Probing Applications

How Firms Manage the Commercialisation of Fuel Cell Technology

Hanna Hellman

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How Firms Manage the Commercialisation of Fuel Cell Technology

proefschrift

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Preface

We have made quite a mess of planet earth with our fossil fuelled cars and power stations. What I find fascinating is that we human beings also have the ability to do something about it. Established systems are bound to change as radically new and promising technologies are invented and gradually replace incumbent technologies. Such new technologies typically generate both opportunities and threats as well as enthusiasm and resistance. From my perspective, radically new technologies provide opportunities to bring about significant changes towards developing a more sustainable energy system. Of course it is also important to think about the small things (turn off your lights, recycle etc.) but it is in my nature to pursue the big steps. I like big and effective changes. This personal interest in radically new energy technologies lies behind this PhD thesis. In addition, the thesis has been shaped by my interest in fuel cell technology. I still hope to, one day soon, bicycle behind zero emission cars and walk through London breathing clean air.

There is an allure to hydrogen fuel cell technology. It is an apparently simple zero emission technology. Nevertheless, there are heated debates on the desirability of hydrogen and fuel cells. The commercialisation of this technology is promising but at the same time uncertain. I feel fortunate to have been part of this dynamic and promising industry in the previous years.

This PhD directly follows the graduation project of my masters degree in Industrial Design Engineering (IDE) that explored early applications for fuel cell technology and presented a preliminary design of a fuel cell powered people mover. The project gave insight into the challenges of selecting and developing fuel cell demonstration products. My curiosity to further explore this topic was ignited and the PhD research project provided a great opportunity to do so. At the start of this PhD I set out to develop a tool for designers to support the integration of fuel cell technology into products. However, I soon found that designers do not have a particular problem with fuel cells because designers are masters in exploring and learning about new and unfamiliar topics. Inspired by talks, discussions and presentations at fuel cell conferences, I became intrigued by the young and independent firms of the fuel cell industry and how they manage the challenges of commercialisations.

With an IDE background, I found that PhD research required quite a mind-shift from a problem solving approach of a designer to the process of conceptualization and justification of academic research. However, in my opinion IDE has also provided a unique point of departure. As an IDE I found myself on the interfaces between technology and markets, theory and practice and technological and product innovation. In the process of technological innovation I believe that IDE can play a role in bridging new technologies and markets. For this reason I have positioned this PhD on the market application of fuel cell technology.

This PhD thesis revolves around the market application of fuel cell technology in young and independent fuel cell firms. In my opinion, many of the entrepreneurs of the fuel cell industry are great visionaries, marathon runners and risk takers. I greatly respect these companies and I wish them all the best in the coming years. I am indebted to the fuel cell firms that have enabled the case study research of this thesis. Thank you for taking the time to talk to me, providing insight into the fuel cell industry and your companies.

I owe a great deal to my ‘dream team’, a unique combination of intellect, enthusiasm and perspectives. Our lively discussions have been an invaluable learning experience. First, Prof B, Han Brezet, the creative entrepreneur and the spider in various webs. Thank you for giving me the opportunity to be part of your DFS family and moreover, for believing in me and supporting me all the way through. Casper Boks, the self-denying genius. Your pragmatic, sharp and energetic nature has been extremely inspiring. Robert van den Hoed, the thoroughly critical academic. You have challenged me time and again, analytically and conceptually, boosting my batteries to learn and improve. Thank you for your time, commitment and support.

For all these years I have been part of the Design for Sustainability family, a special and continuously changing international group. Thank you JC, Uri, Renee, Priscilla, Pablo, Daphne, Hitoshi, Susan, Oi, Duygu and many others. I am sorry for having left you all so suddenly, running back and forth to my new life in London. Although ten years of Industrial Design has definitely been enough, I will miss our social aquarium, so full of inspiring eye-opening ideas and projects.

I am also thankful to the ICEPT at Imperial College and David Hart in particular. Thank your for welcoming me into your group and enabling my (extended) visit. I would also like to thank David Joffe for helping me out and the wonderful group of colleagues (Sophie, Poppy, Ausilio, Raffaelle, Marcello and Isabelle) for the ‘warm’ welcome and working environment. I also owe a word of thanks to the NWO (Nederlandse Organisatie voor Wetenschappelijk Onderzoek) for providing financial support to realize this visit.

Furthermore, I have had some priceless support in preparing this thesis for publication. Liesbeth, thank you so much for your meticulous and professional support in proof reading my entire thesis from a to b. Lieke, I greatly appreciate your creative support in the design of my cover. I thoroughly enjoyed working with you.

I am greatly obliged to my incredible family: the endless pool of positivism and support. You have taught me to wake up with a smile and motivate myself every day. In my opinion this was an invaluable asset for the solitary journey of a PhD. I would also like to thank my second family for coping with my fifth gear mode and the continuous support. Last but definitely not least, my Dirk Jan. Thank you for listening to all my enthusiastic stories as well as doubts and uncertainties. I promise you Dirk Jan, fuel cell applications and innovation processes are not ‘rocket science’. But they are fascinating.

I hope you are also curious to learn more about fuel cell technology and the market application of radically new technologies.

Hanna Hellman

October 21, 2007

Summary

Between the invention of a new technology and its commercialisation typically lies a lengthy process of demonstrations, prototypes, early applications and niche markets. Within this process, technology application involves challenging decisions on which markets to pursue at which point in time. The challenges and uncertainties of technology application prevail in the case of *radical technologies,* i.e. technologies new to the world that change the entire order of things, making old ways and competences obsolete. This study addresses how firms manage these early applications of a radical technology prior to widespread commercial sales.

Fuel cell (FC) technology provides an interesting case to study the early applications of a radical technology. For more than a decade, a multitude of FC demonstrations and early applications have been developed and presented. During this process, FC firms face challenging application decisions: there are multiple applications for FC technology to choose from, yet the widespread adoption of FC technology is uncertain to date. The development of FC technology has brought forth the emergence of numerous young and independent FC firms, i.e. independent developers, founded in the previous ten years, whose business activity is exclusively the development of hydrogen and FC technologies. To commercialise their technology, these young FC firms are challenged to identify, select and develop applications of their technology at the right time.

This exploratory study revolves around the selection and development of applications for a radical technology. Both a practical and a theoretical research objective are pursued. On the one hand, this study aims to provide FC firms with insight into their process of commercialization. On the other hand, this study aims to integrate and extend existent theory on the application and diffusion of radical innovations. Thereby, this study builds on innovation and technology marketing literature. Prior literature describes phases of technology development from alternatives and rapid change to a dominant design and incremental change. Additionally, the process of technology commercialisation is described as an accumulation of niche markets. At a firm level, management practices are characterised by experimental applications and learning, or a process of 'probing and learning'. Such experimental probe applications are typically costly and time consuming with no guarantee of success. Given the context of uncertainty, it is relevant to gain a better understanding of how decisions are made and how this process of probing and learning is managed.

Chapter 2 provides an introduction to FC technology and background documentation on the empirical domain of this study. The study shows that FC technology is diversely applicable and competes with several other technologies to replace batteries, combustion engines and grid power. The status of the technology indicates that there are several technical challenges ahead, but there are also expectations for short and mid term niche markets. Furthermore, the evolution of the FC industry shows the emergence of various independent FC firms. Chapter 3 takes a bird's eye perspective of this introduction to FC technology, characterising the technology to gain more insight into the management challenges of FC technology application. In addition, several FC projects are described. The projects indicate that the realisation of early applications can be characterised as a learning process for various stakeholders. The subsequent comparison of FC technology to other technologies suggests that FC technology follows a similar process of commercialisation but is particularly 'application diverse'. Finally, the application challenges for young FC firms are further characterised. Young FC firms typically have limited resources to allocate and multiple markets to choose from whilst the application of FC technology involves strategic choices on the development of legitimacy, skills and partnerships. The characterisation of FC technology and FC firms further specifies the empirical problem under study and focuses subsequent research on the selection of early applications in young technology based firms.

Chapter 4 reviews innovation and technology marketing literature. On the basis of varying degrees of innovativeness, FC technology is described as a replacement technology, radical to stakeholders in terms of their unfamiliarity with the technology and the required changes to their competence base. Literature suggests that this radicality causes uncertainties of technology development and market adoption, characterising radical innovation as a dynamic process of continuous learning and parallel activities in technology and market development. Management practices proposed involve experimental applications and learning. Thereby the concept of probing and learning is found to be particularly suitable to describe and analyse the process of technology application, i.e. a series of probe applications with early immature versions of a technology/product into a variety of market segments as a vehicle for learning. However, prior studies on this phenomenon of probing and learning are preliminary and have raised more questions than have been answered. There is a limited understanding of: i)'probe decision making', i.e. how firms select probe applications over time and ii) what characterises this process of probing.

In chapter 5 concepts from organisational theory on strategic decision making and organisational learning are reviewed. A dynamic capabilities perspective is chosen as an interpretive lens to explain probe decision making. Thereby, both factors internal as well as factors external to the firm are expected to have an effect. Various factors are identified from theory including a firm's resources and history and a firm's level of competences and capabilities. External to the firm, the development of industry expectations, the regulatory environment, partnership and customer familiarity are identified as factors that are likely to influence the strategic alternatives open to the firm. Consequently, there are different theoretical explanations to what drives probe decision making in FC firms, including:

- A firm's history, competences and capabilities, whereby decisions are based on strategic intent and a firm's capabilities.
- Industry expectations, whereby decisions are based on the beliefs and expectations of an industry and firms follow other firms in the industry, irrespective of a firm's internal competences and strategy.
- Resource dependency, whereby firm decisions are explained by the pursuit of probe opportunities for revenue, irrespective of strategic intent or industry expectations.

Applied to the concept of probing and learning, this study suggests that the role of these factors in explaining probe decisions changes over time as firms learn and the external environment changes. This chapter subsequently discusses concepts from organisational learning in the innovation process. Firms can decide to engage in explorative or exploitive activities. Applied to the process of probing and learning, firms can choose to engage in: i) explorative probes in new markets and ii) exploitive probes, building on prior probes in the same market. The second relevant concept from organisational learning is that firms are expected to learn by discovery prior to adaptive cycles of learning within the innovation process.

Chapter 6 proposes two models of technology application, using the literature reviews as building blocks. A descriptive model is presented to structure the description and analysis of probing processes. Probe decision making is modelled along two variables: the breadth of markets and the length of probe paths. On the basis of this structure, three phases of probing are predicted. These phases of probing are characterised by the selection of predominantly explorative or exploitive probe applications and the dominance of learning by discovery or adaptive learning. Finally, a conceptual model is proposed to explain probe decision making over time. The model suggests that in each phase of probing, factors either internal or external to the firm drive probe decision making. Five propositions and four specific research questions are proposed to guide the analysis of a case study research. Four young FC firms are selected for the case study research. The data is gathered from interviews with management personnel in the case firms, press releases and archive documents.

Chapter 7 describes the case study research. For each case firm an historical account is given of the probe applications pursued over time. These probing histories describe the rationale for probe engagement, characteristics of the probe applications and the experience gained. The case studies show that probe applications are pursued for various reasons including demonstrations, technology development, customer education, partnership formation and initial revenue. The probes show variable characteristics in terms of size, duration, involvement and target group. With the experience gained, firms shape their competences and modify their strategies. Each case is analysed individually to explain how and why the firms engaged in initial probes, selected new market segments, chose to shift from one market to another and decided to continue or abort developments in a particular market segment.

Chapter 8 presents a cross-case analysis in which the cases are analysed and compared along the theoretical constructs identified and patterns predicted in chapter 6. The role of these constructs in explaining probe decision making is discussed. Industry expectations appear to influence the scope of applications from which a firm selects initial probes; the level of a firm's value propositions and customer familiarity drives applications in a breadth of market segments; and firms respond similarly to the emergence of market demand. The probing histories are subsequently compared to characterise the probing process and derive patterns of probing. The analysis finds similar phases of probing: an explorative phase of initial probes, a phase of experimental probes and finally developmental probes. The comparison additionally shows variable patterns of probing in terms of breadth of market segments, the length of probe paths, timing, the market segments pursued and the number of probes. Finally, the propositions are tested and new propositions are derived from the case study data to explain probe decisions and probing patterns.

Chapter 9 presents the conclusions and recommendations of this study. The main findings of this study include: i) a model to describe and analyse a firm's probe applications over time, ii) a conceptual model to explain probe decision making over time, iii) a characterisation of phases and different patterns of probing.
The descriptive model provides a useful approach to describe and represent the probing histories of firms, by generating an overview of probe decisions, their consequences and interrelations over time. The conceptual model suggests that in different periods of probing, different factors drive probe decision making. It is concluded that early application decisions of new (fuel cell) technologies are initially driven by industry expectations, subsequently by heterogeneous firm strategies and priorities and finally by market demand. These findings explain the observation of similar and different patterns of probing. This study suggests that firms go through similar phases of probing: firms first explore initial applications and experiment with applications in alternative market segments, characterised by a diverging process of discovery. Subsequently, a transition is made to the development of a select number of probe applications in a converging process of adaptation. Different strategies are primarily pursued in the experimental phase of probing. A focused and a broad archetype of probing are identified: i) focused probing in a select number of market segments characterised by long iterative development paths versus, ii) probing in a breadth of markets characterised by a search for specific (niche) markets and developments through cross-over learning from various applications. These findings are more broadly applicable than to the FC industry alone. Particularly, the findings can be generalised to the application of novel replacement technologies in young technology based firms.

The research findings contribute to an understanding of the innovation process by highlighting how firms manage the process of technology application. Insight into the application process can support firms in managing this process more effectively by enabling them to strategically plan actions accordingly and foresee the consequences of decisions. To manage the process of probing and learning, this study recommends a 'quasi-experimental' approach with prior assessments and post evaluations to: limit the breadth of probing and distractions and maximise the cross-over learning and the competitive advantage from specific probe experiences. This study finds that probing and learning is not only a management practice but also a survival necessity. The case of FC technology and young FC firms suggests that financial support and protection from governments is particularly necessary in this phase of technology applications prior to widespread commercial sales.

Hanna Hellman

Chapter 1: Introduction

> *" The implementation of a technology is at least as challenging as its invention".*
>
> *Leonard-Barton 1988*

1.1 From Invention to Commercial Sales

Fuel cell technology appears to be an ideal energy technology: a clean conversion of hydrogen to electricity, water and heat. The technology can be applied in a broad range of products and penetrate our daily lives, yet, commercialisation is proving to be a lengthy process. Historical cases suggest that the widespread diffusion of new technologies takes several decades[1] and that many technologies fail to gain acceptance past small specialised markets (e.g. Rosenberg 1976, 1995, Geels 2002). As Leonard-Barton (1988) suggests, the implementation of a new technology is a long and challenging journey marked by uncertainties of technology development and market adoption. Within this context of uncertainty, firms are challenged to select and develop applications for their technology. This study revolves around the selection and development of applications for a new technology prior to widespread commercial sales.

Firms have developed numerous prototypes, demonstrations and early applications of fuel cell (FC) technology in a diversity of markets. Fuel cell technology provides a case to study the process of technology application when there are multiple applications to choose from, whilst widespread commercialisation is uncertain to date. Thereby, this study takes two starting points: this empirical problem observed in the FC industry (1.2) and its relevance for studying how firms manage the process of technology application (1.4) to contribute to innovation and high technology marketing studies (1.3).

1.2 Empirical Problem: the Application of Fuel Cell Technology

The commercialisation of FC technology involves the application of a technology that is new to the world. FC technology is applicable to a diversity of products and the FC industry has identified and propagated numerous potential market applications, commonly categorised as portable power, stationary power and transportation. Therein, the automotive market has the largest market potential. The widespread market potential for FC technology has driven innovation in established firms and the emergence of various entrepreneurial firms. However, until recent years there was no observable market or clearly defined consumer demand and the technology lacked cost and performance competitiveness. In this context, it has been difficult to predict the market adoption of FC technology. Before the year 2000, there were near term ex-

---

[1] According to Geels (2002), technological transitions easily last 30 to 40 years. Among others, Geels describes the transition from horse and carriages to automobiles in 60 years. Rosenberg (1995) describes the difficulty and duration of finding applications for new technologies such as transistors, the wireless telephone and the personal computer.

pectations for the widespread diffusion of FC powered cars[2]. However, once the first cost calculations were made, developers realised that widespread adoption was further away than initially expected (Hoogers 2003). In recent years, fuel cell related firms have postponed their expectations for FC cars to 2015 and beyond (Van den Hoed 2004). In the meantime most FC firms have engaged in the development of prototypes, demonstrations and niche market applications. The application of FC technology is proving to be a long term process of numerous niche market applications prior to widespread commercial sales.

This study addresses this application process and how FC firms manage the selection and development of early applications prior to widespread commercial sales. Several niche markets are expected to emerge prior to large scale markets, however, there has been considerable uncertainty about which markets would emerge at which point in time. FC firms face challenging application decisions: there are multiple applications to choose from, yet, the selection and timing of near and long term market applications is highly uncertain. The young and independent firms in the FC industry are primarily concerned with application decisions. By 'young FC firms' this study refers to independent developers whose business activity is exclusively the development of hydrogen and FC technologies, in contrast to large established firms with subsidiary FC activities. Driven to commercialise FC technology, these young FC firms are faced with challenging decisions to identify, select and develop applications of their technology. Therefore, to address this 'problem' of FC application decisions, this study will focus on young FC firms.

In the past 10 years, young FC firms have applied their technology in prototypes, demonstration projects and niche markets despite the lack of cost competitiveness, the lack of clearly defined market demand and the uncertainty of timing. A young FC firm describes such early applications as a survival necessity, *"if we waited, we'd be dead"*[3]. Another FC firm argues that, *"the large industries, they are not going to wait for us."*[4] Moreover, applications were necessary to explain the technology to customers, such as kettle builders and vehicle makers, as a FC firm describes, "*you have to explain everything about how it works.*"[5] In addition this FC firms argues that market applications help to understand 'who wants it' and 'what they want'. The selection and development of early applications appears to be a necessary phase prior to commercialisation. However, this period of early applications involves high investments with low returns whilst the young FC firms are typically constrained in the availability of resources. Thus, application decisions are not only made in an uncertain context but also under resource constraints. Considering the challenges faced, this study focuses on how young FC firms manage the selection and development of early applications: a study on the 'survival' of young FC firms in the long and uncertain process of technology application. Thereby, the 'process of technology application' is referred to as the applications of a firm's technology pursued over time towards commercialisation.

Practical Relevance

Understanding how young FC firms manage the process of technology application is central to the commercialisation of FC technology as well as the development and survival of young FC firms. FC firms face decisions on which markets to pursue at which time, considering the uncertainties of technology development and market adoption. In view of the costs and uncertain outcomes the selection of early applications is critical for young FC firms. Besides, FC firms have to select applications with respect to the experience they wish to gain and the markets they want to be in. This study will look back at the application decisions of young FC firms, gain insight into the applications pursued, the consequences of these decisions and where their applications are now with respect to prior decisions and future plans.

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[2] Illustrative are statements by DaimlerChrysler in 2000 that by 2004 a few thousand FC vehicles would be introduced for a targeted price of $18.000.

[3] Interview Intelligent Energy in London, January 2006

[4] Interview Nedstack in Arnhem, November 2005

[5] Interview Plug Power,in Apeldoorn, January 2006

1.3 Literature Focus

The commercialization of FC technology relates to various fields of literature and disciplines. Literature on the development of new technologies uses different levels of analysis and studies different units of analysis as points of departure: i) a meso level perspective to study technological transitions, the institutional environment, technological cycles and industry development and ii) a micro level perspective to study organizations, individual firms, projects and entrepreneurs. This paragraph briefly describes these two perspectives. To focus this study, the unit of analysis is specified and a selection of literature is made.

FC technology can be studied as part of a technological transition from a fossil fuel based economy to a more sustainable energy economy. Among others, Kemp and Rotmans (2004) have described technological transitions for the hydrogen economy. Scholars in this theoretical field, such as Rip and Kemp (1998) and Geels (2002) have taken a multi-level perspective to study the co-evolution of technology and society in technological transitions. The commercialization of FC technology additionally relates to the formation of an institutional environment as technology and industry develop. From a meso level perspective, scholars have studied the co-evolution of policy institutions, a new technology and an industry structure (e.g. Nelson 1994, Van de Ven and Garud 1994). Furthermore, the commercialization of FC technology involves the emergence of a new industry and relates to literature on the creation of new industries (e.g. Audretsch 1995, Aldrich and Reuf 2006). Thereby, scholars take an industry level perspective to analyze the evolution of a sector and the life cycle of an industry. The life cycle of an industry is strongly related to the life cycle of a technology. Technology life cycle and dominant design literature addresses how new and large scale technological innovations occur and how dominant designs emerge (e.g. Tushman and Anderson 1986, Utterback 1994). These meso level perspectives provide an understanding of the context in which FC technology application takes place, but are less suitable to study a firm's internal aspects such as application decisions.

Literature on entrepreneurship addresses firm-internal aspects of new businesses and innovation. The application of a new technology is strongly related to the emergence and evolution of entrepreneurial firms. Entrepreneurship literature describes the emergence of entrepreneurial firms from the perspective of an individual entrepreneur (e.g. Bhidé 2000, Gartner 2004) and the network or technology cluster the firm belongs to (e.g. Hulsink et al. 2004, Bouwman and Hulsink 2000). This field of literature also addresses firm growth, for example, Aldrich and Reuf (2006) describe how organizations evolve and Kazanjian (1988) has proposed a model of firm growth in relation to the challenges of technology commercialization. Entrepreneurship literature is likely to provide a valuable contribution to understanding the characteristics and growth of young FC firms. However, the discipline is less suitable to explain technology application as an innovation process.

In the field of innovation management, new product development (NPD) and marketing, literature takes a firm level perspective on the development and application of new technologies. These studies can be characterized by a focus on the process and design of an innovation. For example, Van de Ven et al. (1999) address the cycles and stages of the innovation process within firms. NPD scholars have presented several models of the product innovation and design process (e.g. Cooper 1983, Buijs 1984, Roozenburg and Eekels 1995). Furthermore, innovation studies have addressed how firms manage different types of technologies in terms of their innovativeness (e.g. Veryzer 1998, Tidd et al. 1997) and the uncertainties faced in the process of radical innovation (e.g. Rosenberg 1995, Utterback 1994). In technology marketing studies the interaction between a new technology and its users is addressed (Lundvall 1988, Coombs et al. 2001). These innovation and marketing related studies provide insight into how organizations go about innovation and technology application.

Thus, relevant literature on technology commercialization is broad and can be studied from various perspectives and foci, such as policy, the industry, the technology, the firm and the firm's founders. In order to focus the research and outcome targets, this study will use a selection of literature as its point of departure. Starting from the empirical problem of application decisions in FC firms, this study focuses on the process of technology application. The preferred level and unit of analysis to research 'how firms manage the process of fuel cell technology application' is: technology applications from a firm level perspective. Considering this focus, this study chooses literature on technological innovations and technology marketing as its starting point. Furthermore, the innovation and marketing approach is taken for the following reasons:

- This study is conducted for the Delft University of Technology. As a technical university, the technology and its development are of primary interest. It can be argued that innovation studies are most suitable to open the black box of technology development. From a meso level perspective as well as social and business oriented studies, the development of a technology tends to disappear from view (Geels 2002).
- Moreover, this study is conducted for the faculty of Industrial Design Engineering. This faculty is geared towards product innovation and development. Using technological, product innovation and marketing literature as a starting point best fits the research targets, teachings and focus of this faculty.
- Technology application requires a multi disciplinary approach. Innovation studies are inherently multidisciplinary, combining disciplines such as engineering, design, marketing and strategy.

In conclusion, this study will use innovation and technology marketing literature as its point of departure. Other related fields of literature, including technology cycles, new industry development and entrepreneurship, will be touched upon to characterize the context and complement the innovation and marketing studies where necessary. Thus, this study will primarily make use of and contribute to innovation and technology marketing literature to address the application of new technologies.

1.4 The application of Radical Technologies

Academic work on innovation and technology marketing addresses the process of managing, developing and diffusing new technologies. The application of a new technology is considered to be 'disruptive' or 'radical' when market demand is yet to emerge and the undertaking requires different technical, market and business skills than a firm possesses (e.g. Christensen 1997). Radical innovations change the entire order of things, making old ways and skills obsolete as opposed to incremental innovations that build on what is already present (Van de Ven et al. 1999). In the case of 'radical' technologies, the innovation process involves a higher degree of uncertainty and complexity than 'incremental' technologies.

When a technology is new to the world and there is no market demand as yet, markets for the technology will emerge as a technology matures. Therefore, technology commercialisation takes place in a co-evolutionary context in which both technology and market develop: the technology is immature and evolving and the market is not well defined and evolving and the two interact (e.g. Lynn et al.1996, Leonard-Barton 1995, Coombs et. al. 2001). This co-evolutionary context implies that technology application goes through a phase in which both technology and markets are developing. This period is characterised by a diversity of technical alternatives and possible markets that are not clearly defined (Utterback 1997). In this dynamic context, it is difficult to predict what the end product will look like, who will be the customer and when it will be adopted. This process of technology application is, therefore, marked by a high degree of uncertainty with no guarantee of success (Lynn et al. 1996, Van de Ven et al. 1996). Uncertainties of market adoption prevail when the technology is radical because customers perceive the technology to be risky and are likely to resist change (Tidd et al. 1997). Moreover, Hall and Kerr (2003) argue that environmental radical innovations in particular, are under greater scrutiny than incremental approaches. Thus, the application and diffusion of radical technologies is characterised by uncertainty and the difficulty to predict the outcome of application decisions.

Literature on the process of NPD and innovation suggest that the success of a product innovation is derived from understanding and meeting customer requirements and preferences (e.g. Cooper and Kleinsmidt 1987, Maidique and Zirger 1984). Achieving this 'match' concerns both the selection of applications and the development of applications:

- To identify potential applications and specific customers where the technology fulfils a 'latent' need.
- To develop an application that meets customer requirements.

Evidently, 'matching' a technology to market opportunities and customer requirements demands insight into the potential markets for application. However, classic market research methods are argued to be an unreliable source of information when customers are unfamiliar with a new technology (Von Hippel 1988, Shanklin and Ryan 1987). Besides, a technology almost never fits perfectly into a user's environment at once (Leonard-Barton 1995). Apparently, the application of a radical technology requires a different approach to developing market insight. In particular, scholars recommended more exploratory and anticipatory methods to gain familiarity with markets and customers (e.g. Shanklin and Ryan 1987, Deszca et al.1999).

1.3.1 Implications for the Innovation Process

The co-evolutionary context and high levels of uncertainty imply that radical innovations require different management practices than incremental innovations. Product innovation processes are often portrayed as linear models where a product proceeds from one phase to the next. Cooper's (1998) stage gate model, for example, describes a linear process through continue/no-go decision moments. These types of models assume that information is available for analytic and rational decision making. Additionally, the models typically describe the development of one product and assume that a technology is 'ready' to pass through the assessment stages. Scholars have argued that in practice the innovation process rarely proceeds in such a linear fashion (e.g. Arrow 2000, Van de Ven et al. 1999). Particularly the 'front end' of an innovation process has been described as 'fuzzy' (e.g. Moenaert 1995, Khurana and Rosenthal 1998). According to Buijs (2003) these models are useful as a guideline for educational purposes, however, in real corporate life product innovation processes have a more chaotic character.

Van de Ven et al. (1999) describe the innovation process for radical technologies as a dynamic cycle of parallel activities in technology development and applications. In comparison to the linear models of product innovation, multiple applications are pursued instead of a single product. Additionally, the outcome of the process is considered to be intermediate instead of a final product. Furthermore, it is argued that the outcomes of the innovation process are difficult to assess and predict in a context of uncertainty. Therefore, the innovation process is described as more experimental than analytic and involves a great deal of learning. Furthermore, instead of traditional marketing instruments based on demand driven techniques, radical technologies require a supply driven approach. Thereby, developers are responsible for stimulating customer interest and demand (Shanklin and Ryan 1987). Thus, the application of a radical technology is likely to require a different form of management than is needed for more incremental technology and product development processes.

Lynn et al. (1996) have observed that successful firms manage the uncertainties of radical technology application through a process of 'probing and learning'. In the process of probing, firms apply immature versions of their technology to a series of market experiments as a vehicle for learning. Lynn et al. observe that through this process of probing, firms develop market insight and an understanding of their technology in practice. Similarly, Berchicci (2005) recommends an 'experimental' approach for environmental innovations. The framework of 'probing and learning' appears to be an appropriate framework to describe and analyse the process by which firms apply radical technologies.

1.4.2 Literature Gap

A gap is identified within the scope literature. Several innovation scholars suggest that radical technology application is characterised by experimental behaviour and a great deal of learning (e.g. Leonard-Barton 1995, Tidd et al. 1997). The concept of 'probing and learning', observed and introduced by Lynn et al. (1996), appears to be highly appropriate to describe and analyse the process of technology application and application decisions. However, research conducted on 'probing and learning' is preliminary and limited to observations of the process. To further develop this concept and better understand the process, further research is required:

- To derive patterns of 'probing and learning'
- To understand the process of learning
- To explain probe decision making

To further develop the concept of 'probing and learning' as a management practice for technology application, the process should be observed in other cases. Through an analysis of 'probing and learning' patterns a more general model of 'probing and learning' can be derived. Perhaps a variation of 'probing types' can be identified. This study expects that understanding the general patterns of this process can contribute to a better understanding of management principles for the application of radical technologies. Moreover, the concept of 'probing and learning' is based on cycles of learning from probe applications. Consequently, it can be argued that probing is only effective, if learning takes place. Lynn et al. (1996) observe that firms learn and gain experience in markets. However, further research is required to understand how a technology develops and how firms develop market competences through probing.

Finally, this study suggests that further research is required on the selection of probe applications, or 'probe decision making'. Probing applications is generally a time and resource consuming activity with uncertain outcomes. Therefore, there are risks associated with selecting the 'wrong' probes, such as wasting resources or developing competences of limited value. Prior research has not addressed how probe applications are selected in the innovation process. An understanding of probe decision making is particularly relevant to young technology based firms. Firms whose business activity is exclusively the development and application of a new technology, are typically in search of market opportunities for applications. Additionally, decisions on which markets to pursue at which moment in time are, at least partly, determinant for the survival and development of the young technology based firms. Moreover, these firms have limited financial resources and time to allocate. There is, therefore, a relative urgency of determining valuable applications and 'the right' customers for probing without wasting resources.

