOFCs or PEMs with reformer technology to be one of the first major mass markets for fuel cells. The current availability of a natural gas infrastructure provides the firms with an opportunity for market deployment that a hydrogen-based system cannot match. Natural gas has the potential for a much larger impact due to the high costs of developing a hydrogen infrastructure. Thus, the network effects are much larger and more serious for hydrogen than for natural gas.

By using the existing infrastructure, a hybrid solution between hydrogen and natural gas technology can be employed in the form of natural gas reformers. Later, a hydrogen infrastructure can gradually be built up and create synergies with local renewable power production such as solar or wind. The role of hydrogen in the future energy system is still uncertain, as an informant in a system integrator firm explained:

> 'At the moment it is based on natural right, but I am not sure if it is really a discussion only to gain time. We have to be careful so that hydrogen economy is first of all more efficient than other grids which we need and other economies, and we have to be careful that in the end we have to pay the cost for that. This is a really long-term discussion and I am not really sure if a hydrogen economy is coming true in the future, so we have to wait. But in the meantime the most important thing, even if we have to use natural gas, we have an advantage in CO_2, we have an advantage in customer benefits, noise of the system, vibrations, are better than any other micro CHP systems on the market today so, and in particular the CO_2, that is, and if in the end we have hydrogen in the grid, say after 2030 or so, produced by renewables makes more sense.'

Clearly, as this informant states, the use of hydrogen in micro CHP systems, providing zero-emission electricity with high efficiency, is characterised by severe market uncertainty that the firms are not able to reduce in the short or medium term. However, using the existing natural gas infrastructure, as the key actors do today, is an interim solution providing benefits like reduced emissions and high efficiency.

Second, for the example of large-scale power production, hybridisation is a key stabilisation mechanism for the firms. In the end, a pure hydrogen solution is preferable, as it enables zero-emission power production with high efficiency, but in the short- to medium-term firm and HFP strategy, natural gas systems are the targeted solution. The large-scale power production occurs in the form of an 'add-on' to the natural gas infrastructure, and as such is a form of hybridisation strategy. By using the existing infrastructure, the firms can reduce market uncertainty for the technology by avoiding complex institutions such as regulation for hydrogen usage in real life, the building of a costly hydrogen infrastructure, and finally, consumer acceptance of an unknown and possibly unsafe form of energy.

Another form of hybridisation in the large-scale power production example is the hybrid technology of fuel cells and steam turbines. This configuration increases the electrical as well as overall efficiency. In fact, fuel cell/turbine hybrid devices have the potential to achieve combined cycle electrical efficiencies of 60 to 70%, and additional energy can be recovered from the high-temperature exhaust of some fuel cells.[109]

The effect of this hybridisation strategy is that it enables the fuel cells to enter the market together with steam turbines, which are a much more mature technology. The efficiencies of this hybrid configuration make it highly competitive towards the incumbent technologies for large-scale power production. Thus, when decisions are to be made about which technologies to use in replacing the old ones, the fuel cell/steam turbine hybrid solution is clearly in an advantageous position.

8.2.4. Hybridisation for telecom back-up and by-product use

Firms do not consider hybridisation to be an important stabilisation mechanism for telecom back-up systems, as these run directly on hydrogen and are CE marked (certified as fulfilling EU safety directives). For by-product use of hydrogen, the network externalities are non-existent, as these systems operate inside a factory. However, the firms use the existing codes and standards for industrial use of hydrogen in these chemical plants. These fuel cells thus function as add-ons to the existing codes and standards, where the firm circumvents regulation to reach the market. This means that no new codes and standards are necessary, and this reduces market uncertainty. Indeed, market introduction is much easier than for applications in the consumer markets. Thus, the firms use institutional hybridisation enabling new products as an add-on to existing institutions.

8.2.5. Forms of hybridisation

This chapter has shown that hybridisation plays an important role in creating market stability in the formative phase. Hybridisation enables firms to enter the market at an earlier stage than they otherwise could,

[109] <http://dodfuelcell.cecer.army.mil/research/Ramgen.html>, accessed 7 August 2007.

either through creating a hybrid solution to existing technology or through qualifying under existing codes and standards. An interesting finding of the analysis, then, is that I discovered that hybridisation relates not only to technology, but that, in fact, two forms of hybridisation exist: technological and institutional. Previous research has only identified hybridisation as a tool where technology is used in a hybrid configuration with existing technologies. A result that emerged from the empirical analysis in the present study is that firms also use institutions like existing codes and standards to introduce new technologies on the market; thus we have two forms of hybridisation. The taxonomy of hybridisation I developed is presented in Table 8.2, which shows these two forms of hybridisation and the effects they present for firms that target market deployment of fuel cells.

Table 8.2: **Forms of hybridisation**

Type of hybridisation	Effect	Examples
Technological	Symbiosis with the incumbent technology	Micro CHP Fleet vehicles
Institutional	Use existing Codes & Standards for new technology	APU for caravans By-product hydrogen

Source: Analysis of firm interviews.

Technological hybridisation occurs when a firm uses existing technology to enter a market with the new technology. For example, when the new technology alone does not have the required performance to satisfy users, or when related technologies are not adequately developed to support the new technology, the firm can use a hybrid configuration between an incumbent technology and a new technology to enter the market. The technologies then have a symbiotic relationship. One example of technological hybridisation is the use of reformer technology for micro CHP so that the fuel cells can be used in symbiosis with the existing natural gas infrastructure. Another is the use of super-capacitors or batteries to extend the range of HFCV. In the fleet and consumer markets, firms also use hydrogen reformers to enable use with the natural gas infrastructure.

Institutional hybridisation occurs when firms use existing institutions, in particular, codes and standards, to enter a market with a new technology. When a new technology requires a new set of codes and standards for market deployment, a firm can choose a technology variant that it is able to arrange in a hybrid configuration to fit the existing codes and standards. For example, some firms use the existing codes and standards for industrial hydrogen to deploy fuel cells in the by-product hydrogen market and then do not need to wait for the creation of these institutions. Another example is the case of caravans, where a firm can use the codes and standards for methanol to commercialise fuel cells in the caravan market. The use of hydrogen directly in caravans would have required a complex approval procedure, which the firm gracefully avoids.

8.3. Conclusion on market formation

This chapter has explored the role of *market networks* and *hybridisation*, which are coordinated actions to reduce market uncertainty for FC&H2.

First, the analysis showed that *market networks* are a key stabilisation mechanism for several examples in the thesis. First, the results from the analysis of fleet and consumer vehicles show that the market for hydrogen HFCV is top-down initiated, with a high degree of coordination between the key actors. This makes the market formation process highly orchestrated, and as many different actors are included, cooperation between OEMs, hydrogen producers and distributors, and policy makers as well, needs to be coordinated to create stability in the market formation process. The actors explained that there is a separation between the HFP, where the actors discuss political issues, and the confidential market discussions taking place at the bilateral level. The market networks have a clear impact because of the relationships established between the OEMs and the oil companies. These are prime movers and the only actors with the ability to reduce market uncertainty. These market network relationships are crucial for the planning of vehicles and infrastructure. Clearly, this is not a situation in which any single firm can open up the market by itself, but requires highly organised deployment activities. As such, the market networks are complex. A similar pattern exists for the micro CHP and large-scale power production examples, which have high market uncertainty. A key tool for stability for these applications is to develop strong market networks with policy makers as well as energy distributors. Uncertainty in terms of market access is a key point, as the distribution companies have the sole rights to the market.

For the examples of forklifts and auxiliary power units for caravans, the analysis shows that the actors pursuing these markets have a quite different strategy than the OEMs and energy companies. The market dynamics differ from those of the previous example, and here the key to reducing market uncertainty is for the firms to establish market networks directly with user industries. The market networks are thus based on bilateral agreements between the system integrators and the caravan OEMs. The firms initiate these networks by participating at conferences and fairs where they can present their technology to users and enable market relationships. This premise seems to be valid also for the telecom back-up market. Finally, the by-product hydrogen example is characterised more by bilateral relations, and the leading actor leverages on existing relations with plant manufacturers.

Second, for *hybridisation* I revealed that hybrid technologies leveraging on the existing natural gas infrastructure play a key role for market entry, as they do not require the hydrogen infrastructure to be built up. Hybridisation also plays an important role on the vehicle side for fleet and consumer vehicles and for forklifts, where system integrators use fuel cells in hybrid systems along with batteries or super-capacitors. This hybridisation strategy improves performance and makes fuel cell technology more efficient and less costly, thus making it more competitive and thereby reducing market uncertainty. I also discovered that firms use a strategy to create hybrid configurations between existing institutions and new technology. One finding is the taxonomy where I further developed the concept of hybridisation. Thus, both technological and institutional hybridisation play important roles in this TIS in its formative phase.

9. Comparative analysis

The analysis presented in the previous chapters spans several FC&H2 applications with quite different drivers and characteristics. Four different examples of FC&H2 technologies were analysed for both the transport case and the stationary case. These four examples show quite different characteristics in terms of the effect each stabilisation mechanism has on the evolution of technology, market and institutions. In this chapter, I compare the most important stabilisation mechanisms in terms of their importance for the various product examples.