In general, innovation studies have paid limited attention to innovation processes and management practices in the entrepreneurial firms of an emerging industry. Predominantly the focus is on large established firms in moderately dynamic markets, addressing how these firms should react to radical change to remain competitive. Considering the above mentioned 'gap' in innovation and technology marketing literature, this study will focus on 'probing and learning' in young technology based firms. To integrate and extend theory on the process of technology application this study will focus on: 1.the process of learning from applications, 2. the factors that explain technology application decisions, and 3. patterns of technology application.

1.5 The Type of Research

This chapter has specified an empirical domain of study - the FC industry - as well as a theoretical scope of study - the application of radical technologies. The specified empirical problem in the FC industry suggests a practical approach whilst the specification of a literature gap suggests a theoretical approach of the research. Starting from both practice and theory appears to involve contradictory approaches to research. Practically oriented research implies that the empirical domain is specified beforehand to solve problems for the specified sector. A purely theoretical approach would either be inductive, without specifying a population, or entirely deductive and specify an empirical domain at a later stage. So what type of research does this study entail?

Deductive research is dominant in natural sciences and is characterized by rigorously testing hypotheses formulated from theory. This approach implies that the study would start with a literature review to identify a gap, formulate quantifiable hypotheses and subsequently select cases to test the hypotheses. By contrast, inductive research is based on gathering data and making sense of the data to formulate and build theory. This approach is suitable to better understand the nature of a problem and is primarily concerned with the way in which events take place. Inductive research is often conducted in the form of 'case studies'. Case study research is particularly suited to answer 'how' questions, to study real world situations and to explore real world phenomena that are not well understood (Yin 1994). Both the practical and theoretical objectives of this study are concerned with gaining an in-depth understanding of the technology application process. Case study research is typically of an explorative nature and provides an in depth understanding of the phenomenon under study. Therefore, this study will conduct inductive case study research.

An approach to case study research, with the objective of theory building, is described in the work on 'grounded theory building' (Glaser and Strauss 1967, Strauss and Corbin 1990). The grounded theory approach to case study research is, ideally, entirely inductive: the study begins with data and emphasizes the emergence of theory solely from evidence. However, as Eisenhardt (1989: p.536) argues: *"It is impossible to achieve this ideal of a clean theoretical slate".* According to Eisenhardt, some degree of a priori specification enables more accurate measures of the phenomenon under study. Eisenhardt suggests that prior to a case study it is valuable to:

- Specify the research problem and the research question
- Identify important constructs from literature
- Specify a population

From this approach, case study research does not start from a 'clean theoretical slate' to build theory. Rather, the research integrates and extends existent theory. Considering the valuable concepts and models available in literature on innovation processes and technology marketing, this study chooses to build forth on literature. In line with Eisenhardt's (1989) case study approach, this study has also specified a problem in the FC industry. The problem specification has pointed to a research focus on application decisions. Finally, the FC industry has been selected as the population under study, i.e. a 'case' of radical technology application. The decision to focus on the FC industry is further specified in the following section. This case study approach has determined the structure of this study, which will be described in section 1.6.

1.6 The Case of Fuel Cell Technology

Departing from Eisenhardt's (1989) approach to case study research, a population has been specified. It is argued that the selection of a population minimizes the extraneous variables to explain a phenomenon under study. FC technology will be studied as a case of radical technology application for the reasons described below.

Prior studies have charted innovation journeys that have brought about major changes to societies, economies and industries. Studies of the automotive, semi-conductor and computer industry have provided valuable lessons on the process and management of radical innovations (e.g. Abernathy and Utterback 1978, Iansiti 1997, Balachandra et al. 2004 respectively). However, further research is necessary to advance our understanding of radical innovations. As Van de Ven et al. (1999 p.16) state: *"many innovation journeys remain uncharted".* FC and hydrogen technologies have the potential to bring about major changes in the energy economy, energy industry and the products we use in our daily life. FC technology provides an opportunity to learn from and chart a 'major' innovation journey. The comparison with prior studies provides a point of departure to integrate and extend theory on the process of technology application.

Each case of radical innovation has its particularities and is likely to give further insight into the process of application and diffusion. Likewise, there are lessons to be learnt from the commercialisation of FC technology that may contribute to an understanding of innovation journeys. FC technology appears to be a particularly 'application diverse' technology, providing an opportunity to study the process of technology application when there are multiple applications to choose from. Considering the uncertainties and challenging application decisions, FC technology provides an appropriate case to study how firms manage the application of a new technology. Besides, FC technology is an environmental technology. Although this study will not consider FC technology as a case of radical environmental innovation, it is relevant to better understand the application of FC technology, considering the increasing concerns for environmental problems and the apparent slow diffusion of sustainable energy technologies (Tester et al. 2005).

Moreover, FC technology provides the opportunity to study the pre-commercial phase of technology application in real time and in recent history: initial markets and customers have been selected and pre-commercial applications developed, however, as yet widespread adoption is uncertain. By contrast, prior studies on radical innovations are predominantly historic ex post facto studies and few studies have examined the innovation process in real time or in recent history. Although 'looking back' enables an analysis of outcomes and may result in prescriptive and predictive research findings, this study expects that a real time and recent history case study will enable an in-depth analysis of the decisions made, the applications realized and their consequences. The current status of FC technology additionally enables a detailed analysis of how markets for a new technology emerge. Finally, the FC industry is in the process of formation and various entrepreneurial firms have emerged. Therefore, the emerging FC industry also provides an opportunity to learn more about the innovation process in young technology based firms.

Thus, FC technology will be studied as a case of radical technology application. This specification is expected to enable an in-depth study of application decisions and the technology application process. The implication of studying an ongoing process is that there is limited quantitative data available on technology application and it is not possible to measure the success or effectiveness of application decisions. Therefore, the research will be characterised by predominantly qualitative data. Additionally, the research is of an exploratory nature and primarily expects to derive descriptive and explanatory findings from the case of FC technology.

1.7 Research Objectives and Questions

The case of FC technology points to the difficulty of selecting applications in a context of uncertainty when there are diverse applications to choose from. Considering the generally uncertain and lengthy process of radical technology application, this research revolves around the selection and pursuit of applications prior to widespread commercial sales. The general objective of this study is, therefore, to gain a better understanding of how young firms manage early applications of their technology. Thereby, a practical and a theoretical research objective are pursued.

The practical objective of this study is to provide the FC industry and young FC firms in particular with insight into the process of FC technology application. The study will look into application histories, the rationale and consequences of selecting applications and the overall process. Considering differences in firm characteristics and objectives, a single best approach cannot be recommended. However, patterns in the selection of market applications and the development of experience can be identified and may provide insight into the strategies applied and their consequences. Hereby, this study aims to provide FC firms with an analytic view of the prior and current process of FC technology application. Considering that FC technology is likely to face similar challenges and follow similar patterns as other innovations, the practical objective is also to support the entrepreneurial firms targeting the commercialisation of other new technologies. This study expects that insight into the application process can support firms in managing this process more effectively by enabling them to direct actions accordingly and foresee the consequences of decisions.

The theoretical objective of this study is to contribute to literature on innovation and high technology marketing with a better understanding of the technology application process. Departing from the concept of 'probing and learning', this study aims to extend and integrate existent theory. Prior research on the concept of 'probing and learning' is preliminary. Therefore instead of aiming to test or confirm hypotheses, this research is of an exploratory nature. In particular, the study aims to gain a better understanding of the selection of probe applications, the learning experience gained from probe applications and the characteristics of the probing process. Thereby, patterns of the probing process and insight into what drives different patterns of probing may be derived. Considering the exploratory objectives of this study, a *how* question is raised on the application of a firm's technology. The following central research question is proposed:

How do firms apply their technology to markets and how do they develop the ability to do so?

The central question is broken down into four main research questions. With the pre-selected case of FC technology, these main questions are specified for FC firms. This study expects that some degree of generalization will be possible. The scope of generalization from FC firms to other technology will be discussed in the final chapter. The central question addresses three topics: i) the challenges FC firms face to manage the process of technology application, ii) the factors that may explain decisions on technology application and iii) the process characteristics of technology application. These topics are addressed through four main questions.

The challenges

1. What challenges do FC firms face in selecting and developing applications for their technology?
   1a What characterizes FC technology?
   1b What are typical challenges and uncertainties associated with the application of radical innova tions?

2. How do FC firms manage the process of technology application?
   2a How can the process of FC technology application be described?
   2b How do FC firms develop market insight to identify and develop market applications?

Explaining decisions

3. What explains the selection of early market applications in FC firms?
   3a What theory is most suitable to explain the selection of early applications in young technology based firms?
   3b How does experience gained in early applications influence subsequent decisions?

The process

4. What characterizes the process of FC technology application?
   4a What patterns of technology application can be derived?
   4b What explains differences in patterns of technology application?

The case study approach described in paragraph 1.3 strongly influences the structure of this study. The subsidiary questions of the main research questions 1 to 3 are addressed in chapters 2-5 on the basis of which chapter 6 further specifies the case study research. In the subsequent chapters 7 and 8, the case study research is described and analysed.

Chapters 2 and 3 further specify the empirical problem and domain. Chapter 2 introduces FC technology, the principle, its applications, the status and prospects and the industry. This information is derived from key FC references, press releases and technology updates, FC websites and surveys of the FC industry. Chapter 3 takes a helicopter view to address question 1a: what characterizes FC technology? This analysis is based on exploratory research, utilising various methods of research and data sources:

- Preliminary interviews, both formal and informal, with stakeholders in the FC industry.
- Archive documents including conference presentations and proceedings.
- Participant observation in FC projects.

The author of this study had the opportunity to participate in several projects targeting the development of FC products. Participation varied from involvement as the designer of a preliminary system to participation as a passive observer. Although these observations are not coded, they are instrumental in defining the key issues in the process of FC technology application.

With a focus on the process of technology application, chapter 4 reviews literature on innovation processes and technology marketing to address research questions 1a, 2a and 2b. Typical challenges and uncertainties associated with the development and application of radical innovations are reviewed (RQ 1a). Additionally, literature is reviewed on the process of identifying, developing and marketing radical technologies (RQ 2a and 2b). The construct of 'probing and learning' is derived from theory to describe and analyse the process of technology application. Thus, both preliminary findings from the empirical and theoretical domain help to specify the research problem and the research approach.

Literature on organisational behaviour is subsequently reviewed in chapter 5 to identify constructs for explaining a firm's application decision (RQ 3a). Literature on organisational learning additionally provides constructs to explain the impact of experience in early applications on subsequent decisions (RQ 3b). Findings from chapters 2-5 are brought together in Chapter 6 to further specify the research problem, the constructs identified from theory and the research questions. A descriptive model to describe technology application and a conceptual model of application decision making is proposed to predict patterns of technology application (RQ 4) and guide the subsequent case study research. Additionally, the case study research design is further specified, whereby four fuel cell firms are selected on basis of variance in technology application strategy. Thus, in line with Eisenhardt's (1989) recommendations for case study research, this case study uses constructs identified in literature, further defined research questions and a pre-selected sample of cases as its points of departure to conduct the case study research.

Case study research has been conducted and is presented in chapter 7. The case study research aims to derive a more in-depth understanding of the case firm's application process and what explains their application decisions. The models described in chapter 6 are used to structure the case study description and the case analysis. Various data sources are used to describe an historic account of the applications pursued in each case firm over time (RQ2). Multiple interviews with case firm managers form the bulk of qualitative data. The data is complemented and cross-checked with archive documents such as press releases and financial reports. The cases are analysed individually to address: what explains a FC firm's application decisions? (RQ3).

In chapter 8 the case study data is analysed in a cross case analysis, enabling a comparison of similarities and differences between the case firms. The analysis is based on pattern-matching logic, described by Yin (1994) as a comparison of empirically based patterns with predicted patterns. The cases are analysed and compared along the constructs, the patterns and the propositions presented in chapter 6 to validate the conceptual model. The cross case analysis is also used to find patterns of technology application (RQ 4). Thus, the empirically observed patterns in the cases study data are compared to the patterns predicted in chapter 6. Chapter 9 draws conclusions on the central and main research questions. Finally, the degree to which the research findings can be generalised to other technologies is discussed, further research is proposed and recommendations to practitioners and academics are provided.

Outline of this study

The outline of this study, as described above, is illustrated in figure 1. In summary, prior to the case study research, chapter 2 and 3 further characterise and specify the problem under study for the case of FC technology. In chapter 4 and 5 literature is reviewed to further specify the literature gap and identify important theoretical constructs. The findings derived from these chapters are brought together in chapter 6 to specify the research questions and the constructs under study. On the basis of the models and constructs proposed in chapter 6, the case study is described in chapter 7 and analysed in chapter 8. The final chapter provides the conclusions and recommendations of this study.

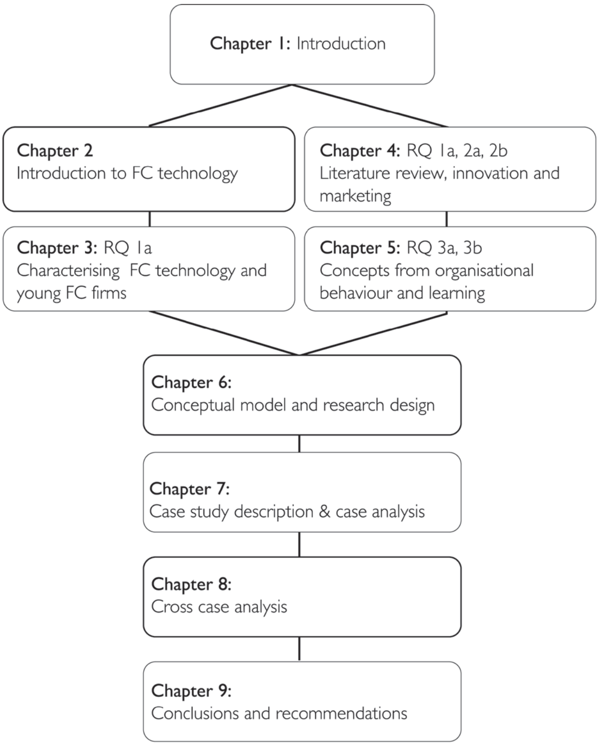

Figure 1 The structure and outline of this dissertation

Chapter 2: Fuel Cell Technology Commercialisation

This chapter provides an introduction to FC technology, the empirical domain of this research. The development of FC technology is driven by environmental as well as economic objectives. From an environmental objective, many believe that fuel cells and hydrogen are of central importance in the transition towards a cleaner energy economy. FC development has additionally been driven by an immense potential for market adoption, in a wide range of applications as well as large scale markets.

Several facets of FC technology commercialisation will be addressed in this chapter. To begin with, the basics of FC and hydrogen technology are explained and their potential to contribute towards a more sustainable energy economy is discussed. Subsequently, the main applications for FC technology and competing technologies in these markets are described in section 2.2. The subsequent section (2.3) addresses several aspects related to the realization of commercial FC products, including the components of a FC system, technical development challenges and the status and prospects for commercialisation. The commercialisation of FC technology is furthermore shaped by developments in the regulatory environment and the FC industry. Therefore, influential emission regulations and governmental support for FC commercialisation is summarised in section 2.4. Finally, section 2.5 describes the evolution of the FC industry and its financial characteristics.

2. 1 Fuel Cell Technology for Sustainable Innovation

Climate change has become the talk of the day. In recent years, overwhelming scientific evidence has found that human activity significantly contributes to global warming. Based on current trends, the stock of green house gas emissions in the atmosphere is expected to cause the temperature of the earth to rise by 2 to 3 °C in the coming 50 years (Stern 2006). Emissions from energy related activities are responsible for 65% of green house gas emissions, including carbon dioxide, methane, nitrous oxides and a number of industrial gases. Of this 65%, approximately 37% are emissions from power generation and 22% from transportation. Our current fossil fuelled energy economy, a carbon dioxide intensive infrastructure, is therefore central to this climate change problem. In addition, it is argued that fossil fuels are running out: the fuels are not regenerated by natural processes within a human time scale whilst energy consumption is increasing exponentially. The decreasing availability is reflected in the decline of oil reserves and the rise of oil prices. (e.g. Campbell 1997, Meadows et al. 2004). Considering the risks of climate change, CO_2 reduction targets have been proposed, such as the EU policies to combat climate change and achieve its Kyoto target of 8% CO_2 reductions by 2020[1]. Moreover, the problems with the future supply and use of fossil fuels are likely to require a shift towards a more sustainable energy system. Tester et al. (2005: p.2) describe sustainable energy as *"the engine to sustainable development"* and new energy technologies are expected to be instrumental in the realization of a more sustainable energy system.

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[1] *European Environmental Agency: www.eea.europa.eu*

An energy system is referred to as 'sustainable' when it follows the following definition of sustainable development: development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland 1987). Applied to energy, Tester et al. (2005: p.8) define sustainable energy as, *"a living harmony between the equitable availability of energy services to all people and the preservation of the earth for future generations"*. The Brundtland report in 1987 introduced this approach to sustainable development and brought to light the required measures: to achieve economic and environmental sustainability, present energy and resource consumption requires a reduction by factor 10 or 20 in the next 50 years. More radical commentators propose that factor 20 and 30 solutions are necessary. To achieve environmental improvements by factor 10 and above, Brezet and Rocha (2001) suggest that system level innovation is necessary. These authors argue that the environmental benefit of product improvement and redesign is limited to, at most, a factor 4. Similarly, Hart (1995) and Hart and Milstein (1999) argue that incremental innovation is not enough to address the pressing environmental issues and that radical innovations are required to develop a more sustainable energy system. Thereby, technological innovation is regarded as a primary means to reduce environmental impact whilst staying economically competitive (Cairncross 1991, Ashford 1993). A system level innovation to achieve a more sustainable energy system involves both technological innovations and substantial changes to the social system and structural environment built around the current fossil fuelled energy economy (e.g. Ashford 2000).

FC and hydrogen technology are widely considered to be of central importance in changing the current energy economy based on fossil fuels. The application of these technologies may contribute significantly to the reduction of environmental impact from electricity generation and transportation. Hydrogen can function as a clean energy carrier and fuelled by hydrogen, fuel cells function as a clean conversion technology. In the following paragraphs the principles of hydrogen and FC technology are explained. The degree to which these technologies can bring about radical changes in the current energy system is subsequently discussed.

2.1.1 Hydrogen as a Carrier

Hydrogen is a simple molecule consisting of two hydrogen atoms. Although hydrogen is the most abundant of the chemical elements, elemental hydrogen is rare on earth. Hydrogen atoms form chemical compounds with most elements such as water, organic compounds and hydrocarbons. Fossil fuels such as petroleum, coal and natural gas are combustible hydro carbons in which hydrogen is responsible for the energy and the carbons are released as carbon oxide compounds. Therefore, from an environmental perspective hydrogen appears to be 'pure energy'.

Unfortunatly, hydrogen is not a primary fuel. To obtain hydrogen, it has to be chemically separated from chemical compounds containing hydrogen atoms. According to the National Research Council, the most common feedstock for hydrogen production is currently natural gas and to a lesser degree of coal (NRC 2004). Steam reforming of natural gas is an established technology supplying the current hydrogen infrastructure for industrial purposes. Thereby, hydrogen is primarily used as an intermediate chemical, or specialty chemical, for example in oil refineries. A number of institutes are developing technology for the sustainable use of fossil fuels through hydrogen production with higher conversion efficiencies and CO_2 capturing (e.g. Energy research Centre of the Netherlands and DUT 2005). However, these hydrogen production methods alone do not contribute to an energy economy independent of fossil fuels.

A zero emission and fossil fuel independent energy economy would have to be based on renewable energy technologies such as solar power and wind power. In this 'utopian' scenario, hydrogen can function as an energy carrier for the diversity of sustainable energy technologies. Thereby, hydrogen 'carries' or 'stores' the energy generated by renewable energy sources such as solar power, wind power or hydro power through separation of water via electrolysis or high temperature chemical reactions. Electrolysis is a zero emission technology to produce hydrogen. However, the process is costly and inefficient, for example, the efficiency of converting solar radiation to hydrogen is less than 8%[2]. To mitigate these limitations, other renewable sources and production technologies are being developed. Developments include thermo-chemical and biological processes for hydrogen production from biomass. Joffe (2006) argues that the gasification of bio-methane, produced through the anaerobic digestion of organic waste, provides a promising option for hydrogen production in the city of London. Evidently, the most suitable source for hydrogen production is determined by local requirements and the availability of energy sources. Furthermore, the report of the International Energy Agency (IEA 2006) and the NRC report of 2004 mention photo-electrochemical hydrogen production as an important research area to utilize solar energy for hydrogen production. Thus, there are various technologies and energy sources to produce hydrogen, whereby hydrogen can function as an energy carrier for renewable energy sources as well as fossil fuels.

The concept of hydrogen as a common energy carrier has led to the propagation of a 'hydrogen economy'. From this perspective, hydrogen plays a central role in the transition to a sustainable energy economy. The following paragraph will describe the end-use of hydrogen as a fuel for power conversion. Although hydrogen can be burned as a fuel in combustion engines, the end-use opportunities for hydrogen are in the chemical conversion of hydrogen in fuel cells.

2.1.2 Fuel Cell Technology: a Clean Conversion

The energy of hydrogen can be utilised through the chemical conversion in a fuel cell. FC technology is an energy conversion technology defined as:

"An electrochemical 'device' that continuously converts chemical energy into electric energy (and some heat) for as long as fuel and oxidant are supplied". (Hoogers 2003 p. 1).

There are several types of fuel cells that function in the same basic way: at the anode a fuel is oxidized into electrons and protons and at the cathode, the oxygen is reduced to oxide compounds. The family of fuel cells differ by their electrolyte and their operating temperature. Low temperature fuel cells include Proton Exchange Membrane fuel cells (PEMFC)[3], Alkaline fuel cells (AFC) and Direct Methanol fuel cells (DMFC). Phosphoric Acid fuel cells (PAFC) are mid-temperature fuel cells. Thereby, PEMFC, AFC and PAFC are fuelled by pure hydrogen and DMFC by methanol. High temperature fuel cells include Solid Oxide fuel cells (SOFC) and Molten Carbonate fuel cells (MCFC). High temperature fuel cells can operate on hydrogen as well as hydrocarbons such as methane and liquid petroleum gas.

In the 1970s and 80s research was predominantly focused on mid and high temperature FC technology. After 1985, research and development has increasingly shifted towards fuel cells characterised by a solid Proton Exchange Membrane (PEM). The low operating temperatures are advantageous for applications requiring fast start up times and minimal complexity. With promising prospects for cost reduction and energy density improvement, PEM fuel cells have become the technology considered for transport applications (NRC 2004). Of all FC technologies, PEM fuel cells are applicable to the widest range of applications. Considering the potential for large scale application in transportation as well as a diversity of other markets, PEM fuel cells are expected to play a significant role in a more sustainable energy economy. Additionally, a large part of the FC industry has focused on PEMFC development relative to other FC technologies (World wide industry survey 2006). For these reasons, this research will focus on the commercialisation of PEMFC technology.

Figure 2.1 illustrates the chemical reactions that take place in a PEM fuel cell. Hydrogen is forced through the 'Proton Exchange Membrane'. When an H_2 molecule comes into contact with the platinum on the catalyst, it splits into two H+ ions and two electrons (e-). The electrons make their way through the external circuit to the cathode side of the fuel cell. Meanwhile, on the cathode side of the fuel cell, oxygen gas

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[2] *Assuming a solar cells efficiency of 10-15% and an electrolyser efficiency of 65%.*

[3] *Also referred to as Solid Polymer fuel cell (SPFC).*

(O_2) is forced through the catalyst. The oxygen atoms have a strong negative charge. This negative charge attracts the two H+ ions through the membrane, where they combine with an oxygen atom and two of the electrons from the external circuit to form a water molecule (H_2O). Electricity is generated through the external circuit and heat and water is emitted from the reaction. A single fuel cell generates about 0.7 V and 0.7 Amps per cm^2. To generate more power, fuel cells are placed in series to form a 'stack' of multiple fuel cells.

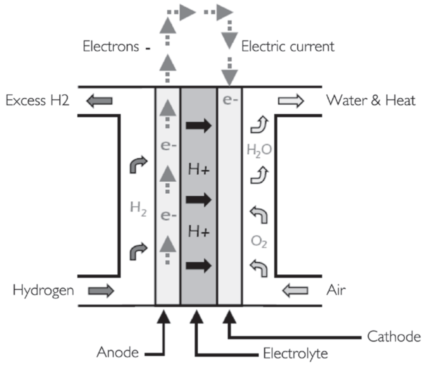

Figure 2.1 Schematic representation of a PEM fuel cell

The chemistry of a PEM fuel cell shows that the conversion is clean: there are no emissions resulting from the conversion of hydrogen to electricity other than heat and pure water. Additionally, high efficiencies can be achieved because, in contrast to heat engines, the chemical conversion in a fuel cell is not bound by the Carnot cycle. In the combustion process of a heat engine, the chemical energy of reactants goes through en intermediate form of heat so that energy is consumed before useful work is done. By contrast, the isothermal electrochemical reaction in a fuel cell directly converts chemical energy to electricity[4]. Despite efficiency losses over system components that reduce the total efficiency compared to the cell or stack alone, high levels of efficiency are still achieved. However, to evaluate the true efficiency and cleanliness of a PEMFC application the total energy efficiency and emissions have to be considered from hydrogen production to utilization. The analysis of the total fuel cycle is often referred to as a 'well to wheel' analysis.

2.1.3 Radical Change of System

Hydrogen and FC technology are, possibly, instrumental in achieving radical change towards a more sustainable energy system. One perspective of a sustainable energy system is the concept of a 'hydrogen economy'. A second perspective involves the large scale application of FC technology in a diversity of markets. The realisation of both scenarios involves radical changes to the current energy system. Propagators claim that hydrogen and FC technology are the most feasible solution to the problem of developing a more sustainable energy system. However, there are also opponents that heavily criticise hydrogen and FC technology. This research will not take part or attempt to analyse the extent to which a hydrogen economy and FC technology is sustainable or feasible or not. Rather, this paragraph will describe the radicality of these changes and the ongoing debate regarding their realisation.

Hydrogen Economy

The concept of a 'hydrogen economy' has been propagated since the 90s as a hypothetical sustainable energy economy based on renewable energy technologies with hydrogen as a carrier. Berry (1996) was one of the first to study the relationship between renewable energy and hydrogen and concluded that hydrogen can be used to facilitate the introduction of renewable energy sources and function as an energy carrier and

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[4] An extensive comparison of efficiency in a FC and a combustion engine is described by Hoogers (2003)

storage medium for both the electricity generation and transportation sector. There are strong advocates of the hydrogen economy concept (e.g. Rifkin 2002, Hoffmann and Harkin 2002). Recently, Clark and Rifkin (2006) called for an aggressive procurement of renewable energy towards building a hydrogen economy. Kammen and Lipman (2003) argue that "green" hydrogen is on its way to becoming commercially viable in the short term. These propagators believe that technical hurdles will be solved by promising developments in, for example, hydrogen storage (e.g. Clark and Rifkin 2006).

On the other hand, the concept of a hydrogen economy has evoked heavy criticism. Romm (2005) has criticised the hydrogen economy as a 'myth' and 'hot air'. Critics argue that a hydrogen economy is not a feasible option from a technical, financial and environmental point of view. Technically, critics argue that there are fundamental problems in hydrogen storage. Financially, the cost of a transition to a hydrogen economy is argued to be unacceptably high. Regarding the sustainability of hydrogen, Tromp (2003) suggests that hydrogen may negatively impact the ozone. Moreover, it is argued that inefficiencies in the whole supply chain of hydrogen production, storage and transportation do not make energetic sense. Based on a study of the energy consumed in each stage from hydrogen production to end use, Bossel et al. (2003: p.29) conclude: *"the analysis reveals that much more energy is needed to operate a hydrogen economy than is required for fossil energy supply and distribution today".* On the other hand, Hart and Bauen (2003) suggest that total FC efficiency may not be the primary measure for comparison. In can be argued that efficiency is not a representative measure to determine the environmental benefit of systems based on renewable energy sources. Nevertheless, the IEA report (2005) suggests that hydrogen as an energy carrier will only provide a viable environmental solution if it is applied on a large scale with clean and efficient solutions for hydrogen production.

The transition to a hydrogen economy requires changes to an integrated system of technologies, from the established infrastructure and the use of fossil fuels to new technologies for hydrogen production, storage, transportation, fuelling infrastructure and end uses. Thus, the concept of a hydrogen economy requires radical changes to the total energy system. The timeframes for full scale implementation are estimated at 20-50 years. However, the implementation of a hydrogen economy is a costly and timely transition and full scale realization is highly uncertain. Technical uncertainties remain and moreover, there is a lack of consensus regarding the feasibility and desirability of a hydrogen economy. The conflicting views on a hydrogen economy cause considerable delay within the investment and finance communities to support its realization (NRC 2004).

Widespread Application of Fuel Cell Technology

FC technology enables the end-use of hydrogen in a broad range of products. A second perspective of radical change towards a more sustainable energy system involves the widespread application of FC technology. It is widely believed that significant environmental improvements can be achieved by replacing internal combustion (IC) engines with FC systems, as transportation accounts for at least two thirds of the total oil consumption (Fulton 2004). Additionally, the application of FC systems in households and commercial buildings can change the established system of electricity generation. FC technology appears to be a cleaner alternative for the large scale markets of transportation and power generation that are currently responsible for a large percentage of $C0_2$ emissions.

In the late 1990s FC vehicles were considered to be one of the only technically feasible solutions to reduce CO2 emissions in transport (Hoogers 2003). However, in recent years, the technology has come under increased scrutiny with regards to environmental performance (Van den Hoed 2004). Some studies conclude that from 'well to wheel' the efficiency improvement and emission reduction of FC vehicles is limited (e.g. Weiss 2000). However, fuel cycle analyses present a highly variable range of conclusions on the environmental benefits of FC vehicles over current technologies. These differences can, at least partly, be explained by variable assumptions. As Hart and Bauen (2003 p.23) remark, *"the underlying assumptions can have a marked influence on the outcomes such that there is unlikely to be a right or wrong answer".* Nevertheless, there is also evidence that hydrogen FC vehicles offer the potential to be more environmentally sustainable than other technology and fuel combinations (e.g. Hart 2002). Critics of FC technology argue that fuel cells require an unnecessary conversion of energy for most applications. According to Bossel (2003), for example, the direct use of electricity is generally a more efficient option. Furthermore, critics argue that FC technology is a costly option to mitigate carbon emissions. The NRC (2004) concludes that fuel cells and hydrogen can play a significant role in emission reduction, providing that cost reduction is achieved in reasonable time frames. Similarly, the IEA report (2005: p.19) concludes that although the technology is not a *"silver bullet"*, FC technology is capable of curbing emissions and securing energy supply. Regarding transport applications, Hart (2002 p.196) concludes that, *"hydrogen FC vehicles are not a panacea to cure all transport problems. They must be considered in the framework of an integrated transport strategy and also in the context of other technology fuel options that may offer similar benefits"*. Thus, FC technology is not a straight forward solution to environmental problems. Besides, there is lack of consensus on the desirability of hydrogen and FC technology. As a consequence, the competition from technological alternatives such as Hybrid Electric (HE) vehicles and cleaner IC engines has increased in recent years (Van den Hoed 2004).