This chapter is organised in four sections. Section 9.1 identifies and classifies the different commercialisation strategies for FC&H2 technologies in Europe. In this section, I cluster the different examples into two forms of commercialisation strategies: *orchestrated strategy* and *bottom-up strategy*. These two forms of strategy correlate, respectively, to applications that are highly complex in terms of technology and market, and applications that have low complexity in terms of technology and market. The first relates to the complexity of coordinating technology evolution, such as whether there are strong inter-dependencies with other technologies (network effects). The latter relates to the complexity of coordinating market introduction, that is, to the organisation of the value chain and of links to user industries, as well as to the effect of institutions like codes and standards.

In section 9.1.1, I describe the dynamics of transport applications in terms of these two forms of complexity for the four examples I used to analyse the transportation applications. Section 9.1.2 presents the stationary applications in the same way. This identification of the two commercialisation strategies in different situations leads to a further analysis of the importance of the various stabilisation mechanisms for each of these strategies. This is the topic of section 9.2, where I perform a comparative analysis across cases, based on firm strategies and FC&H2 applications. The main research question was to investigate the role of each stabilisation mechanism on the co-evolution of the TIS, and I answer this question in section 9.2.

I also posed a second research question, namely to understand in which situations the co-evolution of a TIS occurs as the result of stabilisation mechanisms by the spontaneous actions performed by single or few actors, and in which situations co-evolution results from more programmed coordination, such as that taking place in technology platforms and formal networks. I discuss this second question in section 9.1.

9.1. Orchestrated and bottom-up strategies

The analysis performed in chapters 6, 7 and 8 showed that the evolution of technology, market and institutions are inter-dependent processes. A further conclusion is that in order for the whole TIS to evolve to a growth phase, the evolution of these three dimensions must be aligned, that is, a process of co-evolution must be started. Commercialisation strategy is defined here as the combined efforts of firms to align the technology, market and institutional dimension so that the products are able to shift from a demonstration and prototyping stage, to market deployment. This is the essence of the co-evolutionary process within the TIS. Furthermore, co-evolution is not a random process that acts by itself but is set in motion by the strategic actions of a range of diverse actors.

The first commercialisation strategy strongly connects to the EU strategy formulated in the HFP on developing and deploying FC&H2 technologies. The HFP is the most targeted approach in Europe to date and is a key stabilisation mechanism for the evolution of the whole TIS. The HFP also links together technology, market and institutions; it consists of technological and political networks, thus it touches upon most of the stabilisation mechanisms that I defined in the theory chapter. The HFP, as such, is a case for analysing strategy development that strongly affects the evolution of the TIS in the three dimensions. This strategy I call an *orchestrated commercialisation strategy*.

The second commercialisation strategy is based in the entrepreneurial firms I observed. It is clear that a small group of dedicated fuel cell and hydrogen companies is close to or already has commercialised FC&H2 products. Though some of these firms were not part of the HFP network, I still choose to include their perspective in the sample, first to look for differences in perception of opportunities, but also to gain a broader view of the TIS. These firms are highly successful in developing and selling FC systems in Europe. Interestingly enough, these firms focus on immediate opportunities and avoid complex situations that require, for instance, a high level of coordination with infrastructure or the development of new codes and standards. I call this strategy a *bottom-up commercialisation strategy*. These strategies exist in both stationary and transport applications. Thus, I ended up with four different types of situations in which firms try to commercialise FC&H2 technologies.

FC&H2 at its present stage is in the formative phase, and thus has not yet been fully commercialised. However, some product examples have moved into the market in small numbers. Other products are at the prototype and demonstration stage. The notion of commercialisation strategies thus relates to the particular activities of the firms to commercialise FC&H2 into different niche and early markets. The research in this thesis clearly shows that for the firms targeting these two types of strategy, perception differs as regards commercialisation opportunities.

First, the firms targeting the orchestrated strategies are highly dependent on operating within technology platforms, use lobby groups quite extensively and participate in technological, political and market networks. The key objective for these firms is to create the required framework conditions - including political support and infrastructure development - that these applications require. Thus, this is dependent upon the ability of the firms to connect a multitude of actors within the TIS and, as such, is a situation with a complex form of coordination.

Second, the important task for firms pursuing *bottom-up commercialisation strategies* is to find the right market context for the technology and to avoid situations where codes and standards need to be developed. This is because they are able to add the product on to existing infrastructure. Furthermore, the strategy the firm chooses to follow affects the cooperation pattern it has to develop, because the different markets require different types of relationships. Some pockets of market experimentation exist in which firms follow niche and early markets, and these include profits earlier than the HFP commercialisation strategy predicts. It is clear that in the orchestrated strategy, coordination is more complex, while the bottom-up is more user-oriented. For bottom-up strategies, the political and technological networks are less important, while market networks, and particularly market relationships established through conferences and fairs of user industries, are highly important.

9.1.1. Dynamics of transport applications

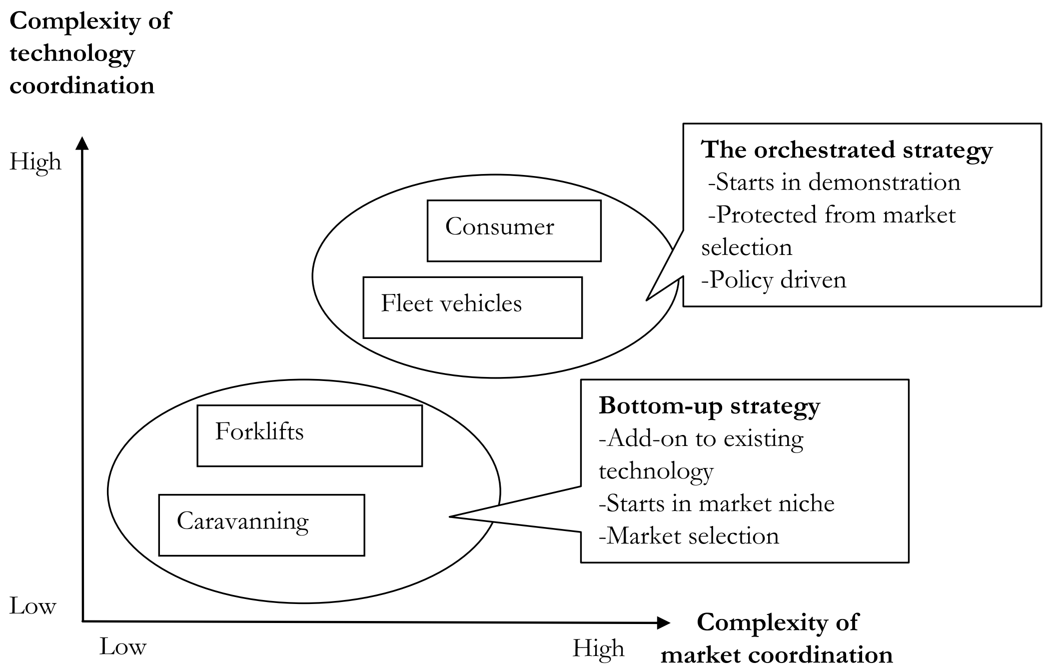
The previous section identified two different forms of commercialisation strategies used, respectively, by companies that target long-range opportunities and companies that target immediate opportunities. The first form is *orchestrated commercialisation strategies*, and the two examples of this in the transport segment are consumer vehicles and fleet vehicles. The second form is *bottom-up commercialisation strategies*, and here the examples of this form are auxiliary power units for caravans and forklifts.

Some applications are characterised by network effects, such as high inter-dependence between fuel and vehicle technology that makes market coordination complex. Furthermore, these applications also require new codes and standards in terms of safety of use, fuelling standards and taxation, thus pointing towards policy tools of high complexity. Finally, these applications challenge existing technology and thus need a high level of performance to be competitive in the market place. As a result, they have high complexity regarding technology and market coordination. I call the strategies of the firms that pursue these examples *orchestrated commercialisation strategies*.

The other category consists of applications that are not networked products but are employed as 'add-on products' to the existing technologies or as 'stand-alone products'. The network effects are thus trivial and the products do not require the establishment of new codes and standards, making market coordination less complex. The FC&H2 technologies have certain specific characteristics that make it possible at this stage to replace an incumbent technology. They offer the users added performance in one or more dimensions relative to the incumbent technology. I call the strategies of the firms pursuing these examples *bottom-up commercialisation strategies*.

Different product groups are used to exemplify what these different market creation processes mean and what the strategies of the actors pursuing them are. The identification of the different commercialisation strategies for the various examples is visualised in figure 9.1.

Figure 9.1: **Technological and market complexity for transport applications**



Source: Based on analysis from interviews with firms.

It is evident from Figure 9.1 that for caravans and forklifts neither market coordination nor the inter-relatedness with other technologies has very high complexity. Some higher complexity exists for forklifts, as the technology uses hydrogen as fuel, while for caravanning, because methanol or propane are used, the technology is an 'add-on' (institutional hybridisation) to the existing codes and standards for methanol. Caravans and forklifts have the characteristic of requiring little coordination with inter-related technologies, in particular infrastructure development. Furthermore, codes and standards either exist or are not a crucial matter. Hence, institutional complexity for these applications is also low, since they can make use of existing codes and standards. In this case, what is important is the ability to develop market links by means of identifying user needs in a niche or early market. The market needs should fit with existing technological performance.