In conclusion, the widespread application of FC technology involves a radical change to replace current energy technologies in established markets. However, the feasibility and benefits of applying FC technology in large scale markets is under continuous scrutiny and discussion. Hall and Kerr (2003) argue that radical environmental innovations such as FC technology are under more scrutiny than incremental approaches since there is a greater degree of perceived risk. Despite the scrutiny over realising widespread FC applications, the perception of business opportunities for the application of FC technology has driven FC developments and the emergence of FC firms. This research will focus on applications of FC technology as there are opportunities for market application, irrespective of the realization of a hydrogen economy.

Although the un-sustainability of present technologies in sectors such as transportation is widely recognised, the application of FC technology is proving to be slow and difficult. There are a whole range of factors that influence this process, such as the high cost of development and implementation, the uncertain desirability of and the dependence on a new fuel infrastructure. The widespread application of FC technology faces a long, challenging and uncertain process of commercialisation.

2.2 Applications of Fuel Cell Technology

The widespread interest in PEMFC technology can be explained by the potential for mass market application. In particular, the large scale potential of the automotive market has driven developments of PEMFC technology. Besides, FC technology has the potential to replace the power source and provide electricity to products in a broad power range. The micro power range includes portable electronics and the low power range includes portable power generation. The mid power range covers a diversity of low power vehicles and combined heat and power generation. Automotive applications, buses, and stationary power generation are at the top end of the PEM power range. This section describes opportunities for applications of FC technology in three main markets: transportation, stationary and portable power. Additionally, various 'niche market' applications are addressed. For each market, the competition from established technologies as well as new technologies is described.

2.2.1 Transportation

FC technology is considered to be one of the most serious contestants to replace the Internal Combustion (IC) engines of current transport applications. The technology provides a number of opportunities for the development of cars (Kalhammer 1998, Wells and Nieuwenhuis 2001). FC technology is an attractive 'zero emission' alternative for transportation. The automotive market is by far the largest market for FC technology. There are more than 750 million passenger cars and commercial vehicles worldwide and this number is growing rapidly (IEA 2005). This market potential has inspired several automotive companies and FC developers to engage in the development of FC vehicles and buses from the 1990s onwards. FC vehicles have advantages and disadvantages compared to ICE and competing alternatives, summarised in table 2.1.

In recent years, FC vehicle prototypes have shown similar performance as conventional IC vehicles in terms of speed and acceleration (NRC 2004). In addition, FC vehicles offer advantages above IC engines including zero emission and quiet operation. Furthermore, the electric motors in FC vehicles enable rapid acceleration from standstill and potentially low maintenance. The electric system in FC vehicles is more suitable for providing electric power, to support the trend towards increased vehicle electronics. Most car manufacturers are actively pursuing the development of FC vehicles. Leading developers, in terms of investments and prototype realization, include Toyota, Honda, Daimler Chrysler and General Motors (Van den Hoed 2004, Hoogers 2003, NRC 2004).

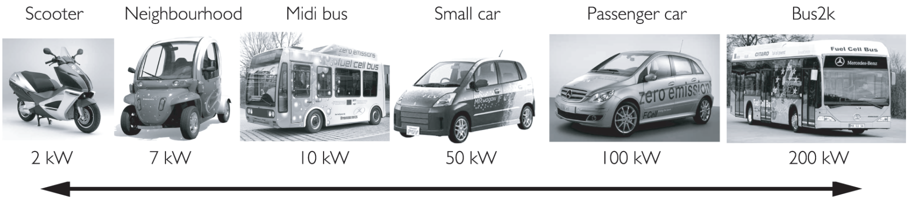

Figure 2.2 Range of transportation applications in the PEMFC power range. Examples from left to right: Honda scooter, Hydrogenics GEM and midibus, Suzuki car, Daimler Chrysler car and Citaro bus.

However, widespread adoption of FC technology in cars has been postponed repeatedly. With over 100 years of development and optimization in cost and performance, IC engines present a difficult benchmark for FC technology. Besides, the fuel economy, emissions and specific output of IC engines continue to improve through optimization cycles and iterative developments. FC technology faces steep competition from the dominant IC engine. Substantial cost reductions of FC technology are necessary to meet the automotive benchmark of 50$/KW. Additionally, the driving range requirements of 600km have not been met. A key disadvantage of hydrogen fuel cells is the low energy density of hydrogen, in comparison to petroleum fuels, complicating the realization of the range requirement. The geographical diffusion of cars favours fuels that are easy to transport and store whilst hydrogen is gaseous at room temperature. Moreover, alternative fuels such as bio fuels, synthetic diesel and methane compete with hydrogen to replace petroleum based fuels. The realization of a preliminary bio fuels infrastructure in Sweden suggests that in certain regions bio fuels have increased in popularity as a feasible short and mid term fuel alternative[5]. Finally, to become a supplier to automotive firms, developers must comply with stringent standards. The diffuse nature and the complex composition of the automotive industry complicate the diffusion of FC technology in automotive markets (NRC 2004). The FC industry is challenged to meet the benchmark requirements set by IC engines. However, in contrast to FC vehicles, IC engines are not suitable for zero emission operation.

The only zero emission alternative to FC vehicles are battery electric (BE) vehicles. BE vehicles go back to before the turn of the century when BE vehicles competed with steam and gasoline powered vehicles to become the dominant automotive technology (Kirsch 2000). With limited specific energy and specific power, the lead acid batteries of BE vehicles at the time failed to compete with the speed and range performance of IC engines. The Ragone graph in figure 2.3 compares these measures for IC engines, battery and FC technologies. In terms of specific energy, hydrogen FCs achieve a higher specific energy (in Wh/kg) than conventional and advanced batteries, implying a longer driving range. The specific power determinant for acceleration performance is similar, although novel lithium-ion technologies may achieve a higher spe-

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[5] Every fifth car in Stockholm now drives at least partially on alternative fuels, primarily ethanol. In: Sweden gets serious on Global warming. The Progressive, July 2007.

cific power level. Super capacitors have a low specific energy, but a significantly higher specific power than batteries and fuel cells, making them suitable for complementary hybrid power in battery and FC systems to boost acceleration.

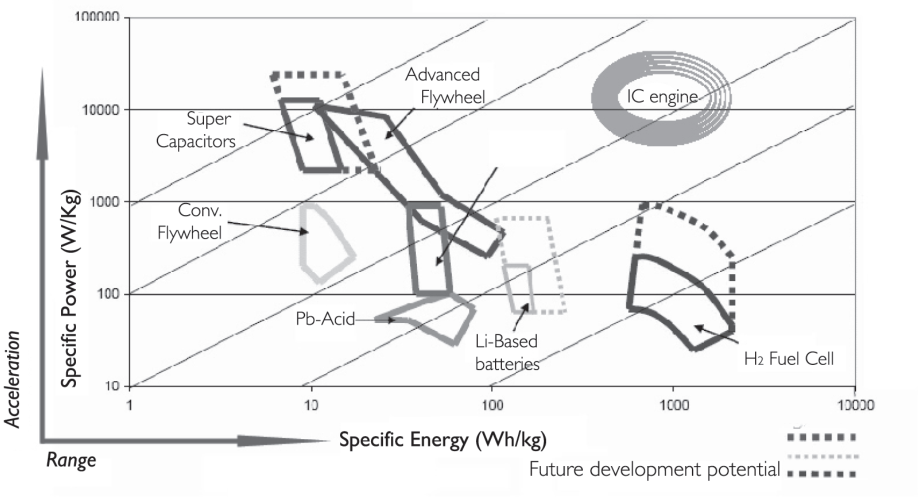

Figure 2.3 Ragone plot of energy conversion technologies. Based on www.Watt.com.

Although batteries and fuel cells are both electrochemical devices, their structural design is significantly different. In contrast to a battery, the hydrogen fuel and the FC conversion are separated in a FC system. Consequently, fuel cells do not have the chemical limitations of batteries such as charging times, limited cycles of charging and discharging and a limited shelf life. On the other hand, batteries are typically more efficient than hydrogen fuel cells. Limitations of conventional batteries are being addressed by new battery technologies. Developments in lithium-ion (li-ion) and lithium-polymer batteries, for example, show promising prospects for future BE vehicles. Such novel developments provide serious competition for FC vehicles, particularly in low and mid power ranges. For BE vehicles, the current batteries are limited to a range of approximately 300 miles and cost remains a critical barrier, however, emerging lithium technologies with nanostructure materials (e.g. $Li4Ti_5O_{12}$ and $LiFePO_4$) appear promising (FreedomCar 2006). Moreover, the role of batteries in future vehicles is not limited to BE vehicles. In hybrid electric (HE) vehicles, batteries enable zero emission operation for a limited range. By operating an IC engine as a prime mover at its optimum, complemented by a battery to buffer below and above this optimum, HE vehicles provide a relatively efficient alternative to IC vehicles. Conventional li-ion batteries appear commercially viable to power assist HE vehicles (FreedomCar 2006). Although initially considered as a transition technology towards FC vehicles, HE vehicles are gaining popularity and market share and pose serious competition to alternative technologies in the ‘race’ to replace IC engines and become the dominant cleaner technology.

Besides competition from various alternative conversion and fuel technologies, a barrier to the adoption of FC vehicles is the lack of a hydrogen fuelling infrastructure. Developing a hydrogen fuelling infrastructure with the user convenience of the current fuelling infrastructure is a costly and timely process. To overcome dependence on hydrogen fuelling stations, automotive companies have developed on-board reformers that convert a liquid fuel to hydrogen. However, on-board reforming has major disadvantages, such as substantial additional costs, added complexity, reduced fuel efficiency, increased emissions and a longer start up time. Generally, these disadvantages are now considered too large and most developers have abandoned this solution (IEA 2005).

Buses have been a popular early transport application for FC technology. On the one hand, the application is not constrained by space for hydrogen fuel tanks. On the other hand, buses can be operated in 'captive fleets' with defined duty cycles and a central filling station, facilitating hydrogen refuelling. Multiple demonstration bus projects have been realised such as the Clean Urban Transport for Europe (CUTE), in which 27 buses were operated in 9 European cities for two years[6]. FC engines of 250 kW were applied in the CUTE buses. However, increasingly, FC bus prototypes such as the Toyota FCHV-Bus2 are hybridized, lowering the FC system size to 180 kW. In the bus segment the power level and range requirements are generally too high for battery technologies. The established diesel engines set the benchmark with particularly high durability and efficiency requirements compared to automotive. Although established diesel engines are becoming more efficient and relatively cleaner, future design modifications to comply with emission legislations may increase the price of diesel engines. Although the current costs of FC buses are not entirely clear, FC buses are not competitive to conventional diesel buses as yet (IEA 2005). The annual mileage of a bus may help to recuperate some of the additional capital costs more quickly. Nevertheless, the realization of bus projects typically requires substantial regulatory support and funding.

Table 2.1 Comparison FC technology and 2 competing technologies for transportation applications

Transportation	FC vehicle compared to IC vehicle	FC vehicle compared to BE vehicle
Advantages	Zero emission operation and quiet Lower GHG emissions over fuel cycle	Higher specific energy and power Longer life and higher durability expected Fuelling instead of lengthy charging times
Disadvantages	High costs Lack of infrastructure for H_2 Lower specific energy and power	Possibly less efficient and more emissions over fuel cycle

2.2.2 Stationary Power

FC technology can replace conventional power generation systems, such as gas turbines in power plants and stationary power applications. For different types of FC technologies the stationary market has large scale market potential. FC developers believe that their technology may offer improvements with regard to hours of operation per year and the efficiency of electricity generation (Hoogers 2003). In the increasingly competitive market for electric power generation these advantages may provide an opportunity for stationary FC applications. The stationary market is categorized into: 1) Large scale central power generation of multi-mega watts. 2) Small-scale combined heat and power (CHP) in the range of 100 kWe (kilo Watt electric) to several MWe (Mega Watt electric) power and 3) Micro scale CHP between 1kWe and 20 kWe. The high temperature FC technologies MCFC and SOFC are most suitable for large scale power generation due to their high efficiencies and fuel flexibility. In the small scale power range, PAFC systems have been produced and commercially sold. With efficiency as the driving requirement for stationary power, PEMFC technology is rarely applied in power ranges above 250 kW.

A key driver for small and micro scale stationary applications is the opportunity for clean and quiet distributed generation. The concept of 'distributed generation' refers to the generation of electricity near the point of use in contrast to centralized power sites, eliminating the cost and complexity of power distribution. An additional benefit of on-site power generation is that the heat generated in the process can be used on-site, increasing the overall efficiency of the system. Moreover, the liberalization of energy markets has increased concerns about power supply failures, particularly in the US market. On-site FC power generation is expected to provide a premium power solution for on- and off-grid power generation. The markets for small scale stationary systems are primarily expected in the commercial sector or remote off-grid locations.

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[6] Clean Urban Transport for Europe (CUTE), a European Union project initiative. www.fuel-cell-bus-club.com

Established technologies for on-site-power generation include fossil fuelled generators, biomass-based generators and gas turbines. Fuel cells provide a clean and quiet alternative and possibly more reliable and efficient operation than generators. On the down side, FC systems are four times more expensive than IC generators and twice as expensive as micro-turbines (NRC 2004). Although renewable energy technologies, such as wind turbines and photovoltaic systems, provide clean solutions for on-site power generation, they require a storage medium. Batteries are applied, but are a suboptimal large storage solution for electricity due to their low specific energy. Integrated renewable hydrogen systems have been proposed to store the energy generated in the form of Hydrogen, utilizing the hydrogen in a FC system when necessary[7]. As a grid and fuel independent solution, these systems are suitable for remote locations. The criticism about such systems is the loss of energy in converting electricity to hydrogen and back to electricity. On-site PEM power systems are also designed with reformers fuelled by natural gas. In the category between 100 and 250kW, PEMFCs face competition from MCFC, PAFC and SOFC technology. The high temperature systems show higher efficiencies and fuel flexibility than PEMFCs. Some small-scale applications of PEMFCs are being developed, but with the primary objective of gaining manufacturing experience. Ballard has developed the iGeneration, a stationary PEMFC power system in the 250kW power range. However, very few systems have been supplied to customers and no further developments have been announced (Hoogers 2003). Some stationary systems for PEMFCs are being developed targeting specific markets with an excess of hydrogen, for example, in chemical industries.

Micro scale CHP in residential and light commercial markets has large scale potential for the application of PEMFC technology. In principal, PEMFCs provide sufficient heat for residential hot water. Therefore, micro-CHP systems not only replace the current central heating boilers in households, but also generate electricity for a household or a group of households. It is thought that the higher initial capital costs can be offset against savings in domestic energy supply. PEMFCs compete with Stirling and steam engines in this sector (Slowe 2006). PEMFCs and SOFC are the only practical FC technologies for micro CHP in the range of 1-20 kWe. The two FC technologies compete in this market and it is currently not clear which technology provides greater benefits (table 2.2). SOFC systems offer higher efficiency of system operation and can be fuelled directly by existent natural gas connections. However, the SOFC systems are mechanically more fragile, operate under extreme temperatures and are less suitable for dynamic start and stop conditions than PEMFC systems. Developments in, for example, mid-temperature SOFC by Ceres Power[8] address the disadvantages of high temperature SOFC and will stiffen the competition for PEM fuel cells in micro CHP systems for residential and light commercial markets.

Japan is the leading market for micro CHP with Europe following and North America lagging behind (Slowe 2006). However, there is considerable uncertainty about the widespread adoption of micro CHP systems and FC micro CHP systems in particular. This uncertainty can be explained by the fact that distributed power generation and micro CHP products address a new market and require extensive changes to the current supply of power and heat in households.

Table 2.2 Comparison of FC technology and 2 competing technologies for micro CHP applications

Micro CHP	**PEMFC compared to SOFC**	**PEMFC compared to grid power**
Advantages	Less fragile, more dynamic start and stop	Heat production on-site
Disadvantages	Less efficient. Less fuel flexible	Costs, fuel infrastructure, durability

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[7] Integrated renewable hydrogen systems are, for example, suitable for remote islands. The project 'Renewable Energy Solutions for Islands' illustrates the design and application of such a system. www.rgesd-sustcomm.org/RenewIslands

[8] Ceres Power. www.cerespower.com

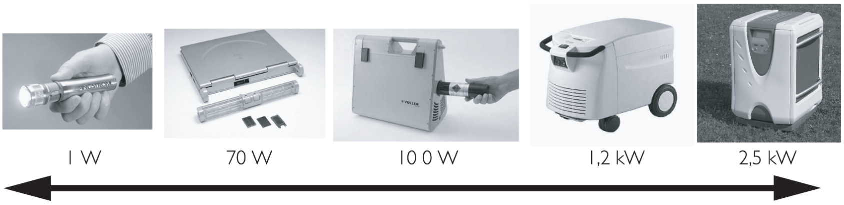

Figure 2.4 Portable power applications in the PEMFC power range. Examples from left to right: Angstrom flashlight, Casio notebook, Voller portable power, Axane generator

2.2.3 Portable Power

The application of PEMFCs in portable power was not a main driving force of FC development. Portable power applications were long seen as a by-product of developments for the automotive industry. However, whilst automotive adoption is postponed, markets for portable power are emerging. The portable power category is described as FC power generation in the range of a few Watts to 2 kW, transportable for use in multiple locations. Portable power roughly includes two categories: portable electronics and portable power generation. Portable electronics, such as cellular phones and laptops are being developed primarily in Asia. In this market, PEMFCs compete with batteries and Direct Methanol FCs (DMFCs). These markets are not driven by environmental improvements but by improvements in functionality. Compared to batteries, PEMFCs operate grid-independent and charging times are negligible, however, there are technical challenges regarding, for example, the storage of fuel and the emission of water. Angstrom, a US developer of micro PEMFCs for portable electronics, claims that their technology can reach twice the run time of Li-ion batteries and achieve refuelling in three to four minutes at competitive prices.[9] The company claims that the metal hydride storage of hydrogen is safe whilst Li-ion has shown problems with dissipating heat at the increasing demands of power in consumer electronics. Furthermore, Angstrom claims that water vapour emission is quite minimal and manageable. Compared to DMFC, PEMFCs dissipate less heat and have a higher power density. Flipsen and Coremans (2005) find the required passive DMFC system for a laptop computer is not competitive with Li-ion battery technology. On the other hand, methanol is a relatively cheap and easy to handle fuel whilst the distribution of hydrogen remains challenging. The technology for sub 100 watt PEMFCs is substantially different than systems at higher power levels.

Table 2.3 Comparison FC technology and 2 competing technologies for portable power

Portable power	FC compared to batteries	PEMFC compared to DMFC
Advantages	Higher power and energy density Lower maintenance expected	Less fragile, more dynamic start and stop. Higher power densities
Disadvantages	Possibly less efficient	Less efficient. Hydrogen is more difficult to store than methanol

Portable FC generators provide grid-independent power and systems have been applied as power generators and back up power units, illustrated in figure 2.4. Applications for portable FC generators also target auxiliary power units on vehicles. In this category, FCs primarily compete with batteries and small combustion engines. Although the cost of small IC engine generators is lower, PEM generators are zero emission and quiet. In comparison to batteries, PEMFCs are argued to offer extended operating time, a longer operating life and possibly a higher reliability. DMFC is a serious competitor of PEMFCs in this market (table 2.3).

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[9] Angstrom presentation at the Hydrogen Fuel Cell Conference in Vancouver 2007

Whilst PEMFCs are restricted by hydrogen availability and storage, methanol is relatively facile to access and store. DMFCs have been considered an 'ideal fuel cells' due to their key features of simplified design and the direct use of liquid methanol fuel. However, PEMFCs show higher power densities and the fuel methanol has particular disadvantages. On the other hand, rapid progress in the field of DMFCs is likely to pose increasing competition for PEMFCs, particularly in the portable power market.

2.2.4 Niche Market Applications

Large scale markets for automotive and stationary applications are proving to be further away than initially expected. In the mean time, 'niche market' applications for FC technology are emerging. Niche markets are found where the performance and cost of FC technology is acceptable to a market's requirements because an added value is provided compared to the established technology. Niche markets are found in specific market segments of transportation, stationary and portable applications. The described advantages and disadvantages of FCs compared to established technologies, indicate where FCs provide a significant added value. Initially, hydrogen and FCs primarily targeted the advantages of clean and quiet IC engine replacement. However, these advantages do not outweigh the current high cost of FCs. The majority of initial niche markets for FC technology are found in the replacement of batteries, thereby replacing another quiet and zero emission technology. As illustrated in the Ragone plot (fig. 2.3.), FCs have a higher specific energy and therefore primarily provide a desirable alternative to conventional batteries when a large amount of energy needs to be stored, for example, for back up power or range extension in small vehicles. Additionally, hydrogen is believed to be a more reliable form of 'storage' than batteries. Moreover, the cost of conventional batteries is not far from the current cost of FC systems, enabling cost effective application on the short and mid term.

Niche markets for FC technology are expected to emerge in transportation applications, where emissions are regulated and batteries fail to provide sufficient range. Material handling and specialty vehicles such as delivery vans, wheelchairs, carts and airport tugs are considered potential niche markets for FC technology. Fork-lift trucks are expected to emerge as a short term commercial niche market, a market in which the current battery powered vehicles are limited by charging times or the exchange of batteries. Another potential niche market for the transportation market is Auxiliary Power Unit (APU) for vehicles and trucks in particular. A competitor in this market is SOFC technology The shortcomings of batteries in reliability and specific energy additionally provide opportunities for FC applications in stationary and portable power generation. Niche markets include remote power and back up power for critical markets in the power range of 100W to 5 kW. As an early adopter, the military has been involved in the development of portable FC power, where FCs enable 'silent watch' operation, i.e. without noise or particulate emissions.

In 2007, back up power is considered to be the only commercial product for FC technology as FC firms receive repeat orders. Emerging niche markets for back up power include telecom providers, emergency response and data centres. In particular, the frequency of US grid outage and failure has generated demand for back up power solutions. For example, in 1998 an ice storm left the west coast without heat and power for months. The costs of such power outages are estimated at billions of dollars per hour. Existing solutions for back up power include batteries, super caps and flywheels. Typically these technologies only provide back up power for a few minutes. Diesel gensets are applied for longer run times. FCs provide a more efficient, quiet and zero emission alternative to diesel gensets and FC developers expect higher reliability.

There is niche market potential for fuel cells in battery replacement markets on the short and near term. Under specific requirements FC technology offers distinct advantages above conventional batteries, particularly where more energy needs to be stored and a higher specific energy is desired. However, in other markets, the 'urgency' for battery replacement is lower. Besides, the feasibility of niche markets largely depends on the availability of hydrogen. New battery developments are expected to address the limitations of conventional batteries and therefore stiffen the competition with FCs in various niche markets. In the meantime the initial commercial niche markets for FC technology are emerging.

2.2.5 Conclusions of Fuel Cell Applications

There is potential for the application of PEMFC technology in a broad scope of markets. The main driver for FC development has been the potential for zero emission solutions and the large scale potential of the automotive market. Additionally, small scale stationary applications and residential micro CHP in particular, have envisaged large scale market potential for PEMFC technology. However, it remains uncertain if and when these large scale markets will adopt the technology. As a replacement of conventional power sources in products, FC technology faces competition from established technologies. The IC engine in particular provides steep competition in cost and performance. Although FC vehicles are widely considered as one of most likely contestants to replace IC vehicles, FCs also compete with emerging technologies, such as alternative fuels, battery and hybrid technologies. In stationary and portable applications PEMFCs also compete with other FC technologies and it is not clear which technology will become dominant in these market sectors. Prior to widespread market adoption, commercial applications of FC technology are expected in various niche markets, particularly where FCs provide added value above conventional batteries. A disadvantage of FC technology compared to batteries is a lower efficiency, which appears to contradict the environmental drive for FC technology development. The main disadvantages of FC technology compared to IC engines are the high cost, the lower specific energy and power and the lack of fuelling infrastructure. Most of these disadvantages are expected to be solved through further R&D and investment, however, competitive price and performance is years away whilst there are short term technological alternatives to replace IC engines such as HE vehicles. Moreover, hydrogen by nature is less practical to store and transport than liquid fuels such as gasoline and bio fuels. A number of competing technologies are considered as transition steps, complementary to the application of FC technology. However, at the same time, the coexistence of options may undermine the economics of scale in the FC industry. Furthermore, Nieuwenhuis and Wells (2003) expect that a step by step approach will take longer than one single leap to FC vehicles. Besides, the outcome of such a transitional process is uncertain and consequently FC technology may not emerge as the dominant technology for wide spread application.

2.3 Realising Applications

In the above paragraphs the principles of FC technology and potential applications have been described. This section will describe the basic design features of FC systems and the key technical challenges to commercialize the technology. Subsequently, the current technical status and prospects for technology development and adoption are addressed. Finally, prototypes of FC applications developed in the previous years are described.

2.3.1 From Fuel Cell to Application

At the heart of a PEMFC is a 'Proton Exchange Membrane'. This membrane is sandwiched in a Membrane Electrode Assembly (MEA) between catalyst layers and anode and cathode electrode layers. The MEA is responsible for the electrochemical power generation in a fuel cell of approximately 0.7 V and 1 W/cm^2. A fuel cell comprises of the MEA between two 'flow field plates' (fig. 2.5). The main tasks of flow field plates are current conduction, heat conduction, control of gas flow and product water removal. In the context of current collection, the term 'bi-polar plate' is often used. 'Flow fields' or channels are designed onto the plates to distribute fuel and oxidant as well as cooling (Hoogers 2003). There are two competing material approaches for bi-polar plates, graphite based materials and metallic bi-polar plates. Metallic bi-polar plates can be made thinner than graphite based plates and are argued to be less costly to manufacture, however, metallic plates may be inadequately resistant to corrosion (IEA 2005).

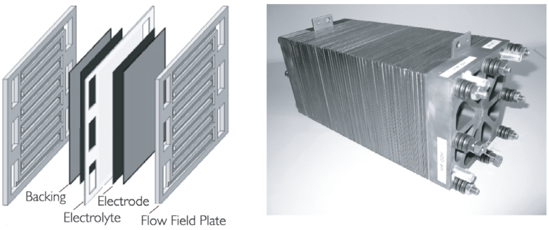

Figure 2.5 A fuel cell MEA (left) and a fuel cell stack (right)

Multiple fuel cells are 'stacked' in series to form a 'fuel cell stack' (fig. 2.5). Humidification and coolant plates may be added to this stack. The plates are pressed between end plates to make the FC stack gas tight. A typical FC stack does not function on its own. Auxiliary components or 'Balance of Plant' (BOP) components are required to manage the air flows, the hydrogen flows, coolant flows and the electrical output (Hoogers 2003). The compilation of these components forms a FC system. FC systems are configured in many different ways with variable design specifications of, among others, the cooling media and operating pressure. At low power ranges, stacks can be air cooled, allowing a simplified system. Above 500W, stacks are generally liquid cooled. Furthermore, stacks are run at variable pressure levels. Ambient as well as pressurised systems have been developed. Higher pressures may increase efficiency, however, the complexity of the system is also increased. Figure 2.6 illustrates a typical system in which the incoming air is pressurised by a compressor and the stack is liquid cooled.

PEMFC systems are fuelled by 99.9999% pure hydrogen. A hydrogen FC system will require a hydrogen storage system. The three main types of hydrogen storage available are, i) compressed hydrogen, ii) liquid hydrogen and iii) metal hydrides (IEA 2006). Hydrogen can be stored as a gas in pressure cylinders. Depending on the required hydrogen storage capacity and the availability of space, cylinders between 200bar and 700bar are applied in products. Hydrogen can be liquefied at a temperature of -252.76C, enabling a more compact storage of hydrogen in cryogenic tanks. However, energy is lost in the process of liquefying and fuelling. Storage in metal hydrides relies on the adsorption of hydrogen in to some material carrier. Metal hydrides are a compact but a relatively heavy solution to store hydrogen in comparison to compressed cylinders. A large percentage of the automotive prototypes between 2000 and 2005 have applied compressed gas cylinders of 350 bar and above. According to Dynetek, a key developer of compressed hydrogen tanks, 700 bar tanks have been supplied to several automotive firms in 2007[10].

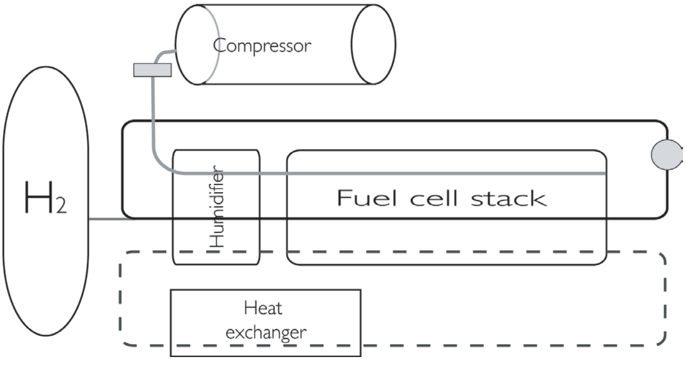

Figure 2.6 A typical FC system and system components.

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[10] *Dynetek information from the hydrogen and fuel cell conference in Vancouver 2007*

A FC system is often a subsystem of a larger system in a product. In FC vehicles, the FC system is integrated into a power train configuration, including an electro motor, a DC/DC converter and electric controls. Power trains are often configured as hybrid systems with a FC system as well as an additional form of energy storage such as batteries and/ or super capacitors. 'Hybridization' is increasingly applied in FC vehicle prototypes. Batteries and super capacitors enable the application of a smaller FC stack, acting as a buffer for acceleration and/ or prime power. A power train configuration is subsequently integrated into the end product, for example, into the floor of a vehicle. In the case of domestic heating appliances, the FC sub system is also integrated into a more complex system. By contrast, minimal product integration effort is required when electricity generation is the prime function of the product, such as generators and back up power units.