Consumer vehicles and fleet vehicles, on the other hand, have much higher complexity in both dimensions. New codes and standards are required, strong technological competition exists with the incumbent technology (ICE), and they require a large mass market with a high degree of coordination across value chains to achieve the cost goals. Thus, the example of the HFCV is, as such, 'top-down initiated', with a high degree of coordination taking place in technology platforms and political networks. For the mass-transportation market, this includes many different actors, meaning that cooperation between OEMs, hydrogen producers and distributors, infrastructure providers, and regulators needs to be coordinated. With regard to consumer vehicles, very high performance is required in terms of technology (as a substitute for the incumbent ICE technology), and demonstration projects are utilised as a market preparation phase and for technological learning. Accordingly, there are quite different dynamics in these two different segments.

In the *bottom-up strategy*, the market knowledge is typically novel, while the technological knowledge does not have to be state of the art in this field. This means that the firm has found a use for existing technological capabilities in a new market. These markets are not served by an existing technology, and thus technological competition is not a strong barrier. In creating the markets for bottom-up transport applications, several stabilisation mechanisms have shown themselves to be important. The step from demonstration to market is much closer and easier here than for the other applications, either because the infrastructure development is trivial due to hybrid solutions, or because market introduction is already coordinated in 'market networks'. As a result of the fact that the technology satisfies a market need and has a performance that is acceptable among users, these examples do not require policy support or subsidies, but are driven by *market selection.*

Results show that these actors are working in large part outside the main networks like the HFP and operate with a strategic view of markets. I also discovered that for actors of this type, relationships within technology platforms are less important; what was emphasised, rather, was a clear presence in the user markets. For the actors following this market creation strategy, it is therefore important to establish close links with fast-adopting users and leading suppliers. Since this is also a very early stage of development, the creation of supply chains for fuel is usually done leveraging on existing technology (methane, natural gas, propane, etc.).

The actors seek to avoid complexity of codes, standards and regulation. Thus, strategies of *hybridisation* and linking up to existing technologies are key stabilisation mechanisms. Newcomers furthermore usually explore these market niches, and the important stabilisation mechanism is to be able to coordinate market opportunities with existing technological knowledge and, as a result, establish market relationships with external sectors. Conferences and fairs are important for establishing links to user industries such as caravans and telecom, and enable the development of market networks. Thus, the key capability of the firm is to identify *user needs* and to create good market connections.

In contrast, in order to succeed in the *orchestrated strategy* for transport applications, firms must solve many uncertainties. Several stabilisation mechanisms explain the industry dynamics and the strategies of the different companies. The key strategic issues for these transport examples are the discussions on how to get from demonstration to market, the uncertainties of infrastructure development, the number of demo sites required, the realisation of the Lighthouse Projects and, finally, the scaling up of activities to enable series production and market introduction. Thus, the key stabilisation mechanisms are coordination in the TP, development of political networks for lobbying and legitimation, knowledge search to improve the technology, market preparation as a continuation of demonstration projects and coordination of Lighthouse Projects as part of the JTI. In addition, 'hybridisation' can play a role on the vehicle side, but not so much on the infrastructure side.

'Conferences, events and fairs' are important for two reasons: for establishing supply chain (part of technology evolution) and for creating legitimation and disseminating knowledge to users, as well as being the starting point for infrastructure development of the kind that the Olympic Games in London, for example, is targeted to be. Thus, these examples are driven by policy (protection and support) and not by market selection.

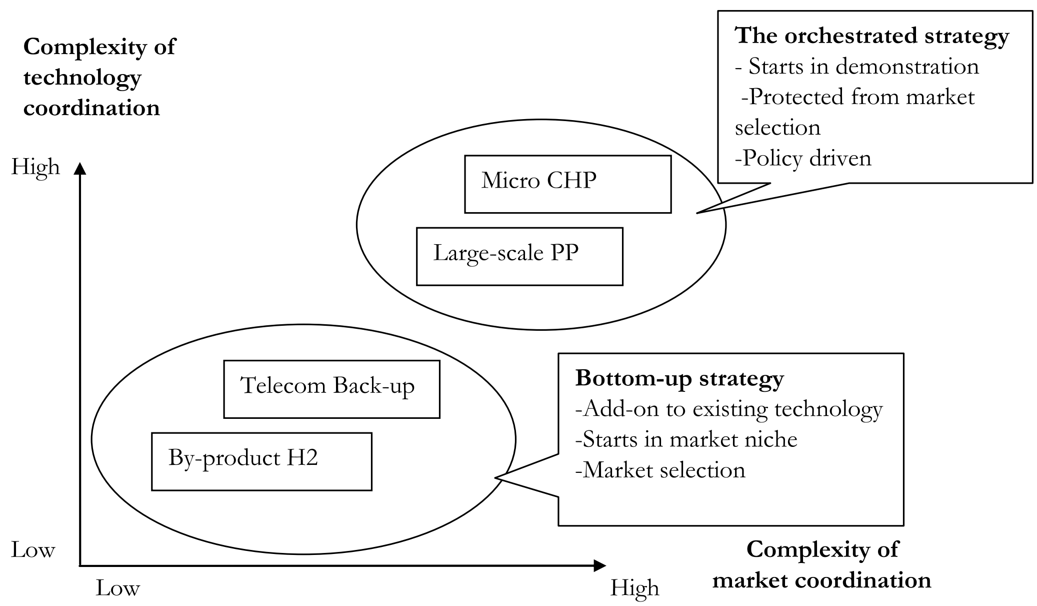
9.1.2. Dynamics of stationary applications

The two different forms of commercialisation strategies are analysed in this section for the examples in the stationary case. For the examples of micro CHP and large-scale power production, a general feature is that the network effects are strong. This therefore requires a high level of coordination between many different actors, so that alignment between technology, institutions and markets occurs. This co-evolutionary process relates to market access (regulation and market networks), safety issues (C&S) and legitimation (political networks). These examples thus require an *orchestrated strategy*.

In the examples of by-product hydrogen in the chemicals industry, and back-up solutions for the telecom sector, the firms use *bottom-up commercialisation strategies*. These applications are based on immediate opportunities and are targeted by a group of actors operating in large part outside the main networks such as the HFP. The approach of these actors takes a strategic view of key markets, in which they seek to avoid the complexity of codes, standards and regulation. Thus, strategies of hybridisation and linking up to existing technologies are key mechanisms. The different dynamics of stationary applications are visualised in Figure 9.2.

The o*rchestrated commercialisation strategy* for stationary applications targets medium- to long-term markets, hopefully with a large impact on energy production and use in most European countries. As such, the focus here is not on niche markets but on large-scale implementation in the major European energy markets. Two examples are used: first, micro CHP, which is small-scale distributed generation, and second, large-scale power production. The first example includes a new production and business model for energy production, while the latter is a continuation of the centralised power production model, but with a shift in production technology. This example has many barriers and unresolved questions to deal with before market introduction can take place.

Figure 9.2: **Technology and market complexity for stationary applications**



Source: Based on analysis of actor strategies.

First, as regards technological complexity, the technologies are still too immature and costly for market deployment, but progress is being made by companies and through field tests in the EU and national projects. A key barrier is the possibility of inertia in the market, but the need for replacement and increase in power production constitutes opportunities for both centralised and de-centralised power production.

Second, regarding market complexity for micro CHP, the lack of knowledge among users is a substantial uncertainty. Firms are reducing this, however, by increasing demonstration projects and disseminating knowledge more widely to consumers, for instance, through work in political networks. Clear commitment from the utility sector as well as policy makers and their position towards fuel cells are an uncertainty and a requirement for success. The situation now, with ambiguity in the marketplace, obstructs possible investments in these technologies.

Third, a key uncertainty for the large-scale power production example is market access, and as a result, de-regulation of markets is necessary for the technology to enter the market. To be realised, these examples require alignment with institutions and support from policy makers; as such, they are policy driven. The technological improvements required are also considerable, as the competition from incumbent technologies is very high.

Fourth, the network effects are strong in this market, with high inter-dependence between fuel infrastructure and energy production technology. However, *hybridisation* is a key mechanism for firms to introduce fuel cells into the energy market as an add-on to the existing natural gas infrastructure. Later, a hydrogen infrastructure can gradually develop that 'adds on' to the renewable energy system, creating synergies with renewables and increasing the grid stability. *Hybridisation* makes possible the gradual coordination of institutional alignment, such as codes and standards as well as legislation, with technology (different forms of hybrid solutions as well as pure fuel cell systems) and the market (gradual market introduction and co-evolution with the renewable energy technologies). This *orchestrated strategy* is a key part of the HFP's long-term strategy and is implemented as part of the JTI. This strategy in addition requires the complex coordination of many actors, from industry and government. Thus, the strategy is driven by policy (protection and support) and not by market selection.

The two examples of *bottom-up commercialisation strategies* are by-product hydrogen (i.e. industrial power production), and back-up solutions in the telecom sector. One example comes from the small-scale stationary application area and the other from the large-scale area. The small-scale consists of a fast-moving early market that has shown itself to be promising for small-scale hydrogen fuel cells, that is, the uninterrupted power supply (UPS) market consisting of banks, hospitals, telecoms and similar sectors requiring uninterrupted power.