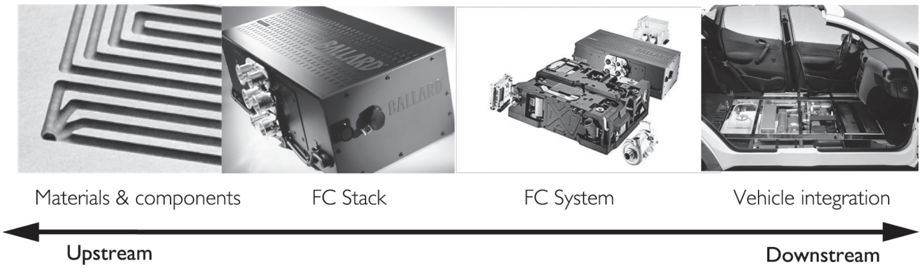

Figure 2.7 Typical supply chain positions: components and materials, FC stack, FC system and power train, product integration

Figure 2.7 illustrates a simplified supply chain for a FC product, from the development and manufacturing of membranes and bi-polar plates to power train design and product integration. These developments are seldom conducted in a single firm. There are, for example, firms that specialise in the development of FC specific materials and components and firms targeting stack manufacturing. Additionally, there are firms that specialise in FC system design as well as Original Equipment Manufacturers (OEM) that integrate FC systems into end products. The supply chains for FC products are gradually taking shape as the FC industry grows. PricewaterhouseCoopers (PwC 2006) reports an increasing number of FC component suppliers in the FC industry. There are various new entrants in the FC industry targeting the development of FC component, stacks, systems or products. Additionally, established R&D and OEM firms are positioned in the FC supply chains.

2.3.2 Key development challenges

In comparison with established technologies, the key development challenge towards competitive application is cost reduction. Cost reduction is primarily addressed through R&D in materials and the scaling of manufacturing capacity. A key challenge is to advance membrane electrolyte materials. Most PEM fuel cells apply Du-Pont Nafion membranes, developed more than 30 years ago. These membranes have disadvantages, including the need for humidification, their low operating temperature (<80 °C) and their high cost. Nafion membranes require a costly platinum catalyst that is sensitive to CO poisoning. Ongoing R&D addresses these problems. To develop membranes that are less prone to CO poisoning, R&D is focusing on higher temperature membranes to operate FCs at approximately 120°C (IEA 2005). For example, new platinum/ruthenium catalysts appear to be more resistant to CO. Additionally, ongoing R&D is targeting the reduction of platinum loading in the PEM catalyst layer. The current average level of 0.4 mg Pt/cm^2 is expected to be halved. It is expected that new membranes will become available and enable significant cost reductions and durability improvements for PEMFC technology (NASA 2004).

FC stack costs are dominated by the cost of the bipolar plates and the electrodes. Currently, both components are manufactured manually and it is expected that large-scale production will lead to significant cost reductions (IEA 2005). A factor 20 cost reduction is predicted for large scale manufacturing of electrodes and a factor 10 cost reduction for bi-polar plate manufacturing[11]. Achieving large scale manufacturing is a technical challenge in itself. Besides, validating and financing manufacturing plants at least partly depend on the emergence of market demand.

FC technology may reach the price and performance benchmarks through further technological developments, however, the FC adoption largely depends on the development of hydrogen technologies. The development of clean and efficient hydrogen production technologies and the development of a hydrogen infrastructure are critical for the commercialisation of FC technology. A key technical challenge for the development of competitive FC systems on board of vehicles is hydrogen storage. Pressure cylinders (at 700 bar) and cryogenic cylinders are still 7 to 9 times more voluminous than gasoline fuel tanks with the same energy content (fig. 2.8). Besides voluminous, the exorbitant pressures of compressed hydrogen cylinders raise safety concerns. 700bar tanks appear to be technically feasible for near term application in FC vehicles, however, the solution is costly. According to the IEA report (2005), the costs need to be reduced by a factor of 36 to compete with conventional gasoline storage on board of vehicles. Besides, pressurising tanks to 700 bar and liquefying hydrogen are energy inefficient solutions. The challenge to develop compact, safe, energy efficient and cost effective solutions for hydrogen storage has, as yet, not been met. Innovative solutions are being developed to lower the cost and improve the energy efficiency of hydrogen storage. Although metal hydrides are a relatively heavy storage solution, developments are considered promising (IEA 2005). Developmental solid storage technologies include carbon fibre hydrides and water-reactive chemical hydrides. Perniu et al. (2005) suggest that nano-structured materials can provide a safe and cheap hydrogen storage solution. With nano-structured metal hydride materials, for example, Duta et al. (2005) describe a novel concept that combines the production and the storage steps in the same device by linking hydrogen photolysis and hydrogen storage.

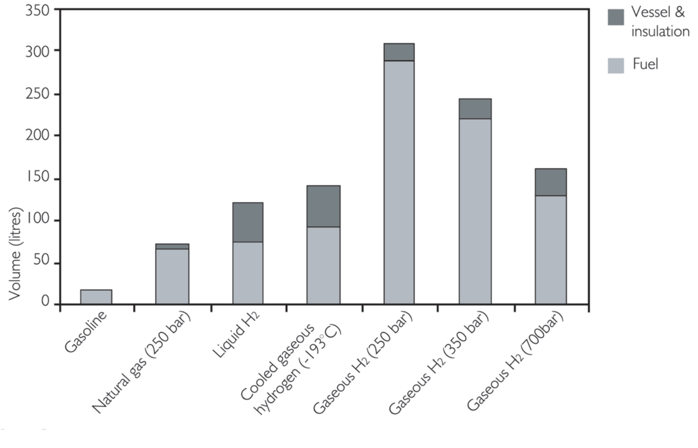

Figure 2.8 Fuel tank volume by fuel type. Source: Berry and Lamont, 2003. The calculations are for 5 kg of hydrogen or energy equivalent for other vehicles

2.3.3 Status and Prospects

The market potential for FC technology is expected to be large. In 2003 the Allied Business Intelligence (ABI 2003) predicted that by 2013 the global FC industry would generate more than $18.6 billion, but if adoption in automotive markets would take off, the FC market would have the potential to reach $35 billion. However, widespread automotive adoption is now expected to be decades away. Currently several hundreds of FC vehicles are produced a year, compared to the current automotive market of 50 million vehicles a year (IEA 2005). In an optimistic prediction based on the penetration scenarios of hybrid electric

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[11] *The IEA report (2005) provides a detailed description of this cost reduction potential*

vehicles, the NRC (2004) predict one percent of US sales by 2015 and a 50% penetration of total vehicles around 2035. These findings are similar to predictions by the Argonne National Library (Santini et al. 2003). The US Department of Energy programme assumes a more optimistic penetration of 78% in 2030 (DOE 2003). The DOE expects hundreds to thousands of FC vehicles by 2012 and presents three development scenarios for FC vehicle increase between 2012 and 2025: 2 million FC vehicles by 2025, 5 million by 2025 and 10 million by 2025. On the other hand, there are less optimistic predictions on the adoption of FC vehicles. According to Romm (2004) PEMFCs are unlikely to achieve significant market penetration in the US by 2030. The IEA (2005: p.189) predict that *"under most favorable assumptions, hydrogen and fuel cells will contribute to meeting the global energy demand in transport, with hydrogen fuel cell vehicles reaching up to 30% of the vehicle stock by 2050. Fuel cells can also help meet the demand for distributed CHP, with some 200-300 GW by 2050".*

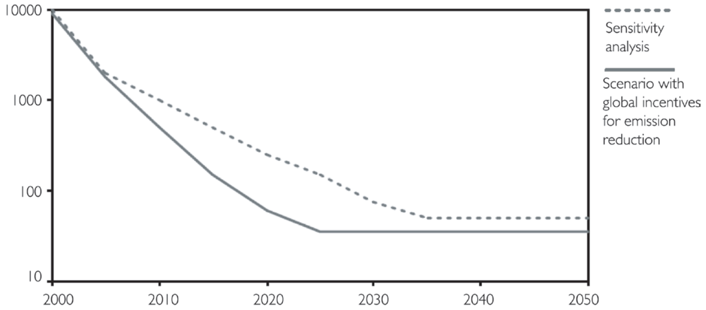

Figure 2.9 Alternative assumptions for PEMFC vehicle cost reductions. Cost reduction projecttions vary widely. Source IEA 2005

Among other factors, large scale adoption largely depends on the cost reduction of FC technology. Currently, PEMFC stacks are 10 to 20 times too expensive compared to the automotive benchmark (NRC 2004). The current cost of a whole FC system is 50 to 100 times the cost of IC vehicles (IEA 205). Besides, performance requirements of density and durability must be met. Technical status and targets for development are summarized in table 4 in terms of durability, costs, energy density and specific energy. The 'targets' for 2015 refer to the automotive benchmark requirements. In comparison to the IEA (2005) expectations, the DOE (2004) programme holds more aggressive targets of 30 \$/kW for 2015, departing from an assumed 500.000 unit production per year.

Data from 2005 suggests that the current cost of FC stacks are estimated to lie between 500 and 1800 \$/kW in which Toyota claims it can build a FC stack for 500 \$/kW and the IEA estimates the costs of a FC stack to be 1800 \$/kW (IEA 2005). However, BOP components of a FC system currently double the costs of a total FC system to a total of 3000-5000 \$/kW for a FC vehicle. The electric motor and the DC/DC converter primarily drive the costs of BOP components and these costs are expected to decline dramatically once large scale manufacturing is introduced (IEA 2005). Thus, cost predictions for FC vehicles vary widely, as shown in figure 2.9. The IEA estimates that a stack cost target between 50 \$/kW and100 \$/kW can be met through large scale production efforts of 100.000 m^2 of FC stacks a year, amounting to 210 \$/kW for a total FC vehicle under optimistic predictions for 2015. However, the development of cost-effective FC vehicles largely depends on the development of cost effective and compact hydrogen storage solutions. The current solutions to store 5 kg of hydrogen, for a 460-580 km driving range, are costly at 2400 \$/kgH$_2$- 3300 \$/kgH$_2$.

The status data for power and energy density indicate that the FC vehicle benchmark has not been met as yet (table 2.4). The targeted and required power densities will differ between markets because power density is a specification with a trade-off: higher power densities, result in lower efficiencies and lower durability. The automotive market requires significantly higher power densities and lower durability than stationary markets, whilst stationary markets require high durability and space is not a prime concern. Buses are a category in between: space is only moderately limited and durability requirements amount to 20.000 hours. The operating life of a FC stack largely depends on operating conditions such as external temperature at start-up, dynamic loading, excessive or insufficient humidification and fuel purity. The current durability of FC stacks has reached approximately 2200 hours for automotive stacks. However, 13.000 hours have been reached under test conditions[12]. Considering the rapid progress in stack durability, this performance indicator is expected to meet the targeted operating life for FC vehicles by 2015. Achieving the durability requirement of 40.000 hours for stationary applications is more challenging. Regarding efficiencies, FC systems are already more efficient than IC engines in operation, yet optimizations of efficiencies are targeted to increase "well to wheel" efficiency. Efficiency is expected to increase by10% to a 60% system efficiency by 2015, primarily through improvements in the BOP components of FC systems.

Table 4 The status of FC technology in 2005 and the targets for 2015. Sources: IEA 2005, DOE 2004

Indicator	Status 2005	Target 2015
Costs stack	500- 1.800 \$/kW	30-100 \$/kW
Costs FC vehicle	3.000-5.000 \$/kW	30-100 \$/kW
Power density FCV stack	1.500 W/ l	2.000 W/l
Hydrogen storage 700bar	2.400 \$/kgH_2- 3.300 \$/kgH_2	67\$/kgH_2
Durability automotive	1.000 - 2.200h	3.000-5.000 h
Durability stationary	12.000h	40.000-60.000h
Efficiency system	53-58%	60%

The current status of FC technology enables cost-effective applications in niche markets on the short and mid term. Figure 2.10 illustrates an approximate adoption curve of niche markets according to the benchmark requirements of the established technology. The back up power market for telecom is expected to be cost effective at around 3500 $/kW and material handling markets at 800 $/kW. Remote residential micro CHP is expected to be cost effective at 1000 $/kW and micro CHP for distributed power generation at 500 $/kW. Auxiliary power for use in trucks is targeted at 400 $/kW. Cars are further down the curve at 50 $/kW. However, these cost targets are not conclusive. Cost economic analyses suggest that cost effectiveness largely depends on specific operating conditions. For example, according to Battelle (2007) forklift trucks are cost effective at highly specific sites with high labour rates and multiple shifts per day

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[12] Hydrogenics presentation of durability data at Hydrogen and Fuel Cell Conference in Vancouver 2007.

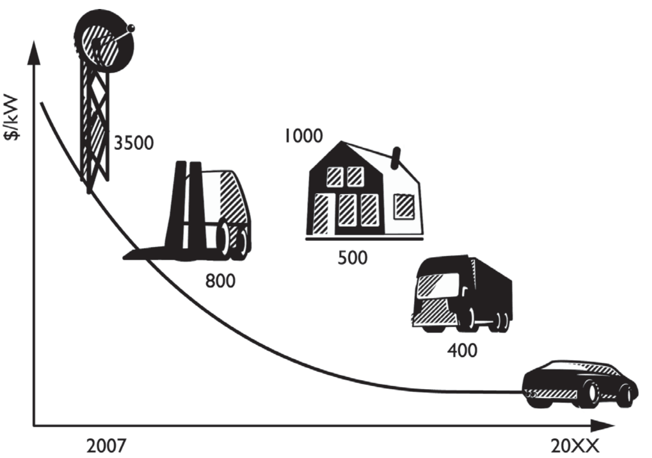

Figure 2.10 Approximate adoption curve niche markets, on the basis of cost/ kW

2.3.4 Prototype Development and Plans

Ballard presented the first PEMFC bus in 1993. Thereafter, a multitude of prototype applications were realised. The total number of prototypes world wide is difficult to estimate but the Fuel Cell Today (2006) databases[13] provide an estimate. Between 1991 and 2006 the total number of FC units installed world wide amounted to more then 20.000, including all types of FCs. This total includes 800 large scale stationary units, of which the majority are high temperature FCs, and almost 5000 small stationary units. Up and to the year 2006, more than 660 FC vehicles were realised and more than 10.000 portable applications were manufactured. The IEA (2005) reports that in 2005 almost 80 buses were in operation in various demonstration projects across the world.

In recent years governmental support has shifted emphasis from R&D to the support of demonstrations and the realization of early markets. For example, the European Hydrogen and Fuel Cell Technology Platform has derived an implementation plan to bring "thousands" of FC products in early light mobility and portable markets by 2010 (HFP 2007). The plan additionally aims to install more than 1GW capacity of micro CHP and power generation by 2015, for PEMFC as well as SOFC technologies. Additionally, large demonstration programmes are being developed such as HyChain, a European project directed towards the deployment of small FC vehicles and niche markets (Hychain 2007). The project was launched in January 2006 with €37 million funding, of which 17 million from the European Commission. HyChain plans to deploy 158 vehicles by 2010, including 40 cargo bikes, 34 wheelchairs, 40 scooters, 44 utility vehicles and10 mini buses. According to Paulmier14, it is challenging to certify pre-series and find 'customers' and locations to deploy the vehicles. The HyChain project is characterised by the application of specialty vehicles, for demonstration projects in Europe. Other projects are developing and operating delivery trucks, neighbourhood vehicles and airport tugs. The London Hydrogen partnership aims to deploy 70 FC vehicles by 2010. First, 10 buses will be realized and then 60 other vehicles will follow for operation in the Mayor of London's functional body (LHP 2007).

In North America, the DOE is engaged in the deployment of applications in emerging markets. The DOE will deploy up to 80 forklift trucks at various US locations this year and 135 units of emergency back up power at weather stations in the US[15]. Several US demonstration programmes are focused on stationary applications, FC vehicles and buses. For example, in the Californian vehicle programme almost 200 FC

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13 Fuel Cell Today: www.fuelcelltoday.com

14 Presentation by Paulmier of Axane at Hydrogen and Fuel Cell Conference Vancouver 2007

15 Presentation DOE by Devlin at Hydrogen and Fuel Cell Conference Vancouver 2007 vehicles have been applied, of which more than 100 FC vehicles are used in daily operation. 24 stations have been realized as part of the Californian Hydrogen Highway. The total number of hydrogen refuelling stations has reached 140 in 2006 (Fuel cell today 2006). Other projects targeting the development of a 'chain' of hydrogen refuelling stations include the British Colombia Hydrogen Highway and the Scandinavian Hydrogen Highway partnership.

The National Institute of Advanced Industrial Science and Technology (NIAIST) in Japan reports that 50 FC vehicles were being used in the Tokyo region[16]. A second phase began in 2006 with applications extended to other areas. Japan will also engage in new applications such as small motor cycles and wheelchairs. In previous years, Japan has conducted large-scale field trials in the residential micro CHP market: 1200 FC systems of 1 kW where installed up and to 2006. In 2007 year micro CHP demonstration will be expanded to 2257 systems. Japan has also started SOFC demonstrations, which appear to be more suitable for Japanese households.

2.4 Emission Legislation and Government Support

FC technology development involves high investments over a long period, requiring substantial regulatory and governmental support. Policy makers play a decisive role in stimulating technological change towards more sustainable energy and mobility practices. Emission regulations and in particular zero emission regulation, stimulate the development and adoption of zero emission technologies. Additionally, governmental institutions provide financial support for R&D and demonstration and apply measures to generate market incentives. Both forms of regulatory support are described for North America, Europe and Japan.

In the United States (US), two public goals drive policy and support for hydrogen and FC programmes: environmental quality and energy security (NRC 2004). In Europe and Japan, legislation is primarily driven by concern for environmental quality and climate change. Historically, emission regulations have addressed two concerns. First, local emission regulation appeared on political agendas in the 1960s, primarily targeting the reduction of local emissions including carbon monoxide, sulphur dioxide, nitrogen gas, lead and fine particulate matter. Such local emissions are responsible for air pollution causing local environmental and health problems. In the 1990s, the political focus shifted towards CO_2 emissions in relation to global warming. CO_2 reduction, energy efficiency and oil depletion became the main political concerns (Van den Hoed 2004).

2.4.1 Emission Regulations on Cars

Since the 1960s local emissions from cars have been appearing on the political agenda in the US. In the 1970s the Clean Air Act was passed, setting health based standards for local emissions, however, the standards did not become tougher until after the 1990s. Emission standards are currently largely in line with the EU emission standards. However, the Federal US government has not proposed measures to reduce greenhouse gas emissions and recent statements indicate that the Environmental Protection Agency (EPA 2007) is not planning to impose mandatory measures. The state of California forms an exception: it has created its own set of emission standards. The Californian emission standards are considered to be leading in the world. In the 1990s the Low Emission vehicle programme was approved, including a Zero Emission Vehicle (ZEV) mandate. This ZEV regulation mandated that at least 10% of the vehicle sales in 2003 would be classified as zero emission vehicles. BE vehicles and later FC vehicles were considered to be the only zero emission options to comply with this mandate. Evidently, these targets have not been met as ZEV regulations were changed, put under pressure and postponed over the years. Nevertheless, the longer term objectives of ZEV sales remain (ZEV 2007). Van den Hoed (2004) finds that the Californian ZEV regulations in 1990 have been a necessary condition for car manufacturers to engage in alternative technology development, including FC vehicles. Despite continuous complaints from automotive companies,

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[16] Presentation NIAIST by Kogaki at the Hydrogen and Fuel Cell conference Vancouver 2007

the ZEV mandate has been effective in stimulating R&D activities and the development of prototypes in FC vehicle development. However, as the ZEV regulations were modified, the focus has shifted from BE vehicles and FC vehicles to a wider range of technologies. In 2007, the ZEV review (2007: p.27) states: *"it is also apparent that there is no single winner among the technologies: many hold promise; all have challenges and benefits"*. California continues to be a front-runner in aggressive emission regulation. In September 2006 California passed new regulations to cut greenhouse gas emissions.[17]

The first European emission standards for cars were drawn up in the early 1970s, with a focus on the reduction of local emissions. The legislation was finalised in 1991. Although almost a decade behind the US, these European standards, known as the Euro emission norms, have been tightening ever since.[18] Global warming concerns and CO_2 emission legislation came higher on the agenda in the 1990s. In 1998 an agreement was signed with European automotive associations, aiming to reach 120g/km CO_2 emissions in 2010. However, this agreement is voluntary and there is no enforcement for non-compliance. Some argue that Europe has become a front-runner in the development of green house emission legislation (e.g. Christiansen and Wettestad 2003).

Japan has largely followed federal US legislation since the 1970s and Japanese regulations set in 1997 are similar to standards in the US and Europe. Japan's dependence on energy and fuel imports is reflected in an emphasis on energy efficiency. Generally, energy efficiency and CO_2 emissions are higher on the agenda in Japan and Europe than in the US. The Californian zero emission regulations focused on cars, whereas Japan and Europe gave more attention to FCs as a cleaner form of electricity generation. Although automotive emission problems have been dominant in shaping emission regulations, environmental problems in urban areas have also driven regulatory developments in Europe and Japan to reduce emissions and increase efficiencies.

Despite increasing concerns about green house gas emissions, there is no general consensus about the desirability of zero emission legislation. However, with BE vehicles and FC vehicles as the only technically viable zero emission solutions, the development of zero emission legislation is likely to influence the demand for FC technology. However, the regulatory developments are often voluntary and open to change. A political shift to low emission regulations, with a focus on CO_2 over fuel cycles instead of local zero emission regulation, implies more competition for FC technology as a broader scope of technologies provide feasible options for compliance.

2.4.2 Government Support

The envisaged potential that FC technology can provide a cost-effective solution to environmental problems and energy dependencies has resulted in financial support from governments and institutions for FC technology development. The pre-commercial phases of FC commercialization require considerable investment in R&D, technology demonstration and validation. Initial financial support was focused on R&D and more recently, financial support has shifted towards activities aimed at stimulating commercialization through demonstrations and market incentives.

The Canadian government has played a decisive role in financing the R&D and early demonstrations of PEMFCs since the mid 1980s. Between 1992 and 2002 the Canadian governments provided over C$150 million to fuel cell R&D (Core technology 2002). In 2002 the Bush administration announced a $1.2 billion 5 year investment plan and this FreedomCar project primarily focused on hydrogen fuelled FC vehicles (Sagar 2004). The Freedom Car project is a public/private partnership between the US DOE and automotive firms Ford, GM and Daimler Chrysler. The budget request for 2007 amounts to a total of $289.49 million, of which 14% is budgeted for infrastructure and technology validation and 17% for basic research of hydrogen and FC technologies (DOE 2006).

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[17] News release 'California Signs Landmark Global Warming Legislation' on www.NRDC.org, National Resource and Defence Council

[18] European Commission, Enterprise and Industry, sector automotive industry: ec.europa.eu/enterprise/automotive/

Until the mid 1990s European governmental institutions primarily funded high temperature FCs for stationary power generation. The European Commission funds allocated to Hydrogen and FC research tripled in 1998 and more than doubled after 2002. In 2003 the EU initiated the Hydrogen Fuel Cell Technology Platform to design an implementation plan for hydrogen and FCs. The programme proposes a total budget for private/public partnerships of €6.7 billion for the period 2007 to 2015 (HFP 2007). It is noteworthy that two thirds of this budget will be allocated to demonstration activities. The Japanese R&D budget in 2007 is reported to be 32.4 billion yen of which 1.8 billion is allocated to demonstration projects[19]. Thus, the trend in financial support for FC development is a continuation of R&D support to solve key technical challenges, with an increase of financial support for demonstrations and early applications in public/private partnerships.

2.5 The Fuel Cell Industry

This paragraph will describe the status of the FC industry and describe the type of firms and collaborations it comprises. Subsequently the evolution of the FC industry is described, to better understand the emergence, historic characteristics and positioning of FC firms. The analysis focuses on developers of PEMFC technology.

2.5.1 Status of the Fuel Cell Industry

Financial data of FC firms indicate the state of industry development, characterised in 2006 by a low return on high investments. The PricewaterhouseCoopers survey (PwC 2006) of public FC firms shows an increase of revenue of 20%, a 19% decrease in net losses and a 6% decrease of R&D expenditure in 2005 compared to 2004 (fig. 2.11). However the Worldwide Fuel Cell Industry Survey (Worldwide survey 2006), with 181 respondents, shows an increase of 11% R&D expenditure and a sales increase of 7% between 2004 and 2005. This survey suggests that R&D expenditure is double the revenue from sales and that sales were limited in 2005. Moreover, both surveys show that none of the companies were profitable up to and including 2005: *"the financial performance reflects the costs of implementing strategies to refine pre-commercial technology develop product capacity and secure market access"* (PwC 2005: p.6). Thus, the FC industry is non self-supporting and considering the long-term process of commercialization, return on investment will take time.

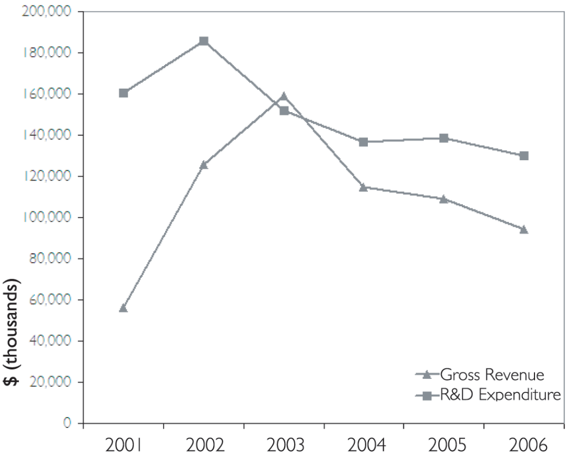

Figure 2.11 Financial data public fuel cell firm. Source: PwC 2002-2006

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[19] *Presentation NIAIST by Kogaki at the Hydrogen and Fuel Cell conference Vancouver 2007*

Most companies are considered to be in a developmental stage focusing on research, development and testing. Few firms have products available for sale. A number of companies report revenue from product sales, selling to a limited number of early adopters including OEM partners, government funded demonstration projects and the military. Most revenues are made from engineering contracts and research and engineering services. Gradually firms in the FC industry appear to be making a transition to marketing and sales: *"several companies are developing marketing and distribution networks, creating supply chain relationships and building the manufacturing capabilities required to meet significant order volumes anticipated in the future"* (PwC 2000: p.5).

The surveys include all FC technologies, hydrogen infrastructure technologies and supply chain positions in the FC industry. Between 25% and 50% of the companies in the FC industry are focused on PEMFC technology. It is notable that the hydrogen infrastructure firms are increasing sales at a more rapid pace than the PEMFC firms (PwC 2006). Since the 1980s the industry has been emerging. The exact number of firms in the FC industry is difficult to estimate, but the industry comprises of hundreds of FC and hydrogen related companies. The number of new entrants is still growing. Approximately 70 percent of the total industry is located in North America where the industry was born (Worldwide Industry Survey 2006). Europe follows at a second place and the number of European companies is steadily growing. The companies involved in the FC industry include large firms with an R&D division dedicated to FCs and/or hydrogen developments as well as independent FC firms. Multiple independent FC firms, with FC technology as their core business activity, have been founded in the previous 10 years. The size of these independent FC firms varies between less than 10, between 30 and 50, and between 200 and 300 employees. The only FC firm with 600 employees, founded for the development of PEMFC technology, is the company Ballard.

2.2.2 Evolution of the Fuel Cell Industry

The FC industry has been described as emerging and growing. The evolution of the FC industry is key to understanding where FC firms come from and how FC firms relate to each other. This paragraph will describe which firms entered the industry at which point in time and the origins of these firms (fig. 2.12). The principle of FC technology is not new: it was invented as early as 1839 when Sir William Grove discovered that it was possible to generate electricity by reversing the electrolysis of water. In the 1960s General Electric (GE) invented an early version of the PEMFC, with a Teflon based solid plastic electrolyte. GE developed a small FC system for the NASA Gemini Project in the early days of the U.S. space programme. GE continued work on its PEMFC technology for a few more years, during which GE applied the Dupont's Nafion membrane and significantly improved operating life and power densities. Although recognising the potential for widespread commercial use of PEMFCs, the company eventually sold its FC division.

NASA chose to apply FCs for the Gemini space programme for practical reasons: FCs were compact compared to batteries and FCs produced water and heat, which was useful for sustaining astronauts in space. (Cohn 1965) Two parallel FC developments competed for this mission: the PEM fuel cell system designed by GE and an AFC developed by the United Aircraft Corporation (UAC). In the early 1960s Francis Bacon, the developer of AFC technology transferred the technology to the UAC. With this technology, the UAC also developed a FC system for the NASA space programme, which was ultimately chosen to provide on-board power for the Apollo moon missions. The company became International Fuel Cells (IFC) in a joint venture between Toshiba and United technologies and focused on the development of PAFC and AFC FCs. IFC was renamed United Technologies Corporation (UTC) Fuel Cells in 2001. Not until the late 1990s did the company shift its focus towards PEMFCs for cars and bus applications. According to UTC, their experience and knowledge in PAFC stationary systems helped the company develop durable PEMFC systems[20].

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[20] Presentation by Tosca of UTC at the Hydrogen and Fuel Cell Conference in Vancouver 2007

In the 1970s and 1980s mid and high temperature FCs dominated R&D. For example, in the 1980s PAFC development was aggressively funded by US and Japanese companies. The Dutch government invested in the development of MCFC technology in the 1980s (Van der Hoeven 2001). In the early 1980s, Los Alamos National Laboratory was the only place where significant research on PEMFCs was being conducted. Tackling basic R&D challenges, such as the design of electrodes and FC modelling, the laboratory demonstrated efficient energy conversion and power density in a PEMFC with very low amounts of precious metal catalysts. Thereby, Los Alamos demonstrated that PEMFCs could have potential, but as a research institute Los Alamos did not continue to build the 'hardware' of a FC system.

Ballard Research Inc. was founded in 1979 by Geoffrey Ballard to research and develop high energy Lithium batteries with the objective of finding a viable technology that could power electric cars (Koppel 2001). The research on rechargeable batteries never became a practical technology and the company looked for other technological opportunities. The Canadian government had set out bids to further develop General Electric's PEMFC technology in order to research the potential for producing a low cost solid polymer FC. Ballard took on this challenge and in 1983 the company began to work on PEMFCs funded by the Canadian Department of Defence. Initial achievements showed potential and in 1989 Ballard Power Systems A.G was formed in Vancouver Canada, the first company primarily focused on the development of PEMFC technology.

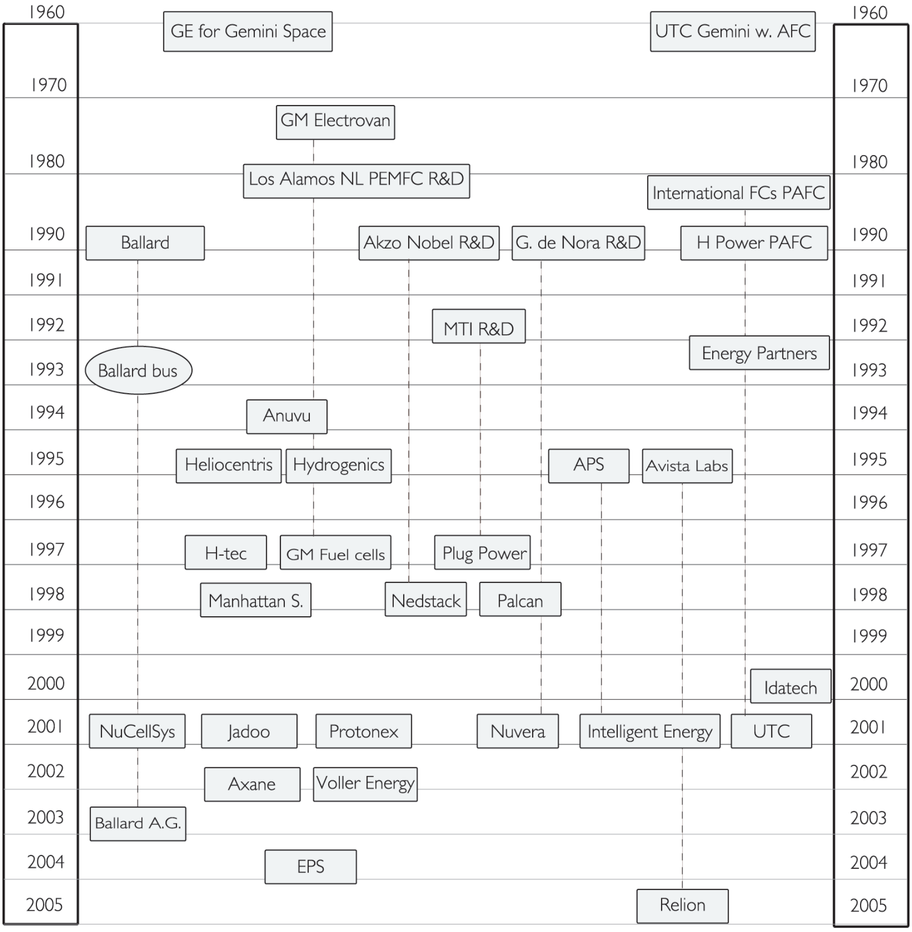

Figure 2.12 Evolution of the FC industry, emergence of FC firms by year of founding

General Motors (GM) became involved in FC development as early as 1964 and in 1968 a first minibus prototype was presented. This Electrovan demonstrated the feasibility of a propulsion system using electrical power generated by cryogenically stored hydrogen and oxygen combined with potassium hydroxide. In 1988 Los Alamos and GM formed a major engineering development partnership and worked together for nearly eight years to perfect a PEMFC. The partnership also involved Dow Chemical Co. and Ballard Power Systems. PEMFC research with Los Alamos was continued by the formation of GM FC activities in 1997. In the late 1980s PEMFC technology was further developed in North America, where it was fostered by large government funded R&D programmes. Numerous research institutes became involved in PEMFC technology in the 1980s including Analytic Energy Systems, founded in 1984 and ElectroChem founded in 1986.

From 1989 onwards, Ballard had repeatedly doubled the power density of its FC stacks and in January 1993 demonstrated the first proof of concept FC bus (Koppel 2001). In the same year the company began with initial public offerings. Ballard collaborated on the development of a FC hybrid electric vehicle with GM in 1995 and in 1997 contracted mega-deals with Daimler Chrysler and Ford. In 1993 Energy Partners Inc. also presented a demonstration: the first FC passenger car powered by a 15 kW PEMFC. In this period other PEMFC firms emerged. Teledyne Energy Systems (TES) was formed by combining Teledyne's Energy Systems business unit with the assets and intellectual property of Energy Partners. TES is a provider of on-site gas and power generation systems based on FC, electrolysis and thermo-electric technologies. In 1989 H Power Corporation was founded with an initial research focus on PAFC, presenting a prototype bus in 1993. Not until the late 1990s did the company shift to the development of PEMFC technology, marked by sales of PEMFCs to the New Jersey department of transport in 1998.

Between 1994 and 1998 several independent firms targeting the development of PEMFC technology were founded. A number of these companies are described below. Anuvu, a Californian corporation was founded in 1994, targeting FC developments for the automotive industry. In 1995 three entrepreneurs founded Hydrogenics in Canada, with a vision of clean sustainable energy. The company began with the development and sales of FC test and diagnostic equipment and conducted R&D on PEMFC systems. Avista lab was founded in 1995 as a wholly owned subsidiary of the energy company Avista Corporation. In 2004 Avista was renamed Relion and continued to develop PEMFC systems in the 50 W to 5 kW power range. In 1995 one of the first independent European firms was founded, namely, Heliocentris of Germany, targeting FC products for educational purposes. In 1995 Advanced Power Systems (APS) was formed as a spin-off company from the PEMFC research at Loughborough University in the UK. In North America firms continued to emerge. North West power systems was founded in 1996 with contractual ties to Idaho Power Company and FC manufacturers. In 1999 the company joined the Idacorp group of energy companies and was renamed Idatech. Additionally in the US, Plug Power was founded in 1997 as a joint venture between Mechanical Technology Incorporated (MTI) and DTE Energy, an early developer of FCs and the largest energy service and utility company in Michigan respectively. In 1997 another German supplier of educational and demonstration products founded, H-tec.

Manhattan Scientifics, a US company committed to the commercialisation of new technologies, became a publicly held company in 1998 to commercialize micro FCs. The Dutch FC stack developer, Nedstack, was founded in 1998 as an Akzo Nobel spin-off. Akzo Nobel's FC activities date back to 1989 and focused on FC materials such as plates, catalysts, GDLs and membranes. The German company Proton Motor was also founded in 1998 as a spin off from Magnet Motor, a developer of electric propulsion systems. Cellex power was founded in 1998 by employees from Ballard, seeking niche market applications in material handling. Similarly, General Hydrogen of Canada was founded in 1999, notably by the founder of Ballard, Geoffrey Ballard.

In 2000 Nuvera was formed through a merger of Epyx Corporation of Massachusetts and De Nora fuel cells, a subsidiary of the group of electrochemical companies Gruppo de Nora of Italy. De Nora had been working on FCs for 10 years. In 2001 Axane was established as wholly owned subsidiary of the French gas company Air Liquide. In the same year Intelligent Energy was founded as spin-off from APS in the UK. In the US, Jadoo was founded in 2001 to develop integrated PEM power systems for professional video cameras, emergency situations and the military. Additionally, OEM companies emerged dedicated towards the development of FC products. For example, Voller Energy was founded in 2002 in the UK to target the portable power market and Electro Power Systems was founded in 2004 in Italy to target the back up power market for telecom. Additionally, this period shows mergers and acquisitions, for example, in 2000 Plug Power acquired intellectual property on reforming technology from Gastec and in 2002 acquired a competitor in PEMFCs, H Power. Hydrogenics acquired Stuart Energy in January 2004, adding hydrogen fuelling and infrastructure to the company's business divisions.

Furthermore, the FC industry comprises car manufacturers involved in the development of FC technology. GM was probably the first car manufacturer to invest in FC R&D. From 1997 onwards an increasing number of automotive companies became involved in FC R&D, reflected by the presentation of demonstration vehicles. Daimler Chrysler and Toyota first presented FC prototype vehicles in the beginning of 1997 and a majority of the large car manufacturers followed. Major collaborations have been formed, for example, in 2003 Ford and Daimler Chrysler partnered with Ballard, GM partnered with Toyota, and PSA Peugeot with Renault and Nissan.

The emergence of independent FC firms in Europe stayed behind the US and focused on high temperature FCs for many years. Europe focused on R&D in research centres such as the Fraunhoffer Institute and the Forschungszentrum Julich in Germany. Within Europe, most FC research and development has been conducted in Germany. In Japan most FC developments take place at car manufacturers such as Honda, Nissan and Toyota. Additionally, large manufacturers of consumer electronics have been conducting FC developments such as Fuji, Hitachi, Mitsubishi and Toshiba.

2.5.3 Industry Development

The description of the FC industry evolution indicates that many of the early FC firms did not start with the development of PEMFCs. The renaissance of PEMFC technology in the mid 1980s was mainly sparked by research accomplishments at Los Alamos National Laboratory and Ballard in North America. Whilst other companies and institutes primarily focused on the development of PAFC, MCFC and AFC, Ballard committed itself to further developing the technology towards viable commercial applications in Canada. The resulting technological advancement enabled PEMFCs to attain high specific power, power density and energy efficiency compared to other FC technologies. Low operating temperature and short start up time made it more suitable for transport applications than other types of FCs. This potential is likely to have sparked the development of the PEMFC industry, primarily in North America and subsequently in Europe and Japan.

A first wave of new independent PEMFC firms is observed between 1995 and 2000. New companies were founded on the basis of different areas of expertise. The most prominent backgrounds come from industrial sectors involved in electrochemical R&D. For example, Nuvera and Nedstack were founded on the basis of FC R&D in the electrochemical companies de Nora and Akzo Nobel respectively. These companies were primarily stimulated by the immense market potential for FC vehicles. By contrast, in the same period, several energy and utility companies were involved in the foundation of firms such as Idatech, Plug Power and Relion (Avista). Other FC firms such as Manhattan Scientific and Intelligent Energy came forth from companies and laboratories dedicated to commercialising new technologies. Another group of companies can be identified, including H Power and IFC, that focused on PAFC or AFC in the mid 80s and shifted towards PEMFC technology in the mid 90s. These companies were primarily geared towards stationary markets for power generation.

After 2000 companies were founded targeting potential niche market applications for FC technology. For example, Protonex targeting portable and remote applications, Axane developing critical power applications, Jadoo focusing on battery replacement for professional video cameras and military electronic equipment and OEM entrepreneurs targeting FC end-products such as Voller for portable power. More recently, the emergence of companies such as Electro Power Systems and H2 Logic suggests that this trend continues as the market opportunities in niche markets become more apparent. Throughout this industry evolution, companies have emerged both upstream and downstream in the supply chain, including companies specialised in FC system integration services and companies developing dedicated FC materials. Firms have positioned themselves in different parts of the supply chain. For example, Nedstack, with an electrochemical background, is specialised in FC stack development and supply to OEM customers. Other companies, typically with an energy utility background, develop end-products, such as back up power and remote power generators for stationary power generation. Several relatively new industry entrants are positioned as dedicated OEMs for FC products.

The number of independent FC firms is still growing and diversifying. Some companies will change course and some companies will discontinue research programmes. There are companies that have not survived the previous years and inevitably, more independent FC firms will cease to exist or be acquired by larger (FC) firms. The firms founded 10 years ago are not profitable as yet, whilst large-scale markets are still far away. For independent FC firms the commercialization of FC technology appears to require staying power.

2.5.4 Finance and the Fuel Cell Industry

Considerable funds and investments have been allocated to R&D in FC technology. Firms in the FC industry derive financial resources from private as well as public funding. Figure 2.13 illustrates the sources of funding used by FC firms in Europe. Typically, the type of financing for R&D is related to the stage in the growth of a technology and the firm. Currently in a developmental stage of technology and firm development, the sources of funding are derived from both public and private sources, however, this varies strongly between countries and firms.

The public sector has funded FC technology development with significant R&D grants. In the public sector, average annual spending for Japan has trebled since 1995 to $220 million. The US annual spending amounts to $200 million, in Europe to $60 million and in Canada to $10 million. Japan reports to have passed the peak of public R&D funding for FC development in 2005[21].

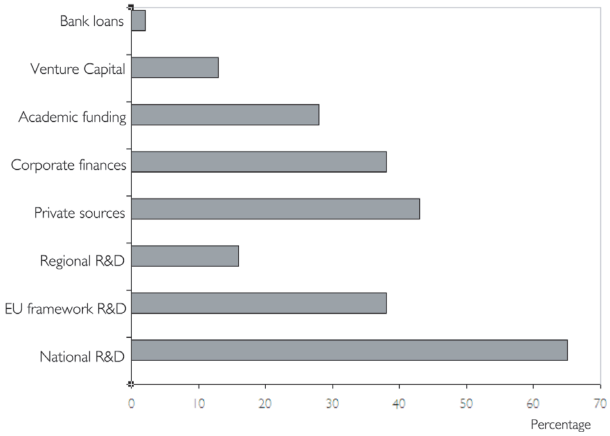

Figure 2.13 The sources of finance in European fuel cell firms. Source: Core technology

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[21] *Presentation NIAIST by Kogaki at the Hydrogen and Fuel Cell conference Vancouver 2007*

European FC firms are dominated by grant funded research. It is notable that few European companies are publicly listed, most publicly listed FC firms are based in North America. The market capitalization of quoted North American independent developers is about $4 billion compared to $0.7 billion for Europe. According to Doran, of Core Technology Ventures (2004), *"the European scene is characterized by a crippling shortage of capital".* In recent years, the first successful flotation of 'pure' FC companies has been announced, which may increase venture capital activity. However, as Wustenhagen and Teppo (2006 p.69) observe, venture capital investors have generally been hesitant to invest in FC technology because *"A lot of business plans in the fuel cell sector, rely on other external factors that you cannot control and a venture capitalist is getting very nervous when you see big investments in a capital intensive and regulated market relying on a fundamental change in the environment".* Besides, to date, there are few FC specific investors. The co-founder and chief scientist of a UK based FC firm describes his experiences in the financing rounds of his company: *"the level of technical understanding you need to understand fuel cell technology is huge. Investors do not understand the technology and the terminology"*[22].

The North American public firms have experienced extreme fluctuation in stock market value. In 2000, Canadian FC companies were worth 1$ billion on stock markets. After 2000, the market value of quoted FC companies has fallen by 85%. Also venture capital investment peaked in 2000 (Core Technology 2002). This curve is illustrated by the WilderHill fuel cell index of several publicly listed fuel cell firms[23]. The index shows a peak in 2000, a steep fall after 2000 and an average increase since 2002. The index appears to follow the so called 'Gartner hype cycle' (fig. 2.14). This 'hype cycle' describes a cycle common to many new technologies and industries. The model suggests that new technologies go through a 'peak' of inflated expectations, followed by a 'trough' of disillusionment before gradually moving towards a period of productivity (Fenn 1995). According to this model, FC firms should reach a level of productivity in the coming years. The current phase of the FC industry, beyond the 'peak of expectations', is likely to imply that investors are becoming impatient. Before long FC firms will have to 'deliver' and shift from R&D to commercial applications. At the same time, the financial data suggests that the majority of independent FC firms have limited resources to allocate.

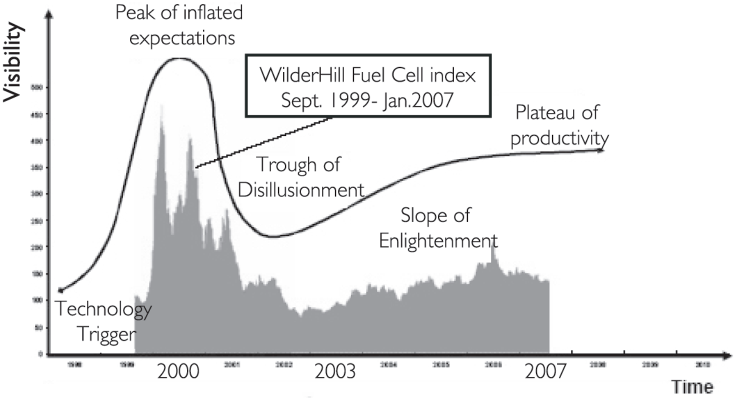

Figure 2.14 The WilderHill fuel cell index under the Gartner hype cycle. Based on Core Technology Ventures 2004

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[22] Presentation on the founding and financing of Ceres Power, London December 2006.

[23] The WilderHill index downloaded from www.h2fuelcells.org

2.6 Conclusions on Fuel Cell Technology Commercialisation

FC and hydrogen technologies have the potential to play a central role in a transition towards a more sustainable energy system. Widespread application of FC technology in transportation and power generation may provide major improvements in air pollution and quality of life as well as a reduction of CO_2 emissions. Technology development and demonstrations are financially supported by governmental organizations and to some degree stimulated by emission regulations. Yet, the commercialisation of FC technology is proving to be a long process with many uncertainties.

The implementation of FC technology on a large scale involves radical and system level changes to infrastructure, supply chains and organizations. However, there is no consensus about the desirability of hydrogen and FC technology and there are multiple competing alternatives for emission reduction and efficiency improvement. This study will focus on PEMFC technology. This type of FC technology competes with established solutions and emerging alternatives as well as other types of FC technologies. The requirements of established technologies set the benchmark for performance and cost requirements. The technology has both advantages and disadvantages above other technologies, and as a result, the necessity for FC applications is disputed. There is market potential for PEMFC technology in a broad scope of market applications. The automotive market in particular provides potential for large scale market adoption, however, this market is taking longer to reach than expected and the widespread adoption of FC vehicles is uncertain to date. In the meantime other applications are emerging, including a variety of niche markets and early markets targeting near- and mid-term adoption. This study will focus on the emergence and pursuit of such niche market applications.

A multitude of challenges complicate and delay the process of FC technology commercialisation. At a technology, contextual, market as well as firm and project level there are issues to address. However, it is the firms developing FC technology that are challenged to manage the process of technology application within this array of uncertainties. Multiple independent FC firms have emerged for whom survival is particularly uncertain. Prior to widespread commercialisation, these FC firms are challenged to identify, select and engage in niche markets from the wide range of possible market applications. Yet, customers are unfamiliar with the technology and market adoption is uncertain. To understand how these FC firms manage applications within this context of uncertainty, it is relevant to study the application decisions and application histories of FC firms. This research will therefore take a firm level perspective to focus on firm level management challenges and decisions with regard to pre-commercial applications.

Chapter 3: Challenges of Fuel Cell Technology Application

> *Deciding, under significant uncertainty about future states of the world, which long-term paths to commit to and when to change paths is the central strategic problem confronting the firm.*
>
> *Teece et al.1997*

The market potential for the commercialisation of PEMFC technology is substantial. Nevertheless, chapter 2 describes the commercialisation of FC technology as a lengthy process with a high degree of uncertainty regarding widespread adoption. This chapter aims to specify the challenges and uncertainties of FC technology application to better understand why its commercialisation is uncertain and lengthy. Thereby, this chapter addresses the following research question: what characterises FC technology? (RQ 1b) Firm level management challenges and decisions are discussed with regard to pre-commercial applications of FC technology.

First, the technology, the market for FC products, the contextual environment and the industry are characterised to gain insight into the challenges of managing the application of FC technology (3.1). The implications for selecting and developing FC products are then described and illustrated through the 'lessons learnt' in a number of FC projects (3.2). Subsequently, FC technology is compared to other technologies in order to clarify which characteristics are common to other technologies and which challenges are particular to FC technology (3.3). Considering the emergence of numerous independent FC firms in the FC industry, this study finally describes the key challenges independent FC firms face in the process of FC technology application (3.4).

3.1 Characterisation of Fuel Cell Technology and Markets

The previous chapter introduced FC technology as a potentially sustainable energy technology and described applications of the technology, components of a FC stack and system, technical challenges ahead, the current status and future prospects, developments in the regulatory climate and the evolution of the industry. Departing from this information, the following paragraphs describe a characterisation of FCs in terms of: i) the technology, ii) the market for FC products, iii) the regulatory context, and iv) the FC industry. For each of these categories, several characteristics are described, derived from the observations and data in chapter 2 (table 3.1). The objective of this characterisation is to bring to light the key uncertainties and challenges of managing the application of FC technology (table 3.2).

Table 3.1 Characterisation of observations in chp.2.

Characterisation category		Chapter 2
Tech. 1	Immaturity: high investments in R&D, technical uncertainty No dominant technology	The cost and performance benchmark for automotive markets has not been met as yet
T2	Application diversity	Can replace power generation system in a broad range of products
T3	A replacement technology: a subsystem in existent products	Competition from established and new technologies
Market 1	Market uncertainty: no market demand	Novelty, replaces incumbent technologies Lack of cost and performance competitiveness
M2	Emerging niche markets	Mass market potential, decades away Multiple niche markets near and mid term
M3	Demonstration and validation	Various prototypes realized for demonstrations. Large demonstration projects being developed
Context 1	Uncertainty regulatory climate	Emission legislation, financial support, however, a lack of consensus on desirability
C2	Complementary technology dependence	Hydrogen storage infrastructure Trend towards more sustainable energy system
Industry 1	Low return on high investment	Firms are non-profitable. Long period of development.
I2	Emergence of entrepreneurial firms	Emerging and developmental industry

3.1.1 The Technology

Technologies can be characterised in several ways. Characteristics that are likely to influence the innovation process include, i) the state of development and novelty (Souder 1987), ii) the type and breadth of applications and iii) the complexity of a technology (Tatikonda and Stock 2003). In the following paragraphs FC technology is characterised as an immature technology (T1), diversely applicable (T2) as a replacement technology (T3), of considerable complexity (T4).

T1. Immaturity

The status of PEM FC technology with respect to cost and durability targets indicates that the technology is immature as yet. This immaturity is reflected in the rapid technological progress in cost reduction and performance improvement. The energy density improvement of automotive FC stacks has, for example, quadrupled between 1994 and 2004 (Van den Hoed 2004). At the same time, technical challenges remain, requiring significant R&D investments. The early state of development manifests itself in the emphasis on R&D activities in the independent firms of the FC industry, rather than product development, marketing and sales. The current period is characterised by high investments in continuous R&D as well as the gradual shift towards manufacturing. A further indication of the early state of development is the lack of a dominant design, as different FC technologies and designs for PEMFCs compete[21]. The immaturity explains why FC technology is not yet competitive with available technologies that provide the benchmark for performance and costs. Due to the current immaturity and envisaged potential that FC technology may provide a cost-effective and superior alternative to the available technologies, investors and governments support the further development of FC technology.

Immaturity of the technology has major consequences for the innovation process. Given the immaturity, private and public actors are responsible for providing capital. Immaturity also provides difficulties in balancing R&D activities, to increase cost and performance competitiveness, with activities in sales and marketing. The immaturity implies uncertainty in decisions on technology development and application. It increases the risks of choosing the 'wrong' technical path, making competences obsolete and 'wasting' resources. Additionally, the timing of commercialization is difficult to predict, as reflected in the continuously modified and postponed technology road maps.

T2. Application Diversity

PEM FC technology is applicable in transportation, stationary and portable markets as well as a diversity of niche market applications. Section 2.2 described the power range of PEMFCs and the broad scope of short, mid and long term potential applications. This application diversity implies that there are multiple market applications to choose from: an apparently 'luxurious scope' of market opportunities. Prior to large scale applications, FC firms are pursuing niche market opportunities. There are several niche market applications to choose from for short and mid term market adoption. Niche markets are identified by their potential to replace established energy technologies cost effectively and with an added value. The sales account manager at a renowned FC firm describes the procedure to select niche market applications as follows: *"we looked at the price of the concurrent product and therefore identified batteries. Second step was identifying the high volume markets where battery solutions face most limitations"*[22]. Despite this apparently facile comparison, it has been difficult to predict which niche markets would be the first to emerge. As a general manager of another FC firms describes: *"we do know in which order these segments shall open up in the future, but we do not know exactly when that will be"* (Plug Power 2006). Apparently, there are uncertainties regarding the time frame and scale of FC market adoption and the development of market demand. Consequently, it is challenging to decide in which markets to invest at which point in time.

The application diversity of FC technology poses firm level management challenges on the development of a firm's business and product portfolio. FC firms face challenging decisions regarding what market applications to focus on at which moment in time. There is a risk of engaging and investing in a market application without gaining benefit in terms of profit or learning. The application diversity also increases the risk of choosing the wrong business and market development path at the wrong time: failure of market acceptance for an application can make acquired resources and developments obsolete.

T3. A Replacement Technology

A PEMFC system generates electricity to power products and can, therefore, replace established power generators such as IC engines and batteries. As a replacement of established technologies in existent market applications, the technology can be characterised as a 'replacement technology'. Replacing a substantial subsystem of a product may cause disruption in established supply chains. The disruption of established supply chains is likely to 'shake out' several current suppliers. In the automotive supply chains, for example, combustion engine part suppliers will become obsolete as FC engines are adopted. Thus, replacing established technologies can affect numerous stakeholders in the product value chains of existent markets. These changes to the structure and partnerships of existent supply chains are likely to cause resistance

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[21] Literature on technology cycles describes that after a period of variation and diversity, one technology becomes dominant in the industry, marking a change in phase of industry development (e.g. Utterback and Abernathy 1975, Utterback 1994). This dominant design incorporates basic choices about components and architecture.

[22] Questions answered by email from the Sales Account Manager of Ballard at the European office in Kirchenheim in Germany, 2006.

among established firms and organisations. The replacement of current energy systems with FC systems may additionally disrupt the (core) competences of established system integrators, making prior competence obsolete. The replacement will require firms to substitute established technologies and acquire new competences and skills to integrate FC technology into their products. For example, replacing batteries with a FC system will require an OEM fork-lift manufacturer to learn about FC system integration. Possibly, the integration requires substantial changes to the configuration and architecture of the firm's fork-lift trucks. Furthermore, OEM customers are likely to perceive the replacement as risky because the established technology, proven in operation, is replaced by a new and unfamiliar technology. Consequently, OEM customers are often hesitant to replace their current technology with FC technology.

Thus, FC technology is characterised as a replacement technology. This characteristic implies that established supply chains and core competences of OEM customers are disrupted. In the process of forming supply chain relationships, independent FC firms may consequently face conflicting interests and resistance. In the process of technology application, it is therefore necessary for FC firms to demonstrate and prove their technology through early applications. Additionally, the process of identifying and convincing OEM customers is likely to require the education of OEM customers in order to overcome their perceived risk of adoption and their hesitance to acquire new skills and competences.

T4. Complexity

The scope of FC system design features, from the MEA and bi-polar plates to the integration of a power train, suggests that FCs can be characterised as complex entities, both physically and in terms of the skills required for development. Stock and Tatikonda (2000) describe technological complexity in terms of the quantity of internal technological components and interdependence, referring to the relationships and interactions between components and subsystems. Similarly, Iansiti (1995) defines complexity as a high level of interdependence among knowledge domains. A FC system comprises numerous components between which there is a high degree of interdependence. It is like a living organism: malfunctioning of one organ or an unhealthy diet is likely to destroy the balance of the whole system. Consequently, the specification and performance of fuel cells, stack, system and product are interdependent. Additionally, there is interdependence between the FC system and the product in which it is to be incorporated. For example, the selection and placement of FC system components may influence the system's performance, the architecture and the design of a product (Hellman 2005). Furthermore, FC technology development and application requires a broad scope of in-depth and interdependent competences and skills. The development of a FC system, for example, requires thermodynamics, fluid dynamics and electro-chemical skills at a micro level and system modelling, integration and power electronics skills at a system level. Apart from a number of large automotive firms, most independent FC firms do not possess all the skills required from material development up to and including FC product development. As a consequence, several supply chain firms are typically involved in the development of a FC product, as the FC firm Nuvera[23] describes, *"the market is horizontal. There are hardly any companies with vertically integrated design, it is almost impossible to achieve nowadays".* Consequently, the development of the FC industry is characterised by the formation of supply chain relationships and partnerships for collaborative development and future supply agreements. The interdependence between components, FC systems and products is reflected in the necessity of close collaboration between supply chain stakeholders.

The complexity of FC technology implies that independent FC firms have to decide on their supply chain position and their portfolio of skills to develop internally and to outsource. A majority of the independent FC firms supply FC stacks and/or systems to OEM customers. Their rationale is that FC technology replaces a subsystem in existent markets, in which established OEMs have better access to distribution channels and market information than the FC firms. As a sales and marketing manager at Nuvera states[24], *"we do not have the competence to go to the market directly alone".* On the other hand, FC firms supplying OEM customers depend on their willingness and commitment to adopt the technology and engage in the development of early applications. FC firms face trade-offs in the decisions on what to develop and who to supply to.

[23] Telephone interview with Sales and Marketing Manager at Nuvera, Feburari 2004

[24] Ibid.

3.1.2 The Market for Fuel Cell Products FC technology and the market for FC products are in a way two sides of the same coin. Nevertheless, a characterisation of the market for FC products highlights the performance indicators of the technology that matter to the end user. The status of market development is characterised by market uncertainty (M1), the emergence of niche markets (M2) and applications for demonstration and validation (M3).

M1. Market Uncertainty

There is a large discrepancy between the potential for widespread adoption and the time to widespread diffusion of FC technology. The reason for this duration is that FC technology is 'immature' and years away from the automotive benchmark for cost competitiveness (as described in paragraph T1). Additionally, the stationary market is argued to be a difficult market to crack (Romm 2004). Although initial cost and performance competitive niche markets are emerging, market demand is weak. The lack of market demand poses uncertainty about if, when and which markets will adopt FC technology. Although price and performance comparisons can be made on the basis of established technologies, it is difficult to predict how market demand will develop. Commercial director of the Dutch FC firm Nedstack (2005), emphasizes the relevance of timing: *"you can only make two mistakes, you are too early or you are too late".*

The lack of market demand implies that it is difficult to predict which market applications have most potential and which markets will come first. Considering the diversity of potential applications, there is a risk of choosing to invest in the wrong business and market development path at the wrong time. The competitive benchmark set by established technologies increases the importance of finding premium markets where the technology can compete on the short and mid-term.

M2. Emerging Niche Markets

The long 'wait' for the potential adoption of FC technology in large scale markets increases the importance of finding premium markets for initial revenue. Independent FC firms are targeting initial niche markets. A sales account manager at Ballard[25] states that *"it is a challenge to convince people they don't have to wait for the automotive market for things to happen - that myth is still out there".* The market for FC products is characterised by a phase of niche market developments as near and mid term niche market applications begin to emerge. Niche markets are primarily emerging in areas where the price/performance of batteries is met or in reach. For example, numerous FC firms demonstrated the feasibility of fork-lift trucks and back-up power systems in 2005 (FC Today 2006). The market for critical back-up power applications is currently emerging as the first commercial niche market for FC technology.

It is thought that niche markets may contribute to the wider adoption of a new technology (e.g. Geels 2002, Kemp et al. 1998). Among others, niche markets are pursued to learn, demonstrate the technology and build relationships. However, benefits from niche markets are not evident. In a study of FC bus demonstration projects, Harborne et al. (2007: p.13) find that *"there is no evidence as yet that FC bus demonstrations are contributing to successful 'adoption' in the bus market."* Additionally, Hendry et al. find that experimentation with different niches for PAFC technology did not result in any long-term committed customers. Besides, niche markets for FC technology may be pursued primarily for initial revenue, irrespective of longer term ambitions.