The telecom back-up solution is an example of a *bottom-up strategy* in the small application area. Results show that this application area is market driven and offers users an alternative that is attractive in terms of performance, environment and cost. Thus, this application is selected in the market and does not require policy support. The key stabilisation mechanism is to develop market links to key users, and a key tool is to establish relationships at conferences and fairs for user industries. Hybridisation is not important, because the technology performance is satisfactory in a stand-alone configuration. The telecom application is the most important market for stationary hydrogen application, since for large-scale power production and micro CHP the use of hydrogen is not regarded as a high priority in the period up to 2020. Telecom has more market-oriented user-producer relations and requires less development of codes and standards. Networks are based on the market side towards base station owners.

The example of by-product hydrogen is characterised by low technological complexity. There are no network effects due to infrastructure requirements, as the technology is used within a factory. Nor are there any uncertainties regarding C&S, as the fuel cell systems can be used with existing codes and standards for industrial use of hydrogen. The market complexity is also low and requires market relationships with the chlor-alkali factory owners. The key stabilisation mechanism is thus market networks.

This section has explained the two forms of strategies for the various examples in terms of technological and market complexity. It is clear that each strategy has different dynamics, where the *orchestrated* is mainly policy driven, while the *bottom-up* is driven by market selection.

9.2. Comparing the stabilisation mechanisms

This section investigates the importance of each of the stabilisation mechanisms in terms of each strategy for the two cases. This relates to the overall research question, which was to answer: 'What kinds of stabilisation mechanisms are at play for the evolution of a technological innovation system in its formative phase?' The results are summarised in Table 9.1, based on the empirical analysis is chapters 6 through 8.

Table 9.1: **The relevance of the stabilisation mechanisms for each strategy**

Case Strategy / Mechanism	**Transport Orchestrated**	**Transport Bottom-up**	**Stationary Orchestrated**	**Stationary Bottom-up**
Knowledge search	++	-	++	-
Technology platform	++	-	++	-
Demonstration project	++	+	++	+
Codes and standards	++	-	+	+
Political networks	++	-	++	-
Market networks	+	++	+	++
Hybridisation	+	+	++	-
Total	**12**	**4**	**12**	**4**

Legend: - not important; + important; ++ highly important

I gave the different mechanisms weight in terms of how important they were for the analysis of the different examples. The results from the analysis show, not surprisingly, that the two *orchestrated strategies* are the most complex examples, requiring 12 of the stabilisation mechanisms to be at play. The way in which each single stabilisation mechanism has an impact on co-evolution in the formative phase is discussed in the following.

Knowledge search is most crucial in situations where the technology stands in direct competition with an incumbent technology and where the technology does not offer any other benefits that can neutralise the difference. This was evident mostly for orchestrated transport and stationary strategies. For bottom-up transport, the technology is already sufficiently advanced to replace the incumbent technology. The benefits it offers clearly justify the higher price. For bottom-up stationary like the telecom back-up example, the technology offers benefits to customers in terms of performance, noise, emissions, reliability and economy. Not to say that improvements are not likely to happen, but this is not as crucial as it is for the orchestrated applications. Hence, knowledge search is highly important for the orchestrated and not important for the bottom up-strategy.

The *technology platform* encompasses the development of all applications and cases. However, as the analysis has showed us, it is more crucial for some applications than for others. The long-term focus of the TP strategy, with complex interaction between technological, market and institutional factors, makes this a crucial tool for co-evolution of the TIS. It is therefore the most important stabilisation mechanism for applications that require an orchestrated strategy; the actors following bottom-up strategies tend to avoid such complex organisational structures and move directly to those market areas where the existing FC&H2 technology can compete. Hence, a technology platform is highly important for the orchestrated strategy, but not important for the bottom-up strategy.

Demonstration projects are important for validating technology and creating a bridge to early markets. These are most important for orchestrated applications, which require a protected space, shielded from market competition from incumbent technologies. For bottom-up stationary examples like telecom back-up, several manufacturers have already launched products on early markets, while others are in the demonstration phase. Thus, demonstration is important for some, for others not. In the bottom-up transport example, products are available on the market here as well, in the form of APU for caravans, and demonstrations thus have little importance. The fuel cell forklifts are currently moving from demonstration into the market, and here validation of performance is crucial for entering into the markets for materials handling. Thus, the role of demonstration for reducing uncertainty is quite different for the various examples.

Codes and standards are highly important for the fleet and consumer vehicles, as they are required for use in practice. The ISO and IEC implement the C&S, and the UN regulates them. The EU projects monitor these activities and establish EU legislation in alignment with the international standards. Thus, the EU codes will follow from UN standards. The specific countries can then use the EU legislation when developing national codes. Clearly, C&S are highly important for these examples. For the stationary examples, C&S play an important role in the long-term perspective for micro CHP and large-scale power production, when hydrogen will be used. At this moment, however, it is the natural gas infrastructure that is used with the existing C&S, and hence C&S is not important at all. In the bottom-up transport of caravan APU as well as the stationary telecom back-up and by-product hydrogen, C&S do not play an important role, as the firms use existing C&S to deploy the technologies. C&S are thus highly important for the orchestrated strategies, and for HFCV in particular they are a key aspect for commercialisation.

The use of *political networks* is key for establishing legitimation for a new technology. These networks clearly have a highly important role to play for both applications that require an *orchestrated strategy*. For the orchestrated applications, strong political networks are a key, as these can establish the needed support from policy makers. This was the case in Germany, where the OEMs and energy companies first had bilateral discussions that later turned into formal projects including the support of policy makers. For the *bottom-up* examples, the actors involved use bilateral relationships to communicate directly with users about the advantages; thus, political networks do not have an important effect on commercialisation.

Market networks are highly important for the bottom-up strategies. There are no examples in which the existence of market networks is not significant for commercialisation, as this is a basic stabilisation mechanism for buying and selling products. The difference, however, lies in how successful the company is in creating linkages that span new borders, thus establishing links to new markets. In that sense, the bottom-up strategy is highly dependent on this mechanism, as the applications are closer to commercialisation and target new markets with existing technology. This strategy considers not how much improvement the technology needs to compete in the incumbent market, but where the technology, as it is today, with the limitations and benefits it can offer, is able to compete. Thus, the idea is to find the right market context for the technology. For the bottom-up strategy, then, market networks are the key stabilisation mechanism and, as such, highly important. For the orchestrated strategies, the focus is more on building links to improve and validate technology, as well as creating policy support and legitimation, and then building market networks. Therefore, market networks are important, but not highly important.

Hybridisation is a highly important stabilisation mechanism for micro CHP, as the technology used is natural gas fuelled SOFC or PEMFC with reformer technology. This application area uses the existing natural gas infrastructure, in a hybrid configuration. For the bottom-up strategy of caravans, hybridisation is important since the actors use the methanol C&S to employ fuel cells in a new market. For the fleet and consumer vehicles, as well as forklifts, there is experimentation using fuel cells and battery hybrids to increase performance and lower costs. Thus, hybridisation is important for these examples, but highly important for the orchestrated stationary examples.

9.3. Conclusion

This chapter has compared the various examples in terms of technological and market complexity. This resulted in two forms of commercialisation strategies: *orchestrated* and *bottom-up*.

A finding is that the examples of fleet and consumer vehicles, micro CHP and large-scale power production have strong inter-relatedness between technologies, by virtue of infrastructure needs and regulative issues. These examples require complex coordination, as these are networked products and are thus highly reliant upon the co-evolution between technology, institutions and market achieved with an *orchestrated strategy*. A further result is that the firms can use fleet vehicles as a key for bridging demonstration projects to early markets in the transportation case, thus reducing a major uncertainty regarding the consumer mass market.

The *bottom-up strategy* requires access to immediate markets and is used for non-networked products. The examples are caravan APU, telecom back-up, by-product hydrogen and (a bit later than the others) forklifts, and they are characterised by market selection. That is, these examples are able to deliver a product on the market at a price acceptable to a customer with present technology performance. The firms taking such an approach tend to avoid products that have high technological and market complexity, as they target a fast route to the market.

In terms of *co-evolution*, two stabilisation mechanisms play a key role. First, a finding is that the demonstration projects enable co-evolution between the technology, institutions and market for both transport and stationary applications. In demonstration projects, users can become familiar with the technology. Thus, the firms integrate the demand side into the validation phase of the technology and reduce market uncertainty. In addition, the firms active in the demonstration projects use the results from these projects to coordinate with the creation of global standards and the EU approval procedure. Thus, the actors create institutional stability by establishing a co-evolutionary process between technology and institutions. Second, the technology platform is the most efficient instrument for co-evolution, as it enables the actors to agree on a common vision, create a long-term strategy for commercialisation and realise this strategy with a large private-public partnership.

IV. CONCLUSIONS AND IMPLICATIONS

10. Conclusions, propositions and further research

This thesis has focused on explaining the formative phase of a technological innovation system (TIS) in terms of stabilisation mechanisms for co-evolution of technology, market and institutions. The starting point of the thesis is the assumption that in order to move from the formative phase to the growth phase of a TIS, these dimensions – technology, market and institutions – need to be aligned. Alignment of actors means that the various actors in the TIS share a joint vision and that their activities are coordinated with each other. Alignment is clearly important for the actors to establish a conception of control and thus reduce uncertainty by knowing that the perspectives of the various actors in the TIS are coordinated with each other.