A consequence of the innovation process is that the application of FC technology through various niche markets is likely to require some form of 'niche market management' to grow from small markets to larger markets effectively. There is a risk of pursuing niche markets that do not contribute to development of larger markets or the development of useful skills and relationships. Besides, predicting which niche markets will emerge at which time appears to be challenging. The diversity of niche markets implies that FC firms have to decide which niche markets to engage in at which point in time, managing the uncertainty of

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[25] Questions answered by email in 2006 by a Sales Account Manager at the European office in Kirchenheim, Germany.

market adoption and considering short term revenue as well as longer term objectives. The selection of niche market applications appears determinant for how independent FC firms manage and survive the long period applications prior to widespread adoption.

M3. Demonstration and Validation

The current phase of market development is furthermore characterised by demonstrations and validations of FC technology. As a new technology in established markets, FC firms are challenged to demonstrate and prove the potential and performance of FC technology. Kammerer (2006), head of sales at the FC firm Hydrogenics, finds that early applications are necessary to validate their technology, *"we need operational information, without it the OEMs have too many questions".* Besides, demonstrations of FC technology are necessary to generate awareness, as the technology is new to customers and end-users. The first Ballard prototype bus in 1993, for example, helped the layman to understand FC technology. Koppel (2001 p.152) explains that *"no matter how often you draw the picture, no matter how much you talk, people don't get it until they see it make the wheels go round".* The application of FC technology for demonstration purposes appears to be highly relevant for the education of customers and consumers. Without demonstration prototypes, consumers tend to judge the technology based on their experience with established technologies. For example, in the Hydrogen Shuttle project[26], the electric vehicle manufacturer Spijkstaal found: "the customer assumes that if you offer him a bus, that it will drive 600.000 km. That is not a topic of discussion. He assumes that it will do so, based on his prior product experience" (Heijboer 2005). Conventional market research techniques were conducted in this project without a demonstration prototype, resulting in unreliable outcomes regarding customer interest (Plomp 2005). At the same time demonstration projects are costly and typically far from commercial. OEM customer Heijboer (2005) explains that to invest in a prototype, a realistic estimate of the costs is a must and "you have to know if it is going to work". Consequently, demonstration projects are often risky and costly endeavours for OEM customers and they appear hesitant to commit to and finance FC demonstration projects. FC firms are challenged to convince OEM customers as well as manage their expectations.

Furthermore, several large demonstration projects are being developed, such as the HyChain and CUTE projects, described in section 2.3. Governmental institutions fund such demonstration projects and provide so-called 'temporary protected spaces', described by Kemp et al. (1998) as a space where a new technology can be tested and developed as normal commercial market considerations do not apply. Such demonstration projects are considered relevant for building knowledge. For example, Harborne et al. (2007) find that for a diverse range of stakeholders learning is a major benefit of FC bus demonstration projects. Thereby, learning embraces the performance, durability and costs of the vehicles, infrastructure issues and a variety of constraints such as regulatory and insurance issues. However, large demonstration projects are also characterised by the diverse objectives of various stakeholders and the strategic objectives of FC firms may be overshadowed by political issues.

The current phase of FC commercialisation is characterised by demonstrations and early applications to generate awareness, educate customers and validate the technology. Moreover, demonstrations appear to be a relevant tool for market research. FC firms have to select which applications to engage at which point in time to demonstrate and validate their technology. There is a risk in failing to convince customers and failing to meet their expectations. Decisions on the timing of demonstrations in terms of technical maturity, appear relevant considering the risk of failure and the impression it will leave on potential customers. Moreover, demonstrations pose a dilemma: on the one hand, the applications are necessary to generate awareness and convince customers, on the other hand, these applications may distract FC firms from the development of commercial applications. Thus, FC firms are challenged to manage the 'marketing' of their technology through applications for demonstration and validation.

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[26] This project is further described in section 3.2

3.1.3 The Contextual Environment

The development and commercialisation of FC technology is additionally related to numerous contextual factors such as institutional barriers and the lack of network externalities. The contextual environment includes developments external to a firm. According to Kemp et al. (1998), a transition to a new energy economy not only involves the control or promotion of a single technology, but also changes to an integrated system of technologies and social practices. Characteristics of the contextual environment include complementary technologies (C1) and the regulatory climate (C2).

C1. Supportive but Uncertain Regulatory Climate

Its "clean" quality gives FC technology a particular status with respect to regulatory support. National and local emission legislation and financial support appears to stimulate R&D and market demand for FC technology. However, the degree to which the regulatory climate will remain supportive is uncertain. It is uncertain how legislation on green house gas emissions will develop and in particular, if mandatory zero emission legislation will be imposed. Hall and Kerr (2003) argue that even though governments may be committed to environmental protection, they often do not send out clear signals. For example, the 'energy neutral' strategy towards sustainable energy in the Netherlands provides no indication of the preferred direction. Governmental institutions consider and invest in multiple technological alternatives to address CO2 reduction, energy efficiency and oil depletion. Consequently, there is a lack of consensus on the desirability of FC technology and as a result the regulatory climate can be characterised as highly uncertain. Despite the uncertainty of the regulatory climate, the regulations are being developed and FC firms can, to some degree, influence the development of this regulatory environment. For example, the implementation plan of the European Hydrogen and FC Technology Platform has been drawn up by both public and private stakeholders, including FC firms, to realize large demonstration projects (HFP 2007). According to Karlstrom and Sánden (2004) demonstration projects can result in the formation of a network of actors to drive technology and policy change. Harborne et al. (2007: p.2007) on the other hand, found that the networks formed through FC bus demonstration projects, *"have been more effective in blocking the commercialisation of FC buses than in supporting them".*

The uncertain and changing regulatory climate emphasizes the need for FC firms to minimize their dependence on regulatory support by finding premium niche markets with commercial potential. Additionally, the changing regulatory environment implies that firms should continuously scan and re-evaluate opportunities and constraints arising from changes in emission regulations and financial support. Finally, the developmental regulatory environment increases the importance of forming alliances and a network of actors to clarify institutional barriers and drive policy change.

C2. Dependence on Complementary Technologies

The commercialization of FC technology is part of a larger system change and success depends on the development of complementary technology and network externalities such as refuelling stations and the distribution of fuel storage tanks (Hall and Kerr 2003, Schneider 2004). It is a classic problem of "the chicken and the egg": infrastructure investment payback depends on the number of FC vehicles in operation and the usability of FC vehicles depends on the number of available fuelling stations. FC firms will not be able to diffuse their technology without complementary technologies for hydrogen storage, production and refuelling. Additionally, FC firms will not be able to commercialize their technology if it is not compatible with complementary technologies. Complementary products are likely to give rise to network externalities, i.e. the attractiveness of FC technology to potential customers will increase with the size of installed fuelling infrastructure and availability of storage tanks. Furthermore, the development of network externalities will partly depend on the emergence of FC standards and certification codes.

This context factor, therefore, implies that FC firms depend on the development of complementary technologies. Regarding development and application decisions, FC firms face the risk of incompatibility with complementary technologies. The risk of incompatibility implies that FC firms are challenged to make strategic decisions with respect to their involvement in complementary technologies, through internal developments, acquisitions or partnering. The dependence on these external developments emphasizes the importance of forming alliances and a network of actors, either to influence developments or to react readily to developments in complementary technologies and standards.

3.1.4 Fuel Cell Industry

There is a dynamic relationship between FC technology, the market for FC products and the FC industry that emerge from the development of this new technology. The status of the FC industry is characterised by a low return on high investments (I1) and emerging (I2).

I1. Low Return on High Investments

The financial data of the FC industry in section 2.3 shows that FC firms are currently non-profitable: the revenue gained from sales and services hardly exceeds R&D expenditure. Extensive investments are required for further R&D and the development of manufacturing capability, whilst the market for FC products is small to non-existent as yet. The low return on high investments indicates that the industry is at a supply-driven stage of development. Shanklin and Ryan (1987) describe this stage as a period in which R&D continues and initial applications are 'pushed' to markets whilst there is a lack of market demand. The majority of early FC applications are supplied to early adopters or function as demonstrations of FC technology. However, the financial data also suggests a gradual transition from a supply driven to a demand driven stage. R&D expenditure is gradually decreasing and there is an increase in orders placed, indicating the emergence of niche market demand. As the industry goes through this transition, historical cases of new industry development suggest that the number of actors in the industry will decrease significantly due to bankruptcies, mergers or acquisitions (Utterback 1994). Considering the low returns on high investments and the lengthy process of widespread diffusion, there is a substantial risk that young and independent firms in the FC industry will 'burn out'. Olleros (1996) suggests that in general this risk of 'burning out' is primarily caused by technical and market uncertainties and an extended payback time. The entrepreneurs of Formula Zero (2005) for example state, *"everyone thinks, what is taking that fuel cell that everyone is talking about. Considering that, we started quite early because we will still have to keep this up for quite long".*

The pursuit of niche markets appears to be a survival necessity for independent FC firms. Additionally, the low return on the high investments pose challenges for the acquisition and allocation of resources for R&D and applications of FC technology. FC firms largely depend on external resources and investors. Consequently, resource dependence and initial revenue opportunities are likely to influence the selection of early market applications. FC firms are challenged to balance priorities between R&D and long term objectives with market applications and opportunities for short term revenue. Additionally, a firm's internal application strategy is likely to be influenced by actors external to the firm.

I2. Emerging Industry

The evolution of the FC industry described in section 2.5, illustrates the emergence of the FC industry. Besides large automotive firms and utility companies, the development of FC technology has also brought forth the emergence of numerous entrepreneurial firms. These independent FC firms, founded in the previous 10 years, are dedicated to the development of hydrogen and FC-related components, systems and products. This trend coincides with prior studies of new industry creation, in which entrepreneurial firms play a central role in the evolution of new industries (e.g. Audretsch 1995, Aldrich and Reuf 2006). Early stages of an emerging industry are characterised by 'fluidity' and turbulence as well as collective efforts and collaboration. The FC industry can be characterised as an emerging industry with similar characteristics. There is a high degree of collaboration and interdependence between firms in the industry. Collaborative efforts are, for example, reflected in governmentally funded R&D consortia and demonstration programmes. Additionally, FC firms are in the process of forming short- and long-term strategic partnerships and choosing supply chain positions with respect to customers and suppliers. A majority of independent FC firms have positioned themselves to supply stacks or sub-systems to OEM customers responsible for system integration and product development. Moreover, the emerging FC industry can be characterised as 'fluid', in terms of uncertainty and rapid change. Thus, the emerging industry implies that the young and independent firms of the FC industry are challenged to grow and survive in a dynamic and uncertain environment. Additionally, the emerging industry implies that besides a firm's internal learning and strategic positioning, there is also a collective process of learning and development.

Table 3.2 Summary of characterisation and consequences

	Characterisation	Consequence for innovation process
Tech.	T1. Immature, no dominant technology	Technical uncertainty Balancing R&D and market application
	T2. Application diversity	Which markets when? Application decisions Decisions on which markets to pursue
	T3. Replacement technology	Radical to customers: attention to customer education Face resistance to change and perceived risk
	T4. Complexity	Close collaboration, customer education, decisions on supply chain formation
Market	M1. Lack of cost and performance competitiveness & market demand	Uncertain decisions on development and application Market adoption uncertain and difficult to predict timing.
	M2. Emerging niche markets	Balance short term potential for revenue and longer term potential. Short versus long term market strategy. Challenging selection and timing of initial niche markets.
	M3. Demonstration and validation	Customers and end-users are unfamiliar with the technology. Limitations to conventional market research Development of applications targeting demonstration and validation.
Context	C1. Uncertain regulatory climate	Search for premium niche markets. Reassess opportunities in context of change. Forming networks of actors to drive policy change
	C2. Complementary technologies	Dependence on emergence of and compatibility with complementary technologies
Industry	I1. Low return on high investment	Supply driven stage. Risk of 'burn out' of pioneers Dependence on external resources
	I2. Emerging industry	Independent FC firms, supply chain positioning and growth in dynamic and uncertain environment Collaboration and interdependence among firms

3.1.5 Conclusions on Characterisation

A characterisation has been described for FC technology, the market for FC products, the context for FC development and the FC industry. This section has addressed how these characteristics influence the innovation process and what consequent challenges FC firms face to manage this process (table 3.2). Several characteristics are related to the early state of technology and industry development and the limited market demand. These pre-commercial characteristics imply that FC firms face a long period of balancing R&D activities and the development of early applications for demonstration, validation and marketing in a dynamic and uncertain environment. Although the end-markets for FC products are established, FC firms face a lack of market demand and some degree of hesitance and resistance from established firms. Consequently, it is difficult to predict the timing of market adoption for niche markets as well as large scale markets. The broad applicability of FC technology combined with the uncertainty of market adoption implies that there is a risk of choosing applications that will not provide benefit in terms of learning or profit. Given the application diversity of FC technology, the selection, evaluation and timing of market opportunities is challenging. Moreover, the diverse reasons to pursue early applications, including short term revenue, demonstrations, validation and customer education, pose challenges for priority setting. Considering the apparent necessity of early applications and the uncertainties involved, this study will focus on the selection of early applications.

Application decision making is central to how FC firms manage the application of FC technology. For independent FC firms, the development and application of hydrogen and FC technology is their main business activity. Within the FC industry, these independent FC firms are primarily concerned with the identification and selection of market opportunities for technology application. This search for market opportunities characterises the entrepreneurial firms of an emerging industry. Most independent firms in the FC industry are the relatively 'young firms' founded after 1995. Therefore, to better understand the selection of early applications, this study will focus on young and independent FC firms, referred to as young FC firms from this point onwards. Young FC firms include independent spin-offs from existent companies and start up companies, in contrast to established firms or subsidiaries of established firms. It can be argued that particularly the 'young FC firms' face a relative urgency in the selection and pursuit of the 'right' applications. Section 3.4 will specify the challenges young FC firms face in the process of technology application. First, the following section describes a number of FC projects to illustrate the challenges of selecting, evaluating and developing applications for FC technology.

3.2 Technology Application and Product Development

The characterisation of FC technology and FC firms has highlighted a number of challenges for the application of FC technology. The diversity of potential applications and the uncertainty about market adoption puts emphasis on the selection and evaluation of early market applications. Additionally, pre-commercial applications, such as demonstrations and prototypes play a central role in technology and market development. The author of this study has participated in FC projects, targeting the development of FC products. These FC projects are described to illustrate the challenges of selecting, evaluating and developing applications for FC technology. On the basis of the experience gained and the project documentation, this section addresses how and why these early applications were developed. The motivations for selecting the market applications and the process of evaluating the technical and economic feasibility are described for the following projects: 1. The Hydrogen Shuttle, 2. The FC boat, 3. The Formula Zero kart (fig. 3.1). Additionally, projects targeting the innovative design of a FC product are described. The following projects have explored new forms and functionalities for FC technology application: 1. FC outboard motor, 2. FC Hybrid, 3. FC sweeper. The projects were conducted by consortia. Although a consortium of various stakeholders functions differently than young FC firms, FC product development crosses firm boundaries and deals with diverse interests in both organisational settings. Moreover, young FC firms often pursue projects in consortia. Such consortia are typically formed on the basis of commitment and the scope of skills required for development.

Figure 3.1 FC projects from left to right: the FC boat, the Formula Zero kart and the Hydrogen shuttle

The consortium for the Hydrogen Shuttle project comprised specialists from the Energy research Centre of the Netherlands (ECN) - for expertise in FC stack and system design - and the electric vehicle manufacturer Spijkstaal who provided the performance and vehicle requirements. Industrial Design Engineers from the Delft University of Technology (DUT) were responsible for the market research of the Hydrogen shuttle and the packaging of the FC system. The FC boat consortium consists of 5 companies: Integral, Alewijnse, Hoekloos Linde, Lovers, Marine Service Noord, responsible for project management, electronics in shipbuilding, gas applications, channel boats exploitation and piping and propulsion systems respectively. The Formula Zero consortium comprised the initiator Formula Zero BV, ECN for the FC system design, Ballard to supply the FC stack, TNO automotive to design the drive train, Bradford engineering to design the hydrogen storage tank and the design office Springtime for the overall design. Although the consortia are different, each consortium is interdisciplinary and includes a FC developer or supplier, an OEM customer, a product designer and a power train specialist.

3.2.1 Motivations for Application

Early applications of FC technology are pursued for various reasons, such as demonstration and validation. Niche markets are found where the technology provides an added value above current alternatives. Section 2.2 described that near term niche market opportunities for FC technology are primarily found in the replacement of batteries. Additionally, opportunities are found where zero emission regulations are imposed. The FC projects observed show variable motives and rationale for the selection and pursuit of the applications.

The Hydrogen Shuttle project targeted the development of a FC powered shuttle bus. The project was initiated in 2004 following a preliminary study at the DUT. The DUT study found that there was potential to extend the range of an electric shuttle bus and reduce the weight of the power train by replacing the current batteries with a hybrid FC system (Hellman 2003). The Dutch electric vehicle manufacturer Spijkstaal was keen to further explore the potential and feasibility of FC technology for the company's Zero Emission Urban Shuttle (ZEUS). The ZEUS is a battery electric midi bus with a capacity to carry 32 people (standing), at an average speed of 16 to 18 km, with a range of 80 to 90 km. However, daily operation requires a driving range of 150-175 km. Therefore, the lead acid batteries have to be exchanged during the day. The exchange of batteries is considered to be cumbersome and requires a special exchange location, a fork lift truck and qualified personnel. Spijkstaal sought an alternative for the current batteries to mitigate these operational limitations. The consortia found that advanced batteries alternatives were 5 to 10 times more expensive than the current lead acid batteries and were unable to provide the required range (Plomp 2005). The motivation for the Hydrogen Shuttle project was, therefore, that FC technology could potentially solve the battery limitations of the ZEUS and enable increased functionality. The FC developer Hydrogenics has developed a similar FC midi-bus for demonstration purposes. The company perceives a small market demand for such demonstration vehicles and has supplied midi buses to demonstration projects in Germany. Apparently there is an added value for FC technology above batteries in this market.

The FC boat project, initiated in 2006, is currently in the process of developing a FC powered passenger boat. According to the initiators of the FC project, there is a compelling opportunity for FC boats in Amsterdam, as recent policy mandates zero emission operation for new channel boats. Batteries are not considered to be a feasible alternative, considering the required power and energy demand of channel boats. In addition, the company Shell has shown interest in an innovative and sustainable way to transport its employees from Amsterdam Central station to the company's office across the river. Therefore, the consortium claims that it will launch the first commercial channel boat[27]. The motives and rationale of the FC boat project show how opportunities for FC applications can emerge from local circumstances.

The Formula Zero 'transition coalition' project comprised an initial feasibility study, conducted in 2004. The project was initiated and managed by the entrepreneurs of Formula Zero B.V. This company[28] aims to develop a FC powered racing class in order to demonstrate the power of FC technology: *"Formula Zero believes that mixing these innovative technologies with FUN can bring tremendous added value to create awareness and a positive attitude among motorists".* On the 26th of October 2006 the company set a FIA international world record for FC vehicles on 1/8 mile. The application is not a commercially viable market on the short or near term, but functions as an exciting application to demonstrate the potential of zero emission technology, as the founders of Formula Zero [29]explain, *"the FC kart will set the standard for acceleration and top speed, rather than being a rather slow demonstration of fuel economy".* Thus, the selection of this niche market is driven by a vision and the objective to enthuse consumers with vehicle power and speed. In contrast to the practical rationale of the Hydrogen Shuttle, Formula Zero argues, *"due to practical reasons, demonstrators are often fleets, so buses and commercial vehicles. But from a marketing perspective that is swearing, because in that way it will not sell".*

In each project different opportunities for the application of FC technology were perceived: opportunities arose from problems with current batteries and from (local) zero emission regulations. Formula Zero considered the race kart as a particularly suitable application for demonstration. Market opportunities emerged from current problems with batteries, emission regulations and demonstration potential. The projects have in common that a 'technical opportunity' emerged where FC technology offered an added value with respect to the established technology. This study finds that the 'value proposition' of a FC application depends on the 'match' between these market opportunities and the added values of FC technology (fig. 3.2). A value proposition expresses the attractiveness of an application relative to a consortium's objectives. Moreover, the projects suggest that opportunities emerge as the technology, customer interest and the regulatory environment change. The identification of early applications for FC technology therefore appears to require a continuous reconsideration of application opportunities.

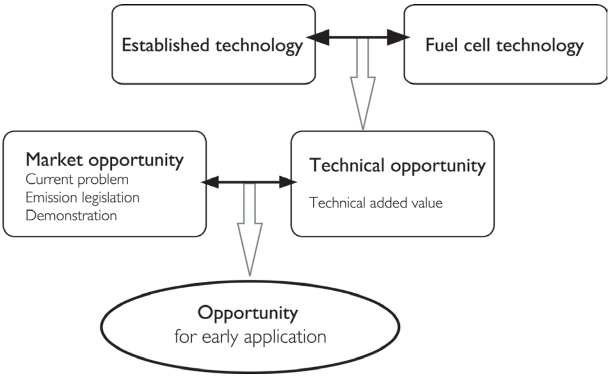

Figure 3.2 Diagram for the identification of early application opportunities

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[27] *The new article on www.fuelcelltoday.com of 02-02-2007, refers to the FC boat as "the world's first commercial hydrogen boat".*

[28] *www.FormulaZero.com*

[29] *Interview with the founders of Formula Zero March 2006*

3.2.2 Technical Feasibility

To evaluate the technical feasibility of an application, an initial technical design study is typically conducted. There are different approaches to a technical design study: the design of a dedicated system or the design of a system around a multi applicable FC stack, the design of a dedicated product, or the integration of a FC system into an existent product. The projects illustrate a variety of these approaches. In the consortia with customers, the design process was dictated by product requirements. Among others, product requirements include: the required performance, a maximum weight and volume, the operational environment and maximum costs.

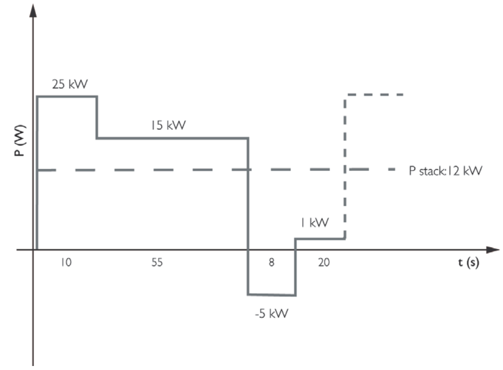

Figure 3.3 A single drive cycle for the ZEUS. Source: Plomp et al. 2005

A dedicated FC system was designed for the Hydrogen Shuttle. The FC system (excluding hydrogen tank) was designed to fit into the battery tray of the ZEUS, in order to leave the shuttle design unchanged. The design process included the design of: i) the power train, ii) the FC system and iii) vehicle modifications. Spijkstaal prescribed the governing requirements: a robust and reliable system based on the performance and drive cycle of the current shuttle bus. To specify the components of the power train, the ZEUS drive cycle was closely examined. Spijkstaal provided the data to analyse the power requirements for acceleration, driving at constant speed and standing still (fig. 3.3). The ZEUS drive cycle was characterised by a predictable repetition of cycles from one stop to the next. In dialogue, the options for hybridization, combining a FC system, battery and/or super capacitors, were discussed. Comparing the advantages and disadvantages, a power train configuration and the respective power levels were decided upon. The power train design dictated the performance requirements for the FC stack. With these FC stack requirements, ECN designed a FC system. To integrate the new power train into the shuttle bus, vehicle modifications, issues of safety and sensitivity to the operational environment were discussed. Subsequently, the hybrid FC system package was designed to fit into the former battery tray, with the hydrogen storage tanks on the roof and hydrogen sensors to ensure safe operation. Finally, technical uncertainties of product integration were discussed, such as the impact of vibrations and sub-zero temperatures (Plomp et al. 2005). Hereby, the Hydrogen Shuttle project illustrates the specification of a power train configuration, the selection of system components and the design of vehicle modifications. In dialogue, the technical specifications were aligned to the customer's requirements. The project concluded that it is technically feasible to design a hybrid FC system that would triple the range of the vehicle and reduce the weight of the power train by 930kg (Hellman et al. 2005).

Formula Zero conducted a feasibility study in which a dedicated FC system as well as a dedicated kart were designed. The project comprised of the FC system design, the power train design and the kart design. Similar to the Hydrogen Shuttle project, the power train was configured on the basis of the performance and drive cycle requirements set by Formula Zero B.V. Departing from an acceleration target, a hybrid FC system with super capacitors was selected as the most suitable configuration to achieve maximum acceleration at a minimum weight. Different power levels were computer simulated to specify the size of the FC stack that in turn, determined the design of the FC system. In parallel, the kart was designed, first, by configuring the FC system and power train components in a 3D computer model of the kart. Product integration concerns included weight distribution, cooling and the damping of vibrations. The feasibility study resulted in a blueprint for the design of the FC race kart. Besides power train configuration and FC system design, the Formula Zero project illustrates that product integration and design requires the consideration of: i) the output of electricity, heat and water, ii) the weight configuration and distribution of the components, iii) the operational measures including insulation, ventilation and damping. Although the kart design was heavier than expected, the project concluded that the design of a FC kart is technically feasible (Formula Zero 2004).

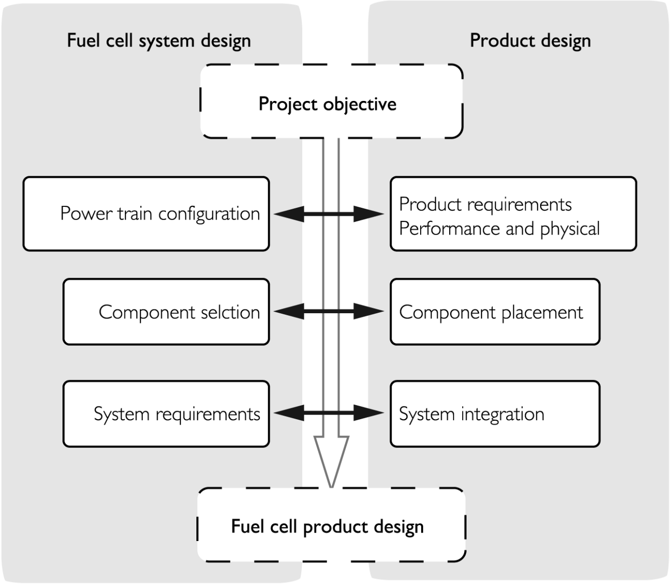

Figure 3.4 A schematic representation of product - FC system interfaces

The projects illustrate that during an initial design study, product requirements and FC system specifications require alignment through a dialogue between stakeholders. FC product design involves alignment at three product / system interfaces: i) the performance interface, to determine a power train configuration that meets performance requirements ii) the component interface to select and place the system components in a product according to product requirements and iii) the operational interface to integrate the system into a product according to system requirements (fig. 3.4).

In the above projects, dedicated FC systems were designed. However, the development of FC products can be simplified through the application of a FC module that includes an entire FC system. This option can be chosen to reduce the overall costs or when FC system integration expertise is lacking in a consortium. Eventually, the dedicated FC system of the Formula Zero project proved to be too costly and the blueprint was modified to integrate a FC module. The FC boat consortium did not include FC system expertise. Therefore, to speed up the realisation of the FC boat, the consortium has considered purchasing a FC module to integrate as a 'black box'. The consortium has analysed the required power level of this module and the considerations for boat integration. Recent guidelines for marine certification, for example, mandate the separation of the hydrogen and FC system from the passenger compartment. However, there are limited commercial FC modules to choose from and there are a limited number of modules available for sale. Moreover, the successful operation of these modules in a marine environment cannot be guaranteed as yet. The FC boat consortium, therefore, faces difficulty in selecting the FC stack and/or system supplier in the current phase of industry and technology development.

The FC projects illustrate that the preliminary design of a FC system and the assessment of its technical feasibility requires a continuous dialogue between stakeholders of the consortia to align customer requirements and system specification. In retrospect, the stakeholders in the Hydrogen Shuttle and Formula Zero consortia describe their projects as a valuable learning experience. Formula Zero explains, *"now we understand what we started on, we started as naïve boys… we have gained a sense of reality… it is a lot more complex than we thought… and that it cost a lot more than we thought"*[30]. The R&D partner[31] explains that experience was gained on working with the real life design requirements: *"a lot of knowledge and experience has been gained. It was particularly a challenge to develop a compact and light design"*. Spijkstaal[32], the OEM customer in the Hydrogen Shuttle project states that on the one hand he learnt a lot from the project, such as *"the characteristics and performance of the fuel cell"*. However, Spijkstaal found that during the project, more questions than answers arose. In particular, questions on operation and costs remained unanswered and vague. Heijboer, the director of Spijkstaal concludes that the status of the technology is not mature enough to realize a reliable and economically feasible Hydrogen Shuttle. The projects illustrate that FC developers learn about real life operation and customer requirements in the development of early applications. Additionally, OEM customers learn about the advantages and disadvantages of FC technology, what the system will look like, the technical uncertainties and the status of the technology. Finally, the projects illustrate that close collaboration between stakeholders in a FC design project is required, due to the interdependence of FC stack, system and product.

3.2.3 Evaluation of Economic and Market Feasibility

The FC projects additionally assessed the economic feasibility of their application in terms of: i) the cost of realizing a prototype and ii) the potential for cost effective application in the respective niche markets. The economic feasibility of a niche market application can partly be evaluated beforehand, through a cost comparison with the established technology. For example, the Hydrogen shuttle compared the current battery costs of the ZEUS to the expected costs of the hybrid FC system and concluded that the costs of operating a Hydrogen Shuttle would be slightly higher than the ZEUS, but acceptable. However, the estimated cost to realize a Hydrogen Shuttle prototype was much higher than expected. The R&D partner describes, *"in the end when we had to define the future costs of the future trajectory, you could see the OEM was shocked… so then I think we have done something wrong in the prior conversations"*. Similarly, the FC boat project is coping with higher costs to realize the first boat than initially planned[33]. The projects illustrate that the development of a single prototype is not representative for the commercial cost of a niche market application, due to additional R&D costs, cost of certification etc. Apparently, the economic feasibility of realizing a prototype is difficult to evaluate and predict.

Moreover, the projects illustrate a variation in expectations and objectives within consortia. In general, the OEM customers expected the projects to take a bigger step towards commercial products than was actually made. Whilst the R&D partners expected a prototype that would require further development and several development cycles prior to commercial application, OEM customers tended to expect near commercial performance and costs. The observations suggest that few OEM customers are willing or able to accept the cost and risk of developing prototypes that are far from commercially viable. Thus, the projects show a discrepancy in expectations and objectives between the developers and customers in the consortia.

Furthermore, the projects illustrate that the potential for market adoption was difficult to asses. Market assessment interviews were conducted in the Hydrogen Shuttle project. Regarding the outcome Heijboer (2005) reflects, *"people had so little critique…. the reactions where always positive in the first instances…. So the market research turned out to be a nice talk that can hardly be used as a criterion for what the market thinks*

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[30] Interview with the founders of Formula Zero March 2006

[31] Interview with Manager PEMFC & Supercaps at ECN, December 2005

[32] Interview with Heijboer, the Director of Spijkstaal, December 2005

[33] Informal discussions with FC Boot Consortium members

about it. You can even put the specifications under his nose, but still he has a particular approach to the product and specifications". Formula Zero BV (2006) found that once they had built a prototype, it was much easier to communicate their message and evaluate the response of the public and private stakeholders: *"now we have something, before it was just PowerPoint and pictures. Now we can show a list of publications and events and what we are doing. That makes all the difference".*

3.2.4 Fuel Cell Product Innovation

A majority of the prototypes realized to date have placed a FC system into an existent product design to minimize the cost of realization. A step beyond the integration of FC technology into existent products is a dedicated design. Incorporating the particular characteristics of FC technology into a dedicated design of a FC product may result in innovative solutions. A few FC firms have explored new design possibilities and user functionalities by generating innovative FC concepts and prototypes. The GM Hy-Wire, for example, integrates a FC engine into a flat vehicle platform, enabling modular chassis design[34]. The ENV motorbike by Intelligent Energy, demonstrates a removable FC engine that can also function as a portable generator[35]. These design 'explorations' have received extensive publicity. Three projects conducted at the DUT have developed conceptual designs for the application of FC technology. The projects have explored new forms and functionalities of FC powered products (fig. 3.5).

Figure 3.5 Dedicated FC product design. The VMD (left) and the FHybrid scooter (right)

First, the project named the Versatile Marine Drive FC (VMD-FC) explored the possibility of developing a FC outboard motor with new and added functionality compared to existent outboard motors (Jensen 2006). The VMD-FC project resulted in an innovative design concept for outboard motors, namely a floating 'pod' that can be used to push a boat, as an outboard motor, or pull an individual, somewhat like a Jet Ski. The FC-Hybrid project explored innovative design possibilities for a FC powered scooter (Bouman 2006). The FC system was configured into a different structural layout than conventional scooters and an innovative form was designed compared to conventional designs. In the third project, innovative concepts for a FC powered street sweeper were explored (Assies 2007). The concept design of the street sweeper will be used to communicate the company's vision of innovation, technology and style for 2015. The projects illustrate possibilities for FC product innovation, by exploring new and added functionality, innovative structural designs and a different form language. The complexity and costs of these innovative concepts is typically too high for short term realization. On the other hand, the projects appear valuable to generate publicity and public awareness, enthuse potential customers and to communicate ideas and future directions.

3.2.5 Conclusions, Lessons Learnt

The projects illustrate how consortia identify opportunities for applications and how an initial process of FC product design takes place. At the time of writing, the FC boat project is still being developed and the Hydrogen Shuttle and the Formula Zero race kart have been continued in a different partnership. The projects have all taken more time and were more costly than expected beforehand. The conceptual designs remain on the shelf for another while, but have demonstrated and communicated future potential. None-

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[34] The GM Hy-Wire 'skateboard' concept vehicle: www.hydrogencarsnow.com/gm-hy-wire-concept.htm

[35] The ENV motorbike: www.envbike.com

theless, stakeholders are positive about the experience gained and lessons learnt. The projects illustrate that the development of early applications is a learning process for the stakeholders involved. OEM customers learn about the basics of the technology, the potential for application in their products and the status of the technology. Additionally, a preliminary design indicates the physical dimensions of a FC system and the considerations for product integration. FC developers learn about the performance requirements for an application as well as the 'real life' operating conditions. The projects show a high degree of collaboration between the stakeholders in the consortia, particularly between FC developer and OEM customer, to align product requirements and FC system specifications.

The preliminary design studies targeted the alignment product requirements and system specifications. The technical feasibility of the applications was assessed through a process of power train design, FC system design and product integration considerations. However, the economic feasibility appears to be more difficult to evaluate. The projects suggest that the fictive cost of a niche market application and the real cost of realizing a prototype for the same application, lie far apart. Real costs typically include further R&D as well as the cost of realising a single customised FC application. Consequently, the initial prototypes or demonstrations are likely to be many steps away from commercial products. The projects suggest that the real costs and perceived risks were far beyond the expectations of the OEM customers. Besides, technical uncertainties remained and OEM customers were hesitant to accept the high costs and uncertainties of operation. Moreover, an OEM customer experienced uncertainty regarding the market's potential: it was difficult to evaluate the potential for market adoption prior to the realisation of a prototype. Thus, there appears to be a gap between the cost and status of early applications and the acceptable cost and risk for an OEM customer. This discrepancy does not appear to result from misjudgement; rather it illustrates the process of learning within FC projects. Lefevre (1984: p.488) similarly finds that *"premature demonstration is not caused by naïve optimism. Pre-maturity often becomes evident only as the demonstration project unfolds.*

The FC projects illustrate considerable learning among stakeholders and thereby a key function of realizing real life demonstrations and applications of FC technology. The projects additionally demonstrate the diversity of disciplines involved in developing a FC product in consortia. It is notable that several projects 'missed' a commercial company with 'FC system integration expertise', capable of packaging a FC system and integrating this system in the end product.

3.3 Similarities and Differences with Respect to Other Technologies

The commercialisation process of FC technology is likely to follow similar patterns as the commercialisation of other 'radical' technologies. The characteristics of FC technology, described in section 3.1, will largely determine the degree to which findings of this study can be generalised to other technologies. This paragraph will, therefore, discuss the similarities and differences between key characteristics of FC technology and other technologies. First, FC technology will be compared to other multi-applicable energy technologies: Photo Voltaic (PV) and battery technologies. For comparison FC technology is also compared to the emergence of another 'radical' technology: the personal computer. This paragraph will compare the following characteristics: the pursuit of niche market applications, the application diversity, the required learning and the independent firms of the emerging industry. The implications for managing the process of technology application will be discussed.

3.3.1 Photo Voltaic Technology

FCs and PV solar cells are both clean energy converters, however in contrast to FCs, PV solar cells convert a primary source of energy directly to electricity. Similar to FCs, there are a range of possible applications for PV solar cells. As a sustainable energy technology, PV faces similar challenges in the context of a transition towards a more sustainable energy system, such as the high costs of change, the reliance on the regulatory environment and the dependence on network externalities. Similar to FC technology, there is a long history of PV applications in various markets. However, PV has a longer history of applications. Jacobson (2004) describes five periods in the history of PV solar cell diffusion. The first period of PV applications began when a number of applications from toys to stand alone systems were 'tried out'. In the 1960s, PV was applied in space applications, which became the fist successful and commercial application for PV technology. After the second oil crisis in the 1970s there were bold visions of a quick transition to a solar powered world, however, in the 1980s and early 90s this unlimited solar optimism was over. The main commercial market in this period was the off-grid power market, primarily for remote areas and developing countries. After 1997, a new growth phase began stimulated by governmental market development programmes. Germany and Japan experienced a strong increase of PV installations in relation to policy programmes supporting the installation of solar power. An increase in on-grid market installations can be observed in 2006: a 16% growth of PV installations in Germany and a 33% growth in the US[36]. The 'revival' of solar power installations is likely to be related to the emergence of climate change concerns. Thus similar to FC technology, PV shows a long period of diverse applications in niche markets and a rise and fall of expectations over time. PV technology has been demonstrated in numerous public and private demonstrations. Several governments continue to provide grants and subsidies for PV demonstration programmes. Additionally, after the liberalisation of the energy market in the Netherlands, several companies held campaigns and demonstrations with solar power. For example, Nuon supported demonstrations such as the solar power boat race held in Friesland (the Netherlands) in 2006, and sponsors the Nuon Solar team of the DUT, winning the world solar challenge race in Australia[37]. Thus, similar to the FC industry, demonstrations and field trials are conducted over a long period.

Both technologies show a long period of learning and niche market applications. In comparison to the history of PV technology, PEM FC technology was developed but not extensively adopted for space applications. For both technologies, large markets were envisaged in a subsequent period of applications. However, for PEM FCs, this period began almost 20 years later than for PV. At the time that large scale markets for PEM FC were targeted, the expectations for PV had already been postponed and the focus had shifted to niche markets. Currently, the recent revival of PV in large scale on-grid installations is highly dependent on regulatory support. Similarly, FC technology also depends on regulatory support, however, comparatively for a more diverse scope of markets.

Both FC and PV technology are applicable to diverse applications. For example, PV solar cells power consumer electronics in the lower power range of 1 mW up to 100 W. Solar cells have been applied to a diversity of consumer products such as calculators and watches. In this power range, premium niche market applications have been identified, such as street lanterns and new products have been created, such as solar powered battery charger[38]. At the other end of the power range is large-scale power generation, the largest market for PV technology. Compared to FC technology, PV is limited in the mid range. As the power output of PV is directly related to surface area, PV can only replace combustion engines in a limited number of portable and mobile applications. Thus, considering the possible scope of applications, PV technology primarily has the potential to revolutionize the energy market whilst FC technology has the potential to revolutionize the energy and the transport market. Thus, in comparison, FC technology has a broader scope of applications.

Regarding the development of FC and PV products, both technologies replace existent technologies and may disrupt existent supply chains and skills. In low power products, a PV system cannot simply replace batteries: PV cells are placed on the surface of a product and require significant design modifications. Besides, Kan (2006) argues that the design of most PV products is suboptimal in terms of the match the between

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[36] Source: Solarbuzz, www.solarbuzz.com

[37] Nuon solar power boat race: www.solarnavigator.net/solar_challenge_frisian_nuon.htm. and the Nuon Solar team of the TU Delft: www.nuonsolarteam.com/nl/

[38] The SYN-Energy programme has explored the feasibility of PV in various consumer and professional products and the Design for Sustainability (DfS) programme at the DUT have designed various PV powered consumer products (e.g. Kan 2006).

PV cell characteristics, the energy storage medium and the product user context. The resulting suboptimal solutions have left PV products with an 'image problem'. The integration of a FC system in existent products may not be visible at all. Yet, FC technology is likely to require considerable OEM learning to integrate FC engines in, for example, cars and fork-lift trucks. Thus, the development of both PV and FC products appears to require new skills and learning. Furthermore, both technologies are characterised by rapid technical change. In the case of PV technology R&D is ongoing to reduce costs and improve efficiencies for multi crystalline and further develop other types of PV technologies. Thus, similar to FC technology there are competing PV technologies and uncertainties about their potential performance and costs.

Regarding the role of young and independent firms in the PV industry, it should be noted that the industry spans the range from large companies to small research ventures. The four main manufacturers of solar power modules are Sharp, Kyocera, BP Solar, and Shell Solar.[39]. In contrast to the FC industry, the capital intensive nature of PV panel production appears to limit the number of young independent firms targeting PV production. This may be explained by a later stage of industry development when the number of actors in the industry is reduced. However, similar to the FC industry, there are various entrepreneurs in the PV industry, founded to develop and apply a technological innovation or a focus on the pursuit of niche markets. The above comparison suggests that young firms in the FC industry and the PV industry face similar challenges to commercialize their technology. The application of FC and PV technology requires niche market applications, demonstrations and learning. In the case of both technologies, there are diverse applications to choose from in a context of uncertainty. In comparison, FC technology is more broadly applicable in existent markets.

3.3.2 Battery Technology

Both batteries and FCs belong to a family of electrochemical devices. Similar to FC technology, batteries are multi-applicable energy sources for a diversity of products. Although batteries have been widely applied, the range of battery applications has been limited by a low specific energy. The history of lead acid battery electric vehicles goes back to before the turn of the century. At the time, BE vehicles were 'beaten' by IC engines in becoming the dominant solution for cars. Hoyer (2007: p.369) argues that *"problems in electrochemistry have caused important limitations, as they have through the whole history of electrical cars".* In the 1990s a revival of interest in BE vehicles took place when a majority of automotive firms engaged in BE vehicle development in response to the Californian zero emission regulations. Between 1997 and 1999 BE vehicles and FC vehicles competed as zero emission solutions (Van den Hoed 2004). However, around 1999 there was a decline of BE vehicle sales and a shift towards FC technology, resulting in an industry-wide dismissal of the BE vehicle technology. Recently, the success of Hybrid electric vehicles appears to have revived the interest in batteries and new battery technologies are emerging. Thus, similar to FC technology, batteries have faced a rise and fall of expectations over time. By contrast, batteries have a longer history and have already found widespread application. Lithium ion and Nickel hydride, for example, have been widely applied in consumer electronics. In applications such as back up power and fork-lift trucks, batteries have become the established technology. However, charging times, battery life and limited range are a source of customer problems. Consequently, where batteries have shown limitations, opportunities for the application of FC technology have emerged. This history of applications suggests that batteries are in a mature technology life cycle position compared to FC technology. However, new battery technologies and novel lithium-ion chemistries open up new market opportunities for battery applications. Thereby, similar challenges are faced in the process of technology application. New battery and FC technology face similar technical and cost reduction challenges, whilst uncertainties of market adoption and timing prevail. Both technologies are applied to niche markets prior to widespread adoption and require demonstration and validation.

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[39] Source: Solarbuzz, www.solarbuzz.com

Compared to FC technology, it can be argued that batteries require less demonstration and explanation because OEM customers and end users are familiar with batteries. Start-up batteries, for example, are part of current automotive supply chains. However, several conventional battery technologies suffer from an 'image problem', having 'failed' to comply with automotive standards for propulsion in the past. Therefore, the demonstration and validation of new battery technologies will have to prove otherwise. Moreover, both BE vehicles and FC vehicles will require 'radical' design changes and supply chain alterations. Therefore, both technologies face resistance from established sectors. In comparison to FCs, the application of new battery technologies is more versatile than the application of FC technology due to their role in BE as well as hybrid and FC vehicles. Nevertheless, the battery technologies for these applications differ and firms face decisions on which technologies and applications to pursue.

The comparative age of the battery industry, compared to the FC industry, is reflected in the industry's structure. The battery industry is dominated by large established firms such as Duracell and Energizer in the US and Varta in Europe. Southeast Asian companies have captured a dominant position in Li-ion rechargeable battery manufacturing for telecommunications, wireless, and computer products. Large investments have been made in for example Japan, Taiwan, Korea and China, by companies and as a result of government friendly policies. Nevertheless, entrepreneurial battery firms have emerged to develop new battery technologies. These young firms primarily pursue innovative R&D into new battery technologies and pursue niche market applications. The US Advanced Technology Programme (ATP 2005) describes how entrepreneurial battery firms in the US have primarily been successful in niche markets but have had little success in the development of sizable markets. Similar to young FC firms, young battery firms have difficulty to achieve economies of scale and consequently, the cost of production remains high.

3.3.3 Computer Technology

The evolution of the computer industry has been studied from various perspectives (e.g. Balachandra et al. 2004, Iansiti 1995). Balachandra et al. (2004) describe how the computer industry evolved through three technology stages, from main frame computers for specialised data centres in the 1950s to mini computers and finally personal computers. At the time of main frame computer development, there was hardly any market for computers: it was a new technology in search of applications. As the technology developed, more applications were found. Balachandra et al. (2004: p.7) describe how *"some people felt that there was great potential, and there was much experimentation and exploration. Though there was really no commercial market at this time other companies jumped into the fray hoping to be ready when the applications arrived".* However, at the time, the technology was mainly adopted by hobbyists and a 'killer application' was yet to be found, i.e. an application with great potential so that the technology would not fade away. Following applications in the corporate market, applications were developed for personal productivity and subsequently, this market exploded. Similar to the commercialisation of FC technology, the computer industry went through several niche markets and continuous technology developments prior to large scale adoption. By contrast, the market applications proceeded from market to market, whilst multiple niche market applications for FC technology are pursued at the same time. Moreover, FC and computer technology are different types of technologies: computer technology did not replace technologies in existent markets, it was a 'new technology' in search of new markets. Considering this 'novelty', it can be argued firms faced more market and technical uncertainty in the commercialisation of computers than FC firms currently face. If computers had failed to commercialize beyond hobbyists, they would not have revolutionized information and communication technology. On the other hand, in contrast to FC technology, computer related firms did not face the resistance and hesitance of established markets to the replacement of established technologies and skills. This different type of novelty is likely to influence how firms manage technology applications.

Similar to FC technology, the computer technology brought forth the emergence of entrepreneurial firms. Key IT solutions originated from entrepreneurs in Silicon Valley, such as the micro processor by Intel in

1971 and the first Personal Computer by Apple in 1976[40]. In subsequent years, Silicon Valley became a cluster of high-tech starters. Hulsink et al. (2003: p1) suggest that this cluster illustrates how high-technology starters do not operate and innovate in a solitary vacuum. Rather, *"the activities of a technology-based firm are embedded in socio-economic networks with other companies, investors, universities, vocational institutions, etc".* Porter (1998: p.76) has defined a technology cluster as, *"critical masses in one location with of linked industries and institutions that enjoy unusual competitive success in a particular field."* An official FC cluster has not been identified and considering the size of the FC industry, cluster developments are at an early stage. However, there are regions with a high density of FC firms and developments. A technology cluster appears to be forming in British Columbia, Canada: "*with more than 1,200 workers directly employed in the fuel cell and hydrogen industries, the area has arguably the largest concentration of fuel cell expertise in the world"* (Canadian Roadmap 2003: p.21). There are seven PEMFC developers with headquarters in British Columbia and several other FC firms run subsidiary offices in the region. In addition, hydrogen related companies as well as component suppliers have emerged. A number of characteristics appear to be similar to the development of the Silicon Valley cluster. First, the presence of an anchor player such as Intel: Ballard Power Systems. As described in section 2.5, Ballard was the first company founded to commercialize PEMFC technology and is by far the largest independent firm in the FC industry. Second, the region has received considerable support from federal and provincial governments for early R&D as well as demonstrations. The headquarters of Fuel Cell Canada as well as the National Research Council Institute for Fuel Cell Innovation have been established in the region. Finally, similar to the involvement of universities in the development of Silicon Valley, several universities have been part of the cluster development in the British Columbia region (Canadian Road map 2003).

3.3.4 Conclusion on Technology Comparison

The commercialization of FC technology in comparison to PV, battery and computer technology show similar patterns: a long process of technology and market development and applications of the technology in various niche markets. In each of these industries, entrepreneurial firms have emerged to pursue market opportunities for the applications of a new technology. For each of these technologies, there were diverse applications to choose from. The energy technologies are all characterised by various demonstration applications to convince established markets. These similarities will help to generalize the research findings of this study to some degree.

The comparison additionally reveals some differences that are likely to influence patterns of technology application. PV and FCs are applicable to different market sectors with their own characteristics. The dominance of one sector, such as large scale power generation versus automotive power, is likely to influence application behaviour. Furthermore, the role of young and independent firms in the industries differs. In the PV and battery industry, the young firms primarily conduct R&D and large companies have established capital intensive manufacturing. In comparison, there are more independent firms targeting manufacturing in the FC industry. This difference can be explained by the phase of industry development: the FC industry is younger. FC technology clusters are developing, showing some similarities to the development of technology clusters such as Silicon Valley. In comparison to the computer industry, FC firms are likely to face more resistance from established companies and supply chains. Reducing the perceived risk of established OEM customers appears to be an integral part of the technology application process. The industries have in common that the young and entrepreneurial firms search for opportunities to apply their technology.

A particularity of FC technology is its application diversity. In comparison to PV and batteries, FC technology can replace batteries as well as internal combustion engines in a broader power range. In comparison to computer technology, FCs are a replacement technology for applications in diverse market segments and diverse applications are developed in parallel. In contrast to an entirely new technology, the potential market applications for FC technology are known; however, it is uncertain if and when markets will adopt

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[40] Source: Net Valley, www.netvalley.com

the technology. The case of FC technology is, therefore, particularly suitable to learn more about the selection of market applications when there is a broad scope of applications to choose from. This study expects that the research finding will be applicable to other radically new technologies and energy replacement technologies in particular.

3.4 Young Fuel Cell firms

To research the application decisions of FC firms, this study has focused on 'young FC firms'. Primarily these firms are concerned with the identification and selection of applications for their technology (section 3.1). In this section a firm level perspective is taken to characterise and further specify the challenges young FC firms face in the process of technology application. The FC industry has been characterised as emerging: various new firms have been founded to develop and exploit market opportunities for PEM FC technology. In the late 1990s entrepreneurial firms were primarily driven by the potential for large scale markets and after 2000, firms were founded to target niche market applications. The term 'young FC firms' is used to refer to independent firms, founded to develop FC and hydrogentechnology as their main business activity. With the term 'young', this study refers to firms founded after 1995, to emphasize their early phase of firm development in contrast to 'established' firms. These young FC firms are typically 'small', with less than 350 employees. In comparison, large automotive companies such as Toyota, General Motors and Daimler Chrysler employ around 300.000 employees. Compared to large established firms in the FC industry, young FC firms are developmental, have limited resources to allocate and are vulnerable in their newness. Despite the high rate of new entries, historical cases of new technology emergence suggest that only a small percentage will survive the long and uncertain period of development prior to large scale commercial sales (Olleros 1986). According to Hulsink et al. (2004), the chance that a new entrepreneurial firm survives the first four years after founding is about 50%. Considering the urgency of survival, this section addresses the particular challenges of technology application for young FC firms in terms of: i) firm growth, ii) firm legitimacy, iii) resource limitations and iv) the formation of partnerships.

3.4.1 Firm Growth: a Transformation to Market Led

FC firms can be characterised as 'technology based firms' targeting the commercialisation of FC technology to the solution of market based problems. Young FC firms are businesses with a strong scientific and technical basis, focusing on R&D personnel and rapid technology development. The firm and its future development are focused on the commercialisation of FC technology. Therefore, the fate of a young FC firm is, at least partly, bound to the successful development and commercialisation of its technology. Section 3.1 concluded that FC firms are currently developmental and challenged to balance R&D activities with activities in marketing and sales. In recent years, several young FC firms have shown an increase in personnel dedicated to marketing and sales. Additionally, the firms are gradually building manufacturing capability and an increase in production related patents, which suggests that the firms are making a transition from R&D to production based companies in order to commercialise their technology (PwC 2006). As Kakati (2003: p.456) describes, *"there should be a corporate transformation from a technology-driven to a market-led enterprise, in which technical, marketing, input sourcing skills and capabilities should be put together to produce products and services to meet unique/customized requirements of customers"*.

Literature on the growth of new firms provides insight into the characteristics of this phase in which FC firms transform from a technology driven to a market led company. The initial focus in FC firms on R&D coincides with what Wintjes (2004) describes as a first phase of firm growth: the entrepreneur invests and focuses on forming his technological potential and core competences. The current phase of transformation is described as a second phase in which the focus shifts to organizational aspects and from firm internal to external factors. Finally, as the firms continue to grow, Wintjes suggests that the focus will lie on exploiting the internal competences in the market. Kazanjian and Drazin (1990) describe a model of firm growth on the basis of the problems a new firm faces in particular stages of growth. A first phase of conception and development is characterised by the creation of the idea for a new business. The main problems include the development of the business idea, the construction of a prototype and selling the business idea to financial backers. The second phase of commercialisation is described as a process similar to new product development. Firms experience problems in learning how to make the product work well and how to produce the product beyond the initial prototypes developed in the first stage. Subsequently, phases of firm growth and stability follow. Considering the challenges young FC firms face, the firms appear to be in transition to a phase of commercialisation. In this phase, experience in product and market applications is likely to influence a FC firm's ability to identify and develop market applications (Hellman and Boks 2006).

To commercialize FC technology and grow into a market led company, young FC firms are challenged to develop or acquire market related skills and competences. Thereby, early applications appear to play a central role in gaining experience in markets. Consequently, the selection of early applications is likely to influence the development of a firm's market related skills. The models on firm growth suggest that FC firms are currently in a transformative phase. Firm growth requires a shift from a focus on internal R&D to external factors including markets, potential customers and investors. In order to grow firms must develop legitimacy, access external resources and form partnerships.

3.4.2 Building Legitimacy and Credibility

An 'established' firm, per definition, is recognised by other firms and holds a position in a sector. For example, automotive firms have established a brand and reputation and competitors, markets and organisations are familiar with the companies and their core business. By contrast, young FC firms are in the process of establishing themselves and developing their legitimacy. Freeman et al. (1983) addressed age dependence in the failure of firms and observed 'liability of newness' in various industries. Thereby older more reliable organisations are selected above the new organisations. Young FC firms are faced with two burdens of newness. On the one hand, young FC firms founded in the 1990s and after 2000 faced are challenged to develop credibility and legitimacy as a firm. On the other hand, due to the novelty of their technology, FC firms are challenged to demonstrate and explain the technology. According to Van den Hoed (2005), FC entrepreneurs have lacked the resources, the credibility and the independence to become influential in realizing radical technological change. Several young FC firms are gradually receiving repeat orders from customers, suggesting the development of credibility and legitimacy with customers.

Early FC applications have been instrumental to the process of developing both firm legitimacy and public awareness of the technology. Koppel (2001 p.152), for example, describes the importance of the proof of concept demonstration bus built by Ballard 1993: *"no matter how often you draw the picture, no matter how much you talk, people don't get it until they see it make the wheels go around…And that became the real importance of the bus, because the layman could begin to understand it. It didn't matter if technical people or scientists understood. The people who have influence and make decisions about money had to understand what the FC did".* Shortly after the demonstration of the bus, Ballard secured a long term alliance with Daimler Chrysler. The bus demonstration was instrumental in explaining the technology and developing legitimacy as a firm. A director at Ballard explains that they needed a visible demonstration to show what they could do41. Most young FC firms have presented their technology and prototypes at trade fairs and conferences and as the industry develops, FC firms are gaining legitimacy. A senior project manager at Plug Power explains that at first it was difficult to establish credibility, being 'alone' at trade fairs. *"At the last trade fair, we were with four companies. Then you are not a strange duck in the pond any more. Potential customers have to start making decisions and they are forced to look because it becomes risky not to"* (Plug Power 2006). The legitimacy of FC firms appears to be related to the development of the FC industry. Aldrich and Fiol (1994: p.645) describe this phenomenon as particularly challenging: *"new organisations are always vulnerable to the liabilities of newness, but such pressures are especially severe when an industry is in its formative years".*

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41 Informal interview at Ballard in Burnaby Canada, April 2007.

Many young FC firms have managed to survive for more than five years. In the current phase, survival appears to be more challenging considering the required investments and uncertainty of market adoption. This observation may be explained by more recent literature, suggesting that instead of liabilities of newness, firms may primarily suffer from liabilities of adolescence (Levinthal and Fichman 1988, Fichman and Levinthal 1991). From this perspective it is argued that the first years after founding are a 'honeymoon' period in which firms can survive on their initial stock of assets. It is argued that after this period, the survival of young firms is most challenging. To overcome liabilities of adolescence, firms are challenged to build credibility with customers and investors. Thus, beyond the phase of initial demonstration and the generation of enthusiasm, young FC firms are now challenged to validate their technology to convince customers and become trusted suppliers.

In conclusion, young FC firms are challenged to generate awareness of their existence and establish credibility as a viable company in an emerging industry. In the case of young FC firms, early applications are likely to be determinant for the development of legitimacy and credibility. There is a risk in choosing to demonstrate too early or in the 'wrong' markets, considering the development of a firm's image. Thus, application decisions in young FC firms are additionally relevant for the development of a firm's legitimacy and credibility. The issue of legitimacy implies a higher degree of uncertainty regarding customer recognition and acceptance for young FC firms than for established firms in the industry. This uncertainty is likely to influence the process of technology application.

3.4.3 Limited Resources to Allocate

The FC industry has been described as non-self-supporting, facing high investments and a long payback period. Thereby, the financial surveys primarily refer to the young and independent FC firms. In the current pre-commercial phase of applications, young FC firms are challenged to allocate resources between R&D for further technology development as well as early applications of the technology for marketing and sales. Commercialisation involves costly investments for technology refinement, the build up of manufacturing capacity and the development of prototypes and field tests. The limited resources available to young FC firms are illustrated by a comparison to the R&D expenditure of automotive companies. Daimler Chrysler spent an estimate of $300-400 million on FC technology annually after 2001[42]. GM had approximately 250-300 people working full time on FC related R&D in early 2000 (Van den Hoed 2004). By comparison, the total R&D expenditure of public FC companies was approximately $200 million in 2005 (PwC 2006). Consequently, some car manufacturers appear to have advanced further and faster than young FC firms in solving technical challenges through R&D, prototyping and testing.

A director at Ballard in Canada describes how, *"in the early years it was all about survival. Like most start ups, choices were driven by bringing funding to the table, proving the technology and demonstrating that".* Early applications appear to have played a significant role in attracting funds and investors. To grow and make the transition to commercialisation, the young FC firms at least partly rely on external resources, for example, from venture capital. In comparison to the finance structure of established firms, Van de Ven et al. (1999) find that in general venture capital is more risky, more short term and more difficult to obtain than internal corporate venture funding. Consequently, the limited resources and dependence on external funding is likely to influence the characteristics and the process of technology application in young FC firms. Internal differences may be geographically linked, considering the different finance structures in North America and Europe. According to Doran of Core Technology Ventures[43] most European companies are significantly undercapitalized *"owing to a shortage of private finance and the skills and disciplines financiers bring to seed and early stage companies, European FC companies are financially disadvantaged relative to US companies".* The development and realization of early demonstrations can be costly and typically require more resources than the firms' posses internally. The availability of external resources is likely to influence the early applications a firm is able to pursue and realize.

[42] Daimler Chrysler financial reports

[43] Core Technology Venture Presentation at Gove FC symposium 2003, downloaded at www.coretechventures.com

Furthermore, the fall in market value of quoted FC firms after 2000, described in section 2.5, is likely to have influenced the development of young FC firms and their technology. Five to ten years after the founding of several young FC firms, investors are becoming impatient and the young FC firms will have to start demonstrating through commercial sales that the FC sector is real. Several young FC firms are beginning to generate initial revenue from emerging niche markets. Thereby, niche markets as a source of initial revenue demonstrate the necessity and relevance of niche market selection and pursuit for young FC firms. The young FC firms are subsequently challenged to build capital and manufacturing assets through these niche markets to eventually enable a shift towards larger markets.

Thus, young FC firms typically have limited resources to allocate to R&D and early applications and at least partly depend on external sources of funding such as government grants and venture capital. The resource limitations and dependence on external resources is likely to influence the applications a firm chooses to pursue and is able to realize. Firms have multiple technological paths and market applications to choose from as well as short term opportunities for revenue and long term trajectories to decide on. Given that young FC firms do not have resources to 'waste', they cannot afford to make too many mistakes. The selection and pursuit of initial niche markets is critical as a source of initial revenue and is likely to influence subsequent developments. Considering their limited resources, it is particularly challenging for young FC firms to balance opportunities for short term revenue with longer term ambitions.