I set out to answer two main research questions in this thesis. The first was: *What kinds of stabilisation mechanisms are at play for the evolution of a technological innovation system in its formative phase?*

The second question was: *In which situations does co-evolution of a TIS occur as the result of stabilisation mechanisms by the spontaneous actions performed by single or few actors, and in which situations does co-evolution result from more programmed coordination?*

In fact, the formative phase is poorly understood in theory, as several researchers have pointed out. By proposing to view the dynamics of the formative phase as being dependent upon the co-evolution of these three dimensions, and explaining the stabilisation mechanisms that make co-evolution happen, I have contributed to an improved understanding of the dynamics of the formative phase of a TIS. The approach I have chosen in this thesis to focus on the actors, and through analysing the perspectives of the different actors involved, the thesis thus places a stronger focus on actors and their actions than the existing literature has done.

The focus in this thesis is also a counterweight to long-term historical analysis, which tends to describe evolution and change on an 'aggregated and abstract level without saying much about the interactions between actors' (Geels, 2002, p. 1273). I have thereby provided a deeper and more fine-grained analysis of the formative phase than previous research has done. The perspective chosen in this thesis reveals the relationship between the actors involved in the co-evolutionary process, their motives for action, and the situations that require highly coordinated efforts as well as those that can be pursued by a handful of actors.

This chapter sums up the findings in response to the specific research questions and discusses the theoretical implications of the thesis (section 10.1). In section 10.2 I discuss the findings that relate to coordination, namely the extent to which co-evolution is the result of more spontaneous or more programmed coordination. The research shows that the evolution of the TIS is asymmetric, and this finding has two theoretical implications. First, I discuss the two different strategies for commercialisation in the TIS in section 10.2.1. Second, I discuss the extent to which niche cumulation leads to co-evolution of the whole TIS in section 10.2.2. Following this discussion, I draw implications from the analysis in the thesis in the form of a set of propositions and notes for further research (10.3.1) and implications for firm strategy (10.3.2).

10.1. Theoretical findings for stabilisation mechanisms

One of the principal questions of the thesis was: W*hat kinds of stabilisation mechanisms are at play for the evolution of a technological innovation system in its formative phase?* In the following section, I answer this question and thus explain how the stabilisation mechanisms contribute directly to the co-evolution of the TIS in the formative phase.

First, an important stabilisation mechanism for co-evolution is the creation of a *technology specific platform* (TP). I set out to answer the question: *What role does the technology specific platform play in creating stability in the TIS, and what does the platform accomplish for the purpose of creating stability*? The existing literature views TPs as important for the development of visions and for enabling cooperation among different actors in the innovation system (Kemp & Munch Andersen, 2004). In addition, TPs play an important role for enabling cooperation between firms and governments instead of government taking a leading role (Stiglitz & Wallstein, 1999).[110]

The results of the thesis show that the European Hydrogen and Fuel Cell Technology Platform (HFP) is clearly an important tool to coordinate technology, market and institutions. In fact, the HFP is the most direct mechanism for co-evolution within the particular TIS at hand. The importance of its role consists in the fact that the HFP enables the actors to coordinate technology development with codes and standards development, to create of large-scale demonstration projects, and introducing technology into markets. The HFP coordinates the various actors, aligns their perspective behind a joint vision and enables cooperation vis-à-vis public decision makers at EU and national levels. These achievements help reduce the uncertainties for the actors in the TIS by establishing support and concrete actions for the evolution of the TIS. Clearly, the creation of the HFP has led to co-evolutionary processes between technology, market and institutions, which previous efforts in Europe had not managed to do to the same extent.

In regard to theory, the concept of TPs is under-researched, and thus this thesis makes a contribution to the literature on innovation technological change in understanding the importance of these tools for evolution. My findings confirm the perspective of Stiglitz and Wallstein (1999) that the concept of TP enables cooperation between firms and governments. I also confirm the findings of Kemp and Munch Andersen (2004) that TP is important in developing visions and enabling cooperation in the innovation system. I thus confirm their view with an empirical case, but I also expand their view by identifying that this cooperation in fact spans technology, market and institutions, so that it is much wider than merely technology cooperation. The findings on TP were presented in section 6.1.

Second, in terms of *political networks*, I asked: *What types of political networks exist, and what is their role in creating stability in the formative phase of the TIS?*

[110] The perspective of Stiglitz and Wallstein only indirectly discusses technology platforms. They focus on public-private partnerships, and this has relevance for technology platforms.

Political networks have been explained by Jacobsson and Lauber (2006) as well as Nelson (1995) as playing a central role in creating the legitimation the technology needs, and thus providing a foundation for the co-evolution of the TIS. Legitimation is central in this view for creating *trust* among decision makers so that they perceive this specific technology to be an answer to their perceived problem.

The empirical research showed that the TIS in Europe consisted of both formal and informal networks, and that the informal networks lead to the creation of formal networks. The political networks have affected the evolution of the TIS by succeeding in creating the necessary legitimation in the eyes of policy makers as well as users, thus generating the required support for the emerging TIS. A finding was that in relation to the role of political networks for creating stability in the TIS, the presence of prime movers like OEMs as well as oil and energy companies was clearly a requirement for creating legitimation vis-à-vis policy makers. Thus, the political networks have created stability in terms of aligning the perspectives of actors and policy makers, creating legitimation of the technology and, finally, gaining support for the technology at high levels.

With regard to theory, I confirm the findings of Jacobsson and Lauber (2006) as well as Nelson (1995) that political networks play a central role for creating the legitimation the technology needs, and thereby provide a foundation for the co-evolution and growth of the TIS. As a result, I expand the knowledge about political networks by confirming previous research on political networks, but I also identify that informal networks of important industry actors are decisive in creating powerful formal political networks that have the required resources to realise the evolution of an emerging TIS. The findings on political networks were presented in section 6.2.

Third, co-evolution is also affected by the stabilisation mechanism of *codes and standards* (C&S). The question I set out to answer was: *What types of codes and standards networks exist, and what effect do codes and standards have on the evolution of the TIS?* The role of C&S has been explained by David's findings that technological change creates uncertainty among users, who want to avoid being early adopters of a technology that is later abandoned, the so-called 'angry orphans' (David, 1986). Foray (1998) claims that standards play a crucial role in situations with high uncertainty about future technology. Standardisation can intervene by temporarily creating stability, thus giving the actors the possibility of coordinating their activities. This is in fact the role of the various networks working on standards for FC&H2.

The findings in the empirical analysis showed that the C&S networks are playing an important role in reducing institutional uncertainty by aligning the EU standardisation process with the global activities of the ISO and the IEC. Clearly, the C&S drafting that is taking place in the global networks (ISO and IEC) targets supporting the harmonisation effort more efficiently. This creation of globally harmonised codes and standards will then be ready to support firms in scaling up production, so that interoperability and scale effects can be achieved. Thus, C&S support the market introduction of FC&H2. I also found that it is important not to develop standards too early, as this might lead to a negative lock-in to an inferior technology. I concluded, therefore, that standardisation should be coordinated in conjunction with demonstration projects, as is the case in the large EU demonstration projects scheduled to be part of FP7 and the JTI.

The findings in this thesis extend the existing knowledge of C&S. I confirm what Foray (1998) discusses, namely that standards play a crucial role in situations with high uncertainty about future technology. Clearly, standardisation intervenes in the sense of temporarily creating stability. This stability is exactly the function the various networks working on standards had for FC&H2. I also confirm David's findings about uncertainty among users in adoption of a new technology that might later be abandoned. Through definition of global standards, users experience reduced uncertainty and thus have a sense of stability that the technology will exist in the future. Finally, my finding that C&S drafting should be developed in conjunction with the large-scale demonstration projects extends the previous literature on C&S. The findings on C&S were presented in section 6.3.

Fourth, for *knowledge search* I posed the question: *What kind of knowledge search strategies do firms use to reduce technological uncertainty, and how is* *knowledge creation distributed in the value chain?* The existing literature on knowledge search has viewed external search as increasingly important (Hagedoorn, 1993, , 2002). Providing a sectorial perspective on knowledge search, Powell and colleagues described cooperation in the biotechnology industry (Owen-Smith & Powell, 2004; Powell, Koput, & Smith-Doerr, 1996) and concluded that due to the high complexity of the knowledge base of the technologies, it has become impossible for a single firm to possess all of the knowledge and capabilities required to succeed. This is similar to Richardson (1972) and Gulati (1998), who argue that firms emphasise cooperation with other firms due to concrete strategic *complementarities* that they have to offer each other; thereby specialisation and cooperation occur in the value chain.

The analysis shows that the firms in the FC&H2 industry in Europe emphasise cooperation as the most important source for knowledge search, and thus for reducing technological uncertainty. This is because the knowledge base of FC&H2 is very complex, and the firms specialise either in narrow parts of the technology or in system integration. It is clear that all actors have an important role in creating stability. It is also clear that cooperation between firms has been the most crucial tool for firms in reducing uncertainty. Hence, the findings show that the value chain is characterised by increasing specialisation and that firms enter into cooperation with complementary organisations to reduce technological uncertainty.

In regard to theory, the finding that cooperation is emphasised because of the complex knowledge base of the technologies that makes it impossible for a single firm to possess all the required knowledge, is similar to the findings of Powell and colleagues in describing the biotechnology industry (Owen-Smith & Powell, 2004; Powell, Koput, & Smith-Doerr, 1996). These findings thus confirm their description of the knowledge dynamics in a new sector. The findings furthermore confirm the conclusions of Richardson (1972) and Gulati (1998) that firms emphasise cooperation due to concrete strategic *complementarities* they provide each other. The findings on knowledge search were presented in section 7.1.

Fifth, the use of *demonstration projects* is a key stabilisation mechanism for co-evolution. I posed the question: *Which are the key demonstration projects in Europe for FC&H2, and how do they help in reducing technological uncertainty?* The demonstration projects establish the necessary real-life testing of products that are to be deployed in the markets and are thus important tools for firms to introduce new technologies (Kemp, Schot, & Hoogma, 1998). The literature on strategic niche management and transition management has identified demonstration projects as an important tool providing a protected space where firms can learn about technologies and validate technology (Geels, 2002; Kemp, Schot, & Hoogma, 1998).

The results in this thesis, however, show that demonstration as a protected space for technology learning is not enough by itself to induce evolution of technology. The previous literature has treated protection of a niche as sufficient for evolution, but this is only one part of the solution. Another important aspect is namely that learning on the market side is equally fundamental. Many demonstration projects never reach the market, but die out after the demonstration phase is completed. A finding from this thesis is that in order to establish the foundation for market introduction, the demand requirements of the users must be researched. The firms that were actively involved in the demonstration projects stated that it is vital to involve users directly in order to find their minimum demand and prepare for early markets. This cannot be satisfactorily achieved by demonstration projects in and of themselves, but means that the 'strategic pre-requisites' of users have to be found and met. This form of analysis clearly plays an important role in coordinating the market preparations and linking demonstrations projects to early market opportunities.

As a result, the existing perspective on demonstration projects needs to be extended to focus more clearly on how market learning takes place, and this includes the necessary support activities for obtaining the knowledge of user demand. The findings in this thesis therefore extend the previous literature on demonstration projects. The findings on demonstration projects were presented in section 7.2.

Six, for *market networks* I asked: *Which actors are involved in market networks? How are market networks created? In what ways do they impact market formation?* The existing literature, for example, Fligstein (2001), explains that markets are formed by the interaction between various firms. Thus, markets for new technologies are dependent upon embedded relationships taking place in a TIS or an industry (Granovetter, 1985; Granovetter, McGuire, & Callon, 1998). Conferences, fairs and exhibitions have been explored as a means of establishing interaction between firms that can also lead to market formation (Maskell, Bathelt, & Malmberg, 2006). Firms use these events to identify the current market frontier and to meet users of their technology, establishing connections that enable market formation.

The empirical analysis demonstrated that market networks are a key stabilisation mechanism for several examples in the thesis. Analysis results show that the confidential market discussions for HFCV take place at the bilateral level between the OEMs and the oil companies, thus reducing market uncertainty. A similar finding was made for the micro CHP and large-scale power production examples. For the examples of forklifts and auxiliary power units for caravans, the key to reducing market uncertainty was to establish market networks directly with user industries. The market networks for the latter, for instance, are based on bilateral agreements between the system integrators and the caravan OEMs. The firms initiate these networks by participating in conferences and fairs. This was also the case for the telecom back-up market.

The findings in this thesis confirm the perspective that markets are formed through interaction between firms in the value chain. I also confirm the notion that conferences, fairs and exhibitions are important arenas for establishing market networks. The findings on market networks were presented in section 8.1.

Seven, for investigating the role of *hybridisation* I posed the question: *What is the role of hybridisation for market formation in the TIS, and in which applications does hybridisation affect the evolution of the market?* Hybridisation has been used by several authors to explain how technologies emerge (Geels, 2002; Raven, 2007; Pistorius and Utterback, 1997).

I discovered that hybrid technologies are used to leverage on the existing natural gas infrastructure, and this plays a key role for market entry. The case analysis showed that some firms use the existing codes and standards for industrial hydrogen to deploy fuel cells in the by-product hydrogen market. Another case was that of caravan APU, where I revealed that it is possible to use the codes and standards for methanol to employ fuel cells in the caravan market. Firms active in this example had a strategy to commercialise the fuel cell technology by circumventing market complexity, and the tool was to use a technology that had existing codes and standards which could be used. These examples, then, enhance the understanding of the forms of strategic moves that firms can use in the formative phase to reduce uncertainties, and to deploy technologies into specific markets. An interesting finding is that firms use a strategy to create hybrid configurations between existing institutions and new technology.

Previous research, such as Geels (2002), Raven (2007) and Pistorius and Utterback (1997), only discusses configurations between new and incumbent technologies as hybridisation. I revealed that firms in fact use a strategy to create *hybrid configurations* between existing institutions and new technology. This occurs in situations where a firm uses a technology variant that it is able to arrange in a hybrid configuration to fit with existing codes and standards. Therefore, I extend theoretical understanding of hybridisation by developing a taxonomy that includes technological and institutional hybridisation. The findings on hybridisation were presented in section 8.2.

10.2. Theoretical findings on coordination

This section analyses the theoretical relevance of the second research question: *In which situations does co-evolution of a TIS occur as the result of stabilisation mechanisms by the spontaneous actions performed by single or few actors, and in which situations does co-evolution result from more programmed coordination?*

A first conclusion is that the empirical research in this thesis has provided a new understanding of innovation systems, in that evolution can be described as *asymmetric*. The thesis has shown that as the evolution of a TIS consists of many applications with quite diverse dynamics that evolve at different rates, driven by various actions and actors, it is thus an asymmetric process. I discuss the different implications of asymmetric evolution here, namely in terms of strategies for commercialisation and the extent to which niche cumulation can lead to the growth of the whole TIS.

10.2.1. A typology of orchestrated and bottom-up strategies

There is an unsatisfactory understanding in previous literature of actor strategies in the formative phase. Previous research on innovation systems has tended to focus on evolution related to the structure of the system or to functions, and not on particular actor strategies. Even the transition management perspective has tended to overlook the strategies of the actors involved. In the strategic management literature there is a clear focus on actors and conceptions of strategies like *first movers* and *late movers* (Christensen, Suarez, & Utterback, 1998; Lieberman & Montgomery, 1988), and *incumbent* and *newcomers* (Mitchell, 1989; Rothaermel, 2001; Tripsas, 1997), to explain the dynamics in the early phase of technology development. A finding from this thesis elaborates on the strategies of firms in early phases, where I create a typology of *orchestrated* and *bottom-up* strategies. These are used to explain the findings in the two main application areas: stationary and transport.

The results show that the different examples of FC&H2 applications within the TIS of FC&H2 develop quite differently, and thus the evolution of the TIS is asymmetric. First, the examples of fleet and consumer vehicles, and of micro CHP and large-scale power production, all show a strong interrelatedness between technologies, infrastructure needs and regulative issues. These products all require complex coordination, as they are networked products and are thus highly reliant upon the co-evolution of technology, institutions and market. The evolution of these applications can be achieved only by an *orchestrated strategy*. The *orchestrated strategy* connects strongly to the EU strategy formulated in the HFP on developing and deploying FC&H2 technologies. The HFP is the most targeted approach in Europe, and it links together technology, market and institutions. Further, it consists of technological and political networks. Thus, it includes most of the stabilisation mechanisms.

Second, the product examples of caravan APU, telecom back-up, and by-product hydrogen are all *non-networked products*. They have access to immediate markets and, as such, are characterised by market selection. That is, these application areas are able to deliver a product with present technology performance to the market at an acceptable price. The firms following a bottom-up strategy tend to avoid products that have high technological and market complexity, as they are targeting a fast route to the market. The terminology of a *bottom-up strategy* can be used for these examples. It was evident from the empirical analysis that a small group of dedicated fuel cell and hydrogen companies is close to or already has commercialised FC&H2 products, something that is unique for these technologies. These firms are doing well in developing and selling FC systems in Europe, and an interesting finding is that these firms focus on immediate opportunities and avoid complex situations that require, for instance, a high level of coordination with infrastructure or the development of new codes and standards.

The implications of these findings are relevant for understanding the dynamics within an emerging TIS, as they deal directly with what types of strategies the actors can pursue in different situations, as well as what types of stabilisation mechanisms are required to successfully commercialise a technology in a specific situation. As such, this typology extends the understanding of actors and their strategies in the formative phase.

10.2.2. Niche cumulation to induce co-evolution of the TIS

This section discusses another aspect of asymmetric evolution, namely the extent to which niche cumulation leads to growth of the whole TIS. This is a more detailed response to the issues discussed above (in 10.2.1), as it explains the extent to which the success in the bottom-up examples may affect the orchestrated examples.

One theoretical contribution of the thesis is the finding that relates to which firms use particular strategies. I found out that the bottom-up strategy was used by actors operating outside the networks facilitating mass-market applications. A partial explanation of this is the complexity involved in the mass markets as well as the long periods required. I also discovered that in the examples, a bottom-up strategy is targeted by newcomers that excel in building *market networks* to industries and sectors that are not part of the 'main application' areas. This finding expands the existing knowledge on what types of firms commercialise specific applications.

A critical issue in the emergence of a TIS is the extent to which the evolution of single applications leads to the evolution of other applications within the TIS. This phenomenon is known as *niche cumulation* and has been proposed as an explanation for how emerging technologies advance. Geels (2002) as well as Raven (2007) argue that niche cumulation is a factor that causes evolution of the TIS in the formative phase. This notion of 'upgrading of niches' then tilts the whole TIS into a growth phase, through the synergies between the different applications. An important question, therefore, is to what extent the co-evolution of a TIS involves a gradual upgrading of market applications, or if more structural and larger initiated frameworks are needed. This is relevant for understanding whether there are synergies between the various examples of FC&H2 applications and whether the products that are commercialised with the bottom-up strategy have an effect on the commercialisation of the networked products.

The analysis performed in this thesis confirms the argument from Geels and others to some extent, namely that niche cumulation is valid for stand-alone products, but not for networked products. I therefore expand the detail of the explanation in pointing out that there are particular aspects to consider in terms of the *situations* in which niche cumulation may have this effect. In the remainder of this section I discuss two issues regarding the extent to which niche cumulation can occur in stationary and transport applications.

First, for the case of the transport applications, the empirical situation is that some markets already exist, for example, for auxiliary power units (APU) for caravans, while other applications are close to market introduction, for example, the forklifts. APU for caravans is commercialised based on special needs in a niche market, with the use of methanol fuel to avoid complexity of codes and standards and infrastructure. The technology used is also quite different from what is used in a consumer vehicle.[111] The consumer vehicles require large resources, have large technological and market complexity and can be realised only with an orchestrated strategy. Clearly, then, the possibilities for niche cumulation based on caravan APU for consumer vehicles are small.

Can forklifts and fleet vehicles, on the other hand, lead to growth in the mass consumer market? Forklifts are not products that can help the technology become accepted in consumer markets, as the users have very different demands; given this, there is no expectation of synergies with the consumer vehicle market.[112] Nor, on the infrastructure side, will forklifts lead to any synergies with consumer vehicles, as one of the main benefits of forklifts is the limited requirement for filling stations.

The case is different for fleet vehicles, which require less complex coordination than consumer vehicles and can be of help in creating early markets that will later evolve into mass consumer markets. This is because buses and other fleet vehicles do not require a large infrastructure: one does not need many filling stations to service them. This is an advantage, in that they require less coordination with infrastructure development. Fleet vehicles also require less coordination with codes and standards than consumer vehicles. Fleet vehicles are, in fact, key applications that can be helpful in bridging demonstration projects and early markets. Because they require less coordination in

[111] Particularly in terms of size: from 5kW to 85kW.
[112] They can, however, lead to technical learning as the fuel cell systems are improved.

terms of market and policy tools, they constitute the path of least resistance and make possible a gradual upgrading of infrastructure. Therefore, fleet vehicles can create synergies for consumer vehicles and, by cumulation of different fleet vehicle niches, can lead to evolution affecting consumer vehicles.

Second, for the case of the stationary applications, the empirical situation is that telecom back-up power constitutes a particular market in which the technology offers better performance (reliability) for similar or less cost. This product is thus competitive with the incumbent technologies of diesel generators and lead-acid batteries. The telecom back-up power example is a stand-alone product with no network effects. In relation to situations of niche cumulation between different products, then, to what extent does this example affect the evolution of the micro CHP example? The micro CHP example is also technologically in the 1-5kW range, but it requires several other complex factors, namely codes and standard development, de-regulation of markets (in particular, access to the grid), knowledge about the technology among users, and supportive policy initiatives. Clearly, micro CHP is quite different due to the network effects, and this means that the diffusion effect from telecom back-up will not transmit to the micro CHP example.

The research shows that many of the examples of FC&H2 are characterised by network effects, and these require a new set of related stabilisation mechanisms in order to evolve. I discovered that for the applications which firms realised through a *bottom-up strategy,* firms could easily jump from niche to niche and thus accumulate niches. These examples, however, are not networked products and accordingly require little coordination between technology and infrastructure. Hence, the firms can easily manage the uncertainties involved. Clearly, both for stationary and transport applications, niche cumulation based on bottom-up strategy will not affect the products that require an orchestrated strategy.

Technology, then, can emerge in market niches, but this is limited to *stand-alone* or *add-on* products. In terms of moving from the niche market to the mass market, co-evolution of technology, market and institutions is required. These co-evolutionary processes require coordination at a high level, and include key actors like OEMs and policy makers. This is due to two necessities: first, to create legitimation vis-à-vis policy makers in terms of obtaining available resources and being able to scale up production of vehicles and infrastructure at the right time and pace; second, to develop the necessary partnerships that are able to connect complex technologies involving actors spanning several sectors.

The key issues for mass-market applications are thus: the technology needs a high level of coordination relative to the vehicle and fuel infrastructure; codes and standards need to be in place; and the requirements and the demand need to be assessed. Obviously, the vital issues for commercialising the networked applications are quite different from those of the bottom-up strategies, as the orchestrated strategy requires a much higher level of market and technological coordination. Thus, the impact of success in examples with a bottom-up approach is unlikely to have an effect on networked products like consumer vehicles and micro CHP. Hence, it is clear that niche cumulation is not a sufficient factor for the co-evolution of a TIS; when networked product and mass-market applications are included, policy intervention is a key driver for growth.

Even so, in the formative phase niche markets do emerge and offer opportunities for bottom-up commercialisation strategies, with a fast route to the market. These have little impact, however, on the applications characterised by networks effects. Clearly, the development of niches from the bottom-up strategies will not lead to co-evolution of the whole system and tilt the TIS into a growth phase. This is due to the complex coordination that networked products require, and that firms using bottom-strategies avoid and, in most instances, lack the resources to realise. Examples of niche cumulation in the theory must therefore take these factors into consideration.

Thus, the analysis performed in this thesis partly confirms the literature on niche cumulation, namely that some niches have positive effects on others. However, the context of the products needs to be assessed, because in markets with network externalities, the complexity is high and this makes niche cumulation difficult. As a result, niche cumulation between networked and stand-alone products is not likely to occur. Furthermore, growth of the whole TIS requires strong policy support, something that is not achieved from commercialisation of stand-alone products.

10.2.3. Summary of theoretical conclusions made in the thesis

In this section I summarise the theoretical contribution made in this thesis. First, in relation to the different stabilisation mechanisms I both confirmed existing theory and expanded the previous understanding.

In terms of *confirmation of theory*, I confirm the perspective of Stiglitz and Wallstein (1999), and I also corroborate the findings of Kemp and Munch Andersen (2004) that a *TP* is an important mechanism for developing visions and enabling cooperation in the innovation system. Further, for *knowledge search* I confirm the findings of Powell and colleagues in the biotechnology industry (Owen-Smith & Powell, 2004; Powell, Koput, & Smith-Doerr, 1996) as well as the more general conclusions of Richardson (1972) and Gulati (1998) that firms cooperate due to complementarities between them. I also confirm the perspective of Fligstein (2001) that markets are formed through interaction in the value chain, and I substantiate that conferences, fairs and exhibitions are important to establish *market networks* (Maskell, Bathelt, & Malmberg, 2006).

The findings in this thesis also expand the previous theoretical understanding. While I confirm previous findings on *political networks*, I also extend the view in the previous literature by identifying that informal networks of important industry actors are decisive for creating powerful formal political networks that realise the evolution of an emerging TIS. For the C&S literature, I verify Foray's (1998) findings on the role of standards in situations with high uncertainty, and I also confirm David's findings about uncertainty among users in the early phase. In addition to this, my findings extend the previous literature on

C&S by indicating that C&S drafting should be co-developed with demonstration projects. I have also contributed to the understanding of *demonstration projects* by identifying, more clearly and more emphatically than the existing literature has done, the fact that demonstration projects need to include how market learning occurs. Finally, I have also revealed that firms use a strategy to create *hybrid configurations* between existing institutions and new technology, and have thereby extended the theoretical understanding of hybridisation by developing a taxonomy that includes institutional as well as technological hybridisation.

Table 10.1: **Theoretical contribution in relation to coordination**

Stabilisation mechanism	**Existing literature**	**Contribution**
Technology specific platform	Kemp & Munch Andersen (2004) Stiglitz & Wallstein (1999)	Confirmation
Political networks	Jacobsson & Lauber (2006) Nelson (1995)	Extension
Knowledge search	(Owen-Smith & Powell, 2004; Powell, Koput, & Smith-Doerr, 1996)	Confirmation
Codes and standards	David (1986), Foray (1998)	Extension
Demonstration projects	Geels (2002), Kemp et al. (1998)	Extension
Market networks	Fligstein (2001), Maskell et al. (2006)	Confirmation
Hybridisation	Geels (2002), Raven (2007) Pistorius & Utterback (1997)	Extension

Another theoretical input I made was in relation to *asymmetric evolution*. Here I made two theoretical contributions: first, I developed a new typology of commercialisation strategies in the formative phase, and second, I stated that niche cumulation is valid only in particular situations, and that the context of the products needs to be assessed, as niche cumulation is not likely to occur in markets with network externalities.

10.3. Implications

10.3.1. Propositions

In this thesis I studied the stabilisation mechanisms for the evolution of a TIS in terms of the dimensions of technology, market and institutions. These mechanisms were identified in the meeting between theory and empirical observation, and their importance for evolution was tested in four different situations. A goal of this research, as it is with most case-based research, has been to develop clear propositions of theoretically interesting phenomena that can be tested in similar empirical cases.

Thus, for further research it would be interesting to test the validity of these coordination mechanisms and propositions in other TIS in the formative phase. In this thesis I have researched the dynamics of the early phase of a TIS by means of stabilisation mechanisms. Based on these findings I have developed five propositions about evolution in the formative phase, which can be tested in other TIS in the formative phase.

> Proposition 1: The evolution of a TIS in the formative phase is *asymmetric*, meaning that the various products and applications evolve at different paces and need different stabilisation mechanisms.
>
> Proposition 2: The asymmetric character of the evolution of a TIS affects the way firms commercialise technology. Since the various applications require different stabilisation mechanisms, firms' possibilities to target them are heterogeneously distributed in the TIS. Thus, not all firms can target all applications.
>
> Proposition 3: Bottom-up strategies are targeted by actors outside the main networks that facilitate mass-market introduction. This is due to the complexity of mass markets and the long timeframes. Bottom-up strategies are also targeted by newcomers that excel in building market networks to industries and sectors that are not part of the 'main application' areas.

Proposition 4: The limited number of demonstration units leads to strong competition between regions to demonstrate the technology. Thus, it is necessary to have close links with major actors in order to increase the legitimation of the project.

Proposition 5: Niche cumulation is valid for stand-alone products, but when markets are characterised by network effects, much more coordination is required. Therefore, the transfer to networked markets requires many more stabilisation mechanisms to commercialise the technology (orchestrated strategy).

10.3.2 Implications for firm strategy

This thesis has had a focus on firms and their actions in the formative phase of a TIS. As a result, it is possible to draw some implications for firm strategy in the formative phase.

First, firms can use the framework developed in this thesis to asses the different possibilities and obstacles that exist for the individual firms in the TIS. More specifically, by focusing on these three dimensions of a TIS – technology, market and institutions – the firm can assess and understand the dynamics of different application areas in a TIS, which actors are present in the different applications and how these actors approach commercialisation. The typology of orchestrated and bottom-up strategies is important here.

Second, an important finding is that evolution is asymmetric. This means that the complexity of commercialising various products within the TIS varies. The implications of this for firm strategy relate to market entry into the emerging TIS. The firm should consider market entry in terms of technological and market complexity in relation to size and focus. Furthermore, it is important to consider the type of stabilisation mechanisms the firm is able to make effective use of. This is important, as the research in this thesis has shown that there exist opportunities for fast commercialisation that a single firm can realise, but these opportunities might be too small for a large firm to justify entry into FC&H2. On the other hand, there are opportunities for larger markets available, but these have a much higher degree of technological and market complexity and, as such, require a multifaceted set of stabilisation mechanisms. These might also be too intricate for a small firm to handle, and therefore may fit better with the entry plans of a firm with large resources and a longer timeframe.

Third, another important implication is that in terms of first mover advantages, the research in this thesis showed that there might be large differences in how various firms view these advantages. The findings showed that first mover advantages were highly important for automotive companies, while for the hydrogen retailers the tendency is to explore more alternatives, so that they had a 'wait and see' approach. One reason for this is that the automotive sector is characterised by technological competition, as has been shown in the hybrid vehicles. Thus, the dynamics are quite different from those for fuel supply. When the perspectives on first mover advantages are different, they might lead to differences in commitment and interest in build-up for market entry. Given this, the different actors need to make common decisions on when and how to scale up demonstrations, decisions that can be made in political networks and TP. A conclusion for market entry, then, is that if the market is a niche market with specialised products, it is not likely that large established firms will target this market, but they will target early markets that probably will lead to mass markets. Therefore, for niche markets there will be opportunities for newcomers to enter. However, if network effects exist, the application or product will require a long-term strategy that includes the important role of political networks and policy support. As a result, newcomers need to assess the complexity involved and the extent to which they have the resources required to realise this product.

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12. Appendix:Interview Guidelines

0) Company (Business Unit) main facts

0.1. Name
0.2. Headquarters and locations
0.3. Governance and ownership
0.4. Number of employees
0.5. Main products
0.6. Market share
0.7. Do you have any specific *license agreement* (licensing in) on the technology explored?
0.8. Do you have any specific *patent* (licensing out) on the technology explored?

1) Exploration of new technologies (technology search)

1.1. How do you get access to new knowledge
1.2 How important are the following ways to explore new technologies?

	Not Important 1	2	3	4	5	Very important 6	7
Patent analysis	☐	☐	☐	☐	☐	☐	☐
Research reports	☐	☐	☐	☐	☐	☐	☐
Conferences	☐	☐	☐	☐	☐	☐	☐
Scientific journals	☐	☐	☐	☐	☐	☐	☐
Cooperative agreements	☐	☐	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐	☐	☐

Comments: ……………………………………………….

2) Acquisition of competences

2.1. How important are the following sources for your company to acquire knowledge and competences?

	Not Important 1	2	3	4	5	Very important 6	7
Employment from University	☐	☐	☐	☐	☐	☐	☐
Employment from Industry	☐	☐	☐	☐	☐	☐	☐
Through journals and conferences	☐	☐	☐	☐	☐	☐	☐
Cooperation with Universities	☐	☐	☐	☐	☐	☐	☐
Cooperation with firms	☐	☐	☐	☐	☐	☐	☐
Acquisition of licences	☐	☐	☐	☐	☐	☐	☐
Firms acquisition	☐	☐	☐	☐	☐	☐	☐
Participating in networks or platforms (HFP, H2 Europe, etc.)	☐	☐	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐	☐	☐

Other (explain): ……………………………………………….

3. Cooperation with Universities/Research Centres

3.1 Does your firm cooperate with Universities/Research Centres?
3.2 How many cooperation agreements did you signed with Universities and/or Research Centres in the last 5 years?
3.3 What was/is the objectives of the agreements?
3.4 How do you select your University/Research Centres partners?

	Not Important 1	2	3	4	5	Very important 6	7
General reputation of the U/RC	☐	☐	☐	☐	☐	☐	☐
Specific skills on the technology	☐	☐	☐	☐	☐	☐	☐
Prestige of the researchers	☐	☐	☐	☐	☐	☐	☐
Local proximity	☐	☐	☐	☐	☐	☐	☐
Past experiences	☐	☐	☐	☐	☐	☐	☐
Possibility to exercise control	☐	☐	☐	☐	☐	☐	☐
Commitment	☐	☐	☐	☐	☐	☐	☐
Personal relations	☐	☐	☐	☐	☐	☐	☐

Comments: ………………………………………………….

4) Cooperation with Firms

4.1 How many cooperation agreements ***- R&D and technology co-operations and market cooperation*** - do you have with firms (initial date, length, expiring date, governance model, etc.)?
4.2 With whom (suppliers/competitors/clients/end users – local/international, etc.)?
4.3 Do you have specific agreements involving the public authority (national, regional, local government)?
4.4 What were the objectives of these agreements?

4.5 How do you select your partners?

	Not Important 1	2	3	4	5	Very important 6	7
General reputation of the firm	☐	☐	☐	☐	☐	☐	☐
Specific skills on the technology	☐	☐	☐	☐	☐	☐	☐
Prestige of the researchers	☐	☐	☐	☐	☐	☐	☐
Local proximity	☐	☐	☐	☐	☐	☐	☐
Positive outcomes of past experiences	☐	☐	☐	☐	☐	☐	☐
Possibility to exercise control	☐	☐	☐	☐	☐	☐	☐
Commitment of partner	☐	☐	☐	☐	☐	☐	☐
Personal relations	☐	☐	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐	☐	☐

Comments: ………………………………………………….

5) Networks and platforms

5.1 Are you part of specific networks, scientific communities or technology platforms (Fuel Cells Europe, HFP, local technology platform, etc.)?
5.2 What are the main outcomes expected from participating in these networks?

	Not Important 1	2	3	4	5	6	Very important 7
Source of technical competencies and knowledge	☐	☐	☐	☐	☐	☐	☐
Source of relations and contacts	☐	☐	☐	☐	☐	☐	☐
Source of market information	☐	☐	☐	☐	☐	☐	☐
Lobbying activity	☐	☐	☐	☐	☐	☐	☐
Reputation and image	☐	☐	☐	☐	☐	☐	☐
Privileged access to strategic information	☐	☐	☐	☐	☐	☐	☐
Privileged access to funds	☐	☐	☐	☐	☐	☐	☐
Codes and standards	☐	☐	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐	☐	☐

Comments: ……………………………………………….

6.) Market development

6.1 What is the expected market for your product?

6.2 How do you think these markets will develop in the next 5-10 years?

6.3 What are the critical factors/barriers for the market to develop?
6.4 What is the role of policy makers in commercialisation process?
6.5 What kind of policy instruments do you see as important for the market to develop?
6.6 Who are the key actors? Do you collaborate with them?
6.7. Which are key strategy decisions for your company? (issues regarding development and regarding commercialization)
6.8.1 What role does codes and standards have for the market to develop?