3.4.4 Partnership and Network Formation.

The formation of partnerships, strategic alliances and networks is critical for young FC firms to access markets and resources and establish supply chains. For the renewable energy sector, Jacobsson and Bergkek (2004) argue that networks of actors are particularly crucial to the success of a new technology during the formative phase of markets. The importance of networks in explaining the success of young technology based firms is widely recognised in academic literature. Hulsink et al. (2004) find that in the information and communication technology sector, networks are important for entrepreneurs because they can contribute to discovering opportunities, accessing resources and developing legitimacy. Young FC firms are in the process of developing their network, supply chain relationships and strategic partnerships. Differences are observed in their point of departure in terms of their network and personal relationships at founding. The evolution of the FC industry as described in section 2.5 suggests that FC firms emerged from different backgrounds and industries, including established electrochemical and utility companies. These entrepreneurial spin-off companies have inherited experience and network relations from their founders. There are also start-up companies in the FC industry with no history of previous employment or financial relationships with established firms. These firms are likely to rely more on their personal network and the formation of partnerships in the early years of firm growth. These initial relationships are gradually transforming into supply chain partnerships and strategic alliances.

Wintjes (2004) suggests that the informal and ad hoc relationships in the early years of firm founding are often transformed into more formal partnerships as firms grow. Therein, clients appear to be a particularly crucial factor in the growth of a young company. In the FC industry, PwC (2006: p5) reports that although sales were limited in 2005, *"several companies are, however, developing marketing and distribution networks and creating supply chain relationships….building strategic relationships are key to accessing markets, developing technologies and establishing the supply chain needed for volume production".* Strategic alliances refer to collaborative arrangements within the industry and to associations between FC companies and customers, suppliers, market and distribution companies. As the FC industry emerges and takes shape, FC firms are positioning themselves in the industry with respect to suppliers, customers, competitors and partners. As the characterisation of FC technology suggests, various FC firms develop FC stacks or systems to supply to OEM customers. In several sectors, the OEM customers are established 'system integrators', such as car manufacturers and manufacturers of central heating boilers. In these markets, the young FC firms are challenged to form strategic alliances with large established companies.

Relationships with, for example, large automotive firms, are likely to influence a young FC firms' technology application decisions. A director at Ballard[44] in Canada explains that their relationship with automotive companies drove product choice; the automotive companies were driving Ballard down the vehicular path. On the one hand, partnerships with automotive companies help to build firm legitimacy in the FC industry. Relationships and a reputation in the automotive industry will help young FC firms to establish themselves as suppliers to automotive firms. On the other hand, strategic alliances with automotive companies are likely to influence a young FC firm's independence and flexibility. To certify as an automotive supplier, young FC firms must comply with rigorous automotive standards and procedures, which do not appear to lend themselves to the identification and pursuit of other market opportunities.

3.4.5 Challenges for Young Fuel Cell Firms

Young FC firms are confronted with particular challenges to commercialize their technology. In sum, young FC firms face the following challenges with regard to technology application:

- The fate of the technology linked to the fate of the firm. A firm will grow if it is successful in developing and commercialising its technology.
- The commercialisation of a firm's technology requires a transformation from a technology driven to a market led company. This transformation requires the development of and access to new skills, competences and resources.
- The survival of young FC firms depends on the development of firm legitimacy and credibility, recognition by customers, investors etc.
- Young FC firms have limited resources to allocate and depend on external resources. Developments and early applications typically require more resources than the firm has.
- The identification, selection and pursuit of niche markets are determinant for firm survival and growth.
- Young FC firms are challenged to balance short term revenue opportunities with longer term ambitions.
- The formation of a network, customer relationships and the development of supply chains are key to a FC firm's ability to commercialize its technology.
- Young FC firms are challenged to strategically positioning themselves in the industry, with respect to young and established firms.
- The strategies of young FC firms are prone to continual changes in response to a dynamically changing environment.

These challenges imply that for young FC firms, technology application decisions involve strategic choices on which markets to engage in as well as which skills and partnerships to develop. Young FC firms have limited resources to allocate to early applications. Yet, early applications appear to be instrumental for various reasons, including the development of firm legitimacy and credibility. Considering the diverse applications to choose from and the variety of reasons to pursue early applications, young FC firms may be confronted with trade offs in the selection of applications, such as:

- Short term revenue versus long term developments. Revenue from one-off projects and early adopters such as the military, or developments for further markets such as automotive.
- Technology development versus market development. Early applications with a focus on technical improvements or on demonstrations to stimulate market interest.

There is a risk in making 'wrong' application decisions with respect to the development of skills and competences, credibility and partnerships. Regarding market application decisions, a number of young FC firms appear to manage this risk by developing a broad portfolio. Other firms choose to focus on specific markets. The selection of early applications is a matter of strategy formulation and portfolio management. Thus, application decisions appear to shape the development of young FC firms and appear to be highly relevant

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[44] Informal interview at Ballard in Burnaby, Canada, April 2007

for their development and success. Young FC firms are confronted with similar challenges as young firms targeting the commercialization of other new technologies. To address these firms in general, this study will use the term ‘young technology based firms’ (YTB firms).

3.5 Conclusions on Challenges of Fuel Cell Technology Application

In line with the case study research methodology described in section 1.4, the analysis of FC technology and young FC firms provides a better understanding of the empirical problem, to further specify the research problem and focus the case study research. The objective of this chapter was to further specify the key challenges involved in managing the application of FC technology. FC technology application proves to be a long term process with a high degree of uncertainty regarding the emergence of dominant designs and market adoption. At the same time, the current phase of development is characterised by a multitude of early applications such as prototypes, demonstration projects and field trials as well as the pursuit of emerging niche markets. Thereby, it is particularly challenging to determine which niche markets to pursue at which point in time. Primarily the young FC firms of the FC industry are concerned with the selection of applications for their technology. In paragraph 3.1.5, the decision was made to focus on: the selection of early applications by young FC firms.

The projects described in section 3.2 suggest that the development of early applications is a learning process for various stakeholders, including FC firms and OEM customers. The selection and development of FC applications involves the identification and assessment of opportunities and the alignment of technology specifications to product requirements. The technology comparison suggests that the characteristics of FC technology, including application diversity, niche market applications and entrepreneurial firms, can be observed in other industries. These similarities will be determinant for generalizing research findings after the case study research. In comparison, it is concluded that FC technology is particularly application diverse. This application diversity increases the difficulty of evaluating and selecting early applications, as there are multiple applications to choose from whilst their outcomes are uncertain. For multi-applicable technologies such as FC technology, it is particularly relevant to study how firms manage the selection of early applications.

Young FC firms face challenges common to ‘young technology based firms’: their development and survival is strongly related to the development and successful application of their technology, the firms have limited resources to allocate and are in the process of developing legitimacy. Application decisions are therefore relevant for firm strategy and portfolio management. The early applications a firm chooses to pursue are likely to influence the development of a firm’s skills and competences, the formation of partnerships and the development of a firm’s legitimacy. Therefore, application decisions appear to shape the development of young FC firms and are likely to be relevant for their growth and success. Considering the above specification of the empirical domain, this study will focus on the selection of early applications by young FC firms. In the following chapter, literature on innovation and technology marketing will be reviewed to better understand the process of technology application and identify relevant theoretical constructs.

Chapter 4: Probing and Learning

"By definition innovation is a leap into the unknown."

Van de Ven et al. 1999

4.1 Introduction

This chapter reviews innovation and technology marketing literature on the application and diffusion of new technologies. The previous chapter focused on the empirical domain of FC technology and concludes: young FC firms face uncertain decisions on which market applications to pursue at which point in time. The difficulty of FC technology application lies in the unpredictable nature of market adoption. Radically new technologies face similar challenges in the process of technology application. In this chapter, literature is the point of departure to addresses the following research questions:

- What are typical challenges and uncertainties associated with the application of radical innovations? (RQ 1b)
- How can the process of radical technology application be described? (RQ 2a)
- How do FC firms develop market insight to identify and develop market applications? (RQ 2b)

The commercialisation of a technology draws upon research in multidisciplinary fields. This study has focused on innovation and technology marketing literature to address the application of a new technology (section 1.2). The review of literature reveals what is known and what is less well understood about the application and diffusion of radically new technologies. Innovation literature describes the process of developing and introducing something new and represents a development perspective. High technology marketing is addressed to represent a sales perspective. The literature review will discuss:

- Degrees of technological novelty and the implications for the innovation process (4.2)
- The process of early applications prior to widespread commercial sales (4.3)
- The identification, development and marketing of application opportunities (4.4)

Certain management practices have been shown to be effective for managing technology application and reducing uncertainty with regard to market adoption and customer requirements. The concept of 'probing and learning' is introduced as a construct for analysing the process of early applications. Subsequently, the particularities of 'probing and learning' in young technology based firms are discussed. Finally, 'latent' questions on this concept of 'probing and learning' are described, which help to further specify the research focus of this study.

4.2 The Process of Technological Innovation

Technological innovation encompasses the process of developing and implementing a new technology. Van de Ven et al. (1999: p.65) describe this process as follows: *"the innovation journey crosses a rugged landscape that is highly ambiguous, often uncontrollable and involves a good deal of luck"*. The innovation process is influenced by the nature and the novelty of a technology. The degree of novelty of an innovation is potentially linked to the levels of risk and uncertainty and the duration of an innovation process. First, variable degrees of novelty and the resulting uncertainties are described. Subsequently, the implications of these uncertainties on the innovation process are discussed for the early applications of a new technology.

2.2.1 Novelty and Technology Application

Innovations vary in their degree of novelty. Van de Ven et al. (1999: p.63) explain that *"some innovations change the entire order of things, making old ways and competences obsolete, whilst others simply build up what is already present"*. These innovations are widely referred to as radical versus incremental innovations respectively. However, scholars have proposed many different definitions for radical and incremental innovations and there are disputes about the degree to which a radical innovation is a distinct phenomenon and if so, what makes an innovation radical. In addition, different terms have been introduced to describe the degree of innovativeness. For example, disruptive versus sustaining, to describe the impact of an innovation on existing markets and businesses, or discontinuous versus continuous, to describe the change in industries and markets caused by an innovation Thus, scholars have different opinions and take different theoretical perspectives to define the degree of innovativeness. Danneels and Kleinschmidt (2001) distinguish between literatures from two theoretical perspectives. First, studies on the relationship between organisations and their environment. These studies describe the degree of novelty in terms of 'familiarity', regarding novelty as a characteristic of a technology. Second, a theoretical perspective focused on the resources of a firm that describes the degree of novelty in terms of 'resource fit'. These studies consider novelty as characteristic relative to the resources of an individual firm.

From the perspective of novelty in terms of familiarity, a 'radical' innovation involves a higher degree of unfamiliarity than 'incremental' innovations. Tidd et al. (1997) distinguish between high and low technological novelty and market novelty (fig. 4.1). Similarly, from a strategic management perspective Ansoff (1980) presents a growth strategy matrix categorising an old versus new product and old versus new market. These typologies have the same message: the less familiar a product or market, the higher the risk. Unfamiliarity with a novel technology and novel markets implies that there is a lack of understanding and information about the development of the technology and market. Due to this lack of information, radical innovations pose greater uncertainties for firms than incremental innovations. From this perspective, the highest degree of uncertainty is expected to prevail in 'complex' innovations, where both technology and market are novel. As Friar and Balachandra et al. (1999: p.38) describe, "*the technologies are emerging and no dominant designs have been established because the applications are still to be determined"*. For example, in the late 1970s, it was unclear how microcomputers would develop technically and which markets would adopt the technology on the near, mid and long term. Innovations in new and unfamiliar markets with existent technology, are referred to as architectural. Tidd et al. (1997) describe a 'technological innovation' as a technology that provides new solutions to existing problems. Replacement technologies, such as FC technology, typically belong to this category: the technology provides a new solution, but many of the possible markets for FCs are known.

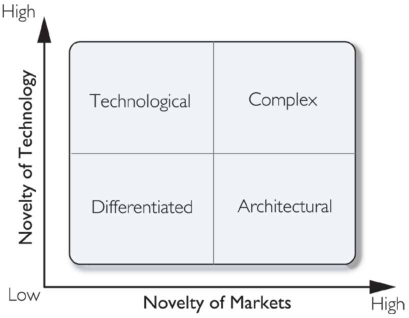

Figure 4.1 Typology for innovativeness. Source: Tidd et al.1997

From a different perspective, the Radical Innovation Research Project refers to a radical innovation in terms of improvement performance: a technology is radical if it has an entirely new set of performance features (Leifer et al. 2000). These scholars assume that in terms of technical performance a radical innovation is a large leap forward that cannot be accomplished merely by improving the product along the same lines as currently. To achieve a leap in performance, Betz (2003) argues that radical innovation is often driven by scientific achievements. However, this description of radical innovations may cause confusion because exactly these innovations are typically not competitive in terms of cost and performance when they are initially introduced. The large leap forward is therefore likely to refer to the potential performance features, which can take many years of development and several applications. Scholars have found that 'radical' innovations involve longer periods of development and implementation and an unconventional progression of activities, due to the uncertainties of technology development and market adoption (e.g. Veryzer 1998). Therefore, it can be argued that radical innovations require a different form of management than more incremental innovations (e.g. Rogers 1995, Rice et al. 1998). From this perspective, the degree of novelty is described as a characteristic of the technology and markets that influence the management of the innovation.

The degree of novelty of an innovation is also described in terms of the change an innovation brings about in a market, industry, system etc. The terms 'discontinuous' and 'continuous' are used to describe innovations from this perspective. According to Utterback (1994), discontinuous innovations permit entire industries and markets to emerge, transform, or disappear. Similarly, Tushman and Anderson (1997) use the term 'discontinuous innovation' to describe innovations that involve breaking with the past to create new technologies, processes and organisational routines. This description refers to the degree of novelty in terms of the required change in organisations.

In contrast to perspectives on the novel character of a technology, Christensen (1997) argues that few technologies are intrinsically disruptive or sustaining in character. According to Christensen, it is the influence of a technology on a company's strategy or business model that creates a 'disruptive impact'. Christensen distinguishes between disruptive and sustaining innovations according to the degree to which an innovation 'disrupts' or 'sustains' the competences of a firm. A disruptive innovation makes a firm's existent competences obsolete, thereby threatening its competitive position and right to exist. From the 'resource fit' perspective of novelty, a radical innovation can have a strong impact on a company's competence and resources. Tushman and Anderson (1986) argue that discontinuous innovations can be either competence enhancing or competence destroying. When a technological innovation does not vary from the firm's traditional area of expertise, the innovation is competence enhancing. When a firm needs to acquire entirely new resources and competences to develop and implement the technology, it is competence destroying. Henderson and Clark (1990) have also categorized innovations in terms component and architectural knowledge. If the innovation improves both component and architectural knowledge, it is incremental, if it destroys both types of knowledge, it is radical. When an innovation changes the way components are linked together, it is referred to as an architectural innovation. When it changes the core design concepts and not the way components are linked together, it is referred to as modular innovation. Most studies from this 'resource fit' perspective focus on established firms and how they react to and manage radical innovations.

An innovation may also disrupt and change current product and market structures, distribution channels and supply chains. However, Afuah and Bahram (1995) suggest that the 'radicality' of an innovation will vary across a supply chain. These authors propose an Innovation Value-added Chain model describing how an innovation has varying implications for different actors in a supply chain. From different points of view, the 'radicality' of an innovation will vary. For example, to suppliers that become entirely obsolete, the technology is radical. Original Equipment Manufacturers may have to change core competences, but sustain the knowledge on how components are linked, implying a modular innovation. In line with this approach, Friar and Balachandra (1999), propose that a technology's 'radicality' is a function of the amount of learning or behavioural adjustment required on the part of the customer using the product.

Finally, a 'radical' innovation is described in terms of the changes in the contextual environment. A so-called system level innovation implies changes to the structural environment and social context (Kemp 1998). For a company this type of radicality implies some degree of dependence on changes and events in the external environment. In addition, system level changes typically involve a lengthy process and a power struggle on several fronts. Regarding meso and macro-level changes, Freeman (1991) describes innovation at an industry and economy level: new technological systems and technological revolutions respectively. The first may give rise to new industrial sectors and induce major change across several branches of the economy. The second are clusters of innovation that can change the whole economy.

The different perspectives on radical innovation describe a similar consequence for the process of innovation: radical innovation involves a more complex and uncertain process than incremental innovation. Considering the disagreements on the definition and impact of radical innovations, this study will choose a point of departure. Young technology base (YTB) firms may develop a radical technology in terms of novel markets and technology. However, it can be argued that for YTB firms, the difficulty and uncertainty of application and diffusion is largely determined by the radicality of the innovation for other firms in terms of 'resource fit'. In the case of a 'technological innovation', applications are known, however, the innovation can disrupt established markets, industries and supply chains. Replacing an established technology is likely to disrupt the competences of established organizations and cause 'resistance' to adoption. A technological innovation is primarily 'radical' in terms of its unfamiliarity to customers and end users and the learning required of consumers and supply chain actors. Therefore, for the purpose of this study a 'replacement' technology is considered to be a 'radical' innovation in terms of the unfamiliarity and required learning for actors external to an YTB firm.

4.2.2 Uncertainties of Technology Application

Considering the above definitions, radical innovations typically imply a higher degree of uncertainty than incremental innovations. Uncertainty stems from unfamiliarity and the lack of information to evaluate and predict development and adoption. Additionally, uncertainty stems from the necessity of different stakeholders to learn about the technology and develop new competences. Sources of uncertainty stem from a difference between the amounts of information required to perform a particular task and the amount of information available or possessed, a definition of uncertainty from innovation processing theory (Galbraith 1973). On the other hand, uncertainty is argued to stem from the unpredictable nature of environmental events (Van de Ven et al. 1999). Innovation literature addresses different types of uncertainties. In the case of a technological innovation there may be technical uncertainties and market uncertainties from various sources.

Technical uncertainty stems from an immature state of development and a diffused focus of research and development. As Rosenberg (1995: p.173) suggest, *"much of the difficulty derives from the fact that new technologies typically come into the world in a primitive condition".* When a technology is immature, there are unresolved technical problems and cost and performance competitiveness is yet to be reached. Prior to application, there may be uncertainty about how a technology will perform in operation. Moreover, when technologies are emerging and there are no standardized and dominant solutions as yet, there is a lack of information to predict the development of technical performance and the most promising core concepts. Consequently, there is uncertainty about which technical pathways will become dominant and it is difficult to select the most likely technical paths of development (Utterback 1994). In addition to uncertainties on 'will it work' and 'what will it look like', Rosenberg (1995: p.176) argues that uncertainties stem from a dependence on complementary technologies: *"the impact of an innovation depends on improvements not only in the invention itself, but also in complementary inventions.*

'Market uncertainty' refers to the difficulty to predict if and when markets will adopt a new technology. In the case of complex technologies, market applications are ill-defined and it is difficult to foresee the uses of the new technology (Rosenberg 1995, Tidd et al. 1997). Utterback (1994) refers to 'target uncertainties' when it is not clear who the target market is and what product features best serve its interests. In the case of technological innovations, uncertainty of market adoption stems from the unpredictable nature of customer behaviour. A customer's perception of the technology and the rate of technological change influence adoption behaviour. Additionally, a customer's necessity to change supply chain relations and competences may cause resistance to change (Afuah and Bahram 1993, Tidd et al. 1997). A customers' perceived risk of adoption and resistance causes uncertainty about market adoption and consequently market adoption behaviour is difficult to predict. Moreover, in the case of radical technologies, there may be a lack of information on customer interest and requirements because customer judgment is only reliable when the persons questioned have sufficient prior knowledge about the new technology (Von Hippel 1988). More reliable customer feedback and information is gained through early applications such as demonstrations. The interaction between technical and market uncertainties result in a paradox: decisions on technology development depend on how the market responds to early versions of the technology, whilst the response of a market depends on the form the technology takes (Lynn et al.1996).

The relative uncertainty of applying a radical technology, compared to incremental innovations, stems from a lack of information necessary to predict technology development and market adoption and a difficulty to predict events in the environment. This does not imply that there is no uncertainty about incremental innovation, but typically radical innovations are relatively more uncertain. Geels (2002) argues that there are additional uncertainties in the case of replacement technologies caused by the persistence of old technologies. Thereby, replacement is challenged by old technologies that may hold on in particular markets for a long time. Due to the high degrees of uncertainty and dynamics involved, it is virtually impossible to make predictions on the basis of the information available. As Van de Ven et al. (1999: p.) state, *"a central problem in managing the innovation journey is determining whether and how to continue a developmental effort in the absence of concrete performance data".* As a technology develops and markets emerge, the uncertainties of an innovation are likely to reduce over time.

4.2.3 Implications for the Innovation Process

The novelty of a technology influences the process of new technology application and radical innovations are likely to require a different form of management. Van de Ven et al. (1999) argue that for innovations of greater novelty, size and duration, the innovation process is more complex, disorderly and uncontrollable than for incremental innovations. There are different models on how the innovation process proceeds. Two polar type models of the innovation process are described: i) linear and rational or ii) cyclic and non rational.

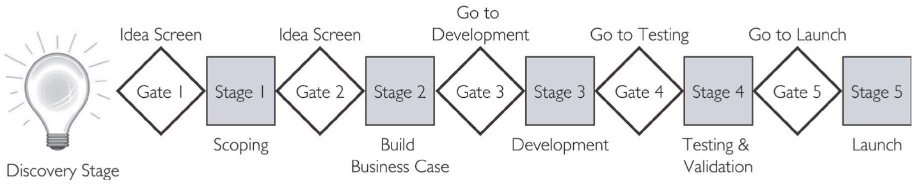

Figure 4.2 Stage gate process model. Source: Cooper et al. 2002

The field of New Product Development (NPD) has described the innovation process as a sequence of cumulative activities from the definition of a problem to the commercialisation of an end product. Cooper's Stage Gate process model illustrates these characteristics (figure 4.2). The process is described as linear and goal-oriented. A 'successful' outcome is targeted through the profitable implementation of a new product. It is assumed that decisions are taken rationally through various analytical methods and assessments at each 'stage gate'. The linear model provides a simplified illustration of the NPD process to support firms in 'getting it right the first time' and maximize development efficiency. Buijs (2003) argues that although these models are useful as a guideline for educational purposes, in real corporate life, product innovation processes have a more chaotic character. Similarly, scholars argue that in practice the innovation process rarely proceeds in such a simple linear fashion and that these models are oversimplified and over-rational (e.g. Arrow 2000, Van de Ven et al. 1999). It can be argued that the process of innovation proceeds in a more disorderly and complex fashion.

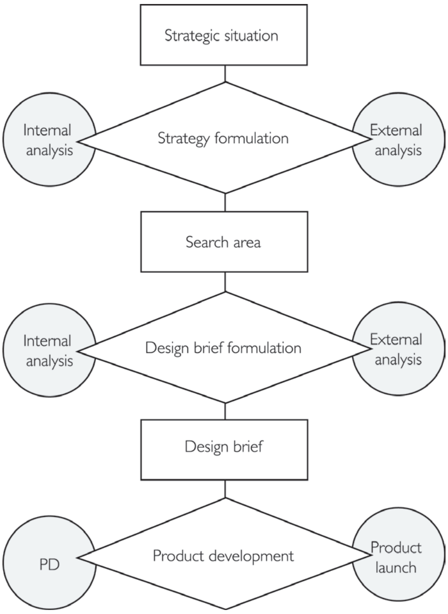

Figure 4.3 Delft Step by Step Product Innovation model. Based on Buijs 1984, 2003.

In contrast to the lineair models of NPD, Van de Ven et al. (1999: p.16) describe the process of innovation as: *"a nonlinnear cycle of divergent and convergent activities that may repeat over time"*. Similarly, Buijs (1984) observed patterns of divergence and convergence in the innovation processes of fifty small and medium sized enterprises. On the basis of these research findings, a product innovation model was proposed (fig. 4.3). This product innovation model is applied at the Delft University of Technology in education and design projects[1]. The Delft Step by Step Innovation model presents four phases: i) strategy formulation, ii) design brief formulation, iii) product development, iv) product launch and use (Buijs 1984, 2003). Thereby, this model links NPD with strategic planning in a company. Each phase is characterised by a divergent exploration of alternatives and a convergent process of decision making. Buijs found that particularly in the first two phases, divergent thinking should be dominant to search for opportunities and ideas. In the later phases of implementation, a convergent process should be dominant. Different patterns of these innovation processes have been observed, some are carried out in parallel, other sequentially, some carry out all steps, others a few (Cooper 1983, Buijs 1984). The product innovation model represents pre-development phases of NPD, often referred to as the "Fuzzy Front End" (FFE). Khurana and Rosenthal (1998) describe the front end as inherently fuzzy because it concerns complex information processing, a broad range of tacit knowledge, conflicting organisational pressures and uncertainty. Schroder and Jetter (2003) utilize the term FFE to emphasise the high degree of technical and market uncertainty in these early stages of NPD. Thus the front end of NPD is described as "fuzzy" to indicate the high degrees of uncertainty, experimental nature and ad hoc decisions compared to the more structured and goal oriented NPD process. Although there are various models of the FFE, similar phases are described including, opportunity identification, opportunity analysis and idea generation. Koen et al. (2002) present a cyclic model of the FFE, suggesting that front end activities are interactive and conducted in parallel (fig. 4.4). The targeted outcome of a FFE for NPD is a well defined product concept. However, in the case of radical products, scholars find that the concepts are less defined and structured after the first evaluation than incremental product ideas and pose a higher degree of uncertainty (Khurana and Rosenthaal 1998, Moenaert et al. 1995). Moreover, the FFE for technological innovations show similar phases, but the targeted outcomes differ: a technology-market mix and business case instead of a well defined product concept (Hellman 2004). Lichtenthaler et al. (2004) suggests that radical innovations require a more flexible and less stringent 'stage gate' selection and technology-market assessments to enable the further development and application of radical innovations.

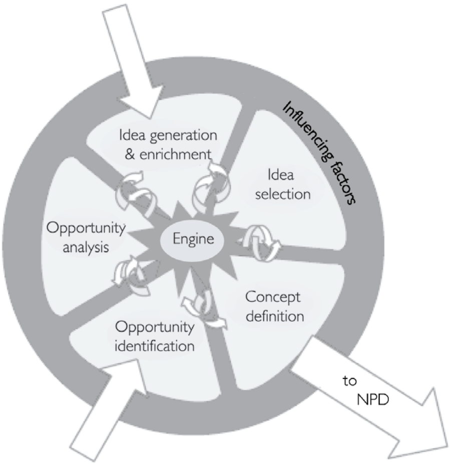

Figure 4.4 Fuzzy front end model (Koen et al. 2002).

In the case of radical innovations there is typically limited information to rationally evaluate alternatives and predict the outcomes. Therefore, in contrast to NPD models, the innovation process cannot be entirely rational and analytic. Instead of analytic logic, the models are based on more experimental logic involving a process of learning towards analysis (Lynn et al. 1996).

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[1] Buijs (2003) introduces a circular model of the product innovation model. Although this model accepts the chaos of innovation processes in practice, the circular model appears to be less suitable for education than the more traditional linear models. At the DUT the model is taught as a tool for 'strategic product innovation' and applied in design projects with and for companies.

Furthermore, there is a key difference in the assumed input and output of the innovation process. The technical and market uncertainty of radical innovations implies that technology development continues as applications are pursued. Consequently, models of the radical innovation process describe parallel paths of development and intermediate outcomes (Van de Ven et al. 1999). Whilst NPD models target the success of a single end product, radical innovation models describe multiple applications that contribute to the reduction of uncertainty and the creation of the value of a new technology. The process of radical innovation involves many setbacks and the success of the innovation cannot be determined until after the innovation process is completed. Moreover, uncertainties in the context of a radical innovation suggest that the innovation process is influenced by factors external to the firm.

For radical innovations, the process of innovation is characterised as a highly uncertain journey of exploration and learning. According to Van de Ven et al. (1999), the main difference between NPD and radical innovations is that the success of an innovation is beyond the control of a manager. Additionally, the innovation process is a learning process. Considering the technical, market and context uncertainties described, the innovation process is modelled as a dynamic process of parallel activities in technology development, early applications and continuous learning.

4.3 The Process of Technology Application

Technological innovation encompasses the whole process of developing and implementing a new idea. Although processes of innovation vary, Van de Ven et al. (1999) show that there are common elements in the innovation process including a period of initiation, development and implementation. In the case of radical technologies, the period of development and early applications is long because technologies do not emerge in laboratories fully developed and ready for commercial sales. In the case of new technologies, for which there is no market demand as yet, markets for the technology evolve as the technology further develops in a co-evolutionary process (Geels 2002)[2]. In this context, scholars have shown that technologies go through a period of experimentation prior to the widespread acceptance of a dominant design. This section will first address the development and application of new technologies at different levels of analysis including technology life cycles and stages of development, phases of firm development and the technology commercialisation stages within in a firm. Subsequently, this section describes the accumulation of niche markets in the process of technology application. Finally, the identification and development of opportunities for technology application is described.

4.3.1 Technology Development

Innovation, technology management and marketing literature have described the development of new technologies. Tushman and Anderson (1986) have proposed a model of technology life cycles (figure 4.5). In a phase of variation, new technologies emerge from experiments that begin to challenge established technologies. Subsequently, an 'era of ferment' follows in which different technological alternatives compete and a diversity of markets are addressed. In this phase, sales of the technology are limited. Historic cases suggest that this pre-dominant design phase can take a long time (Utterback 1994). A 'dominant design' typically emerges from the competing alternatives, marking the subsequent phase of selection. In the phase following, the technology develops through incremental change until the cycle proceeds and the established technology is substituted by a discontinuous innovation.

For a single cycle of technology development, Utterback and Abernathy (1975) describe phases with similar characteristics. These authors describe how a technology moves from a fluid state of uncertainty, through a transitional phase, to a specific state. Similar to the 'era of ferment', the fluid state is characterised by a great deal of change and a high degree of uncertainty regarding alternatives (Utterback 1994). In this phase, the

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[2] Geels reviews literature on various co-evolutionary processes that take place within technological transitions such as, the co-evolution between technology and social systems, between technology and policy, between technology and users.

rate of product change is rapid, the new technology is often crude, expensive and unreliable and the needs of users are often not well understood. In the transitional phase, a dominant design and market acceptance emerges. Finally, the specific phase development is characterised by incremental change and a focus on process (manufacturing) innovation to achieve high levels of efficiency and production.

The development of a new technology has also been described in terms of firm development. Shanklin and Ryan (1987) identify three stages of firm development: i) a patent driven stage in which the attention is focused on R&D effort and its protection, ii) a supply driven stage, in which early applications are 'pushed' to the market and early adopters experiment with the technology. Thereby, R&D continues in addition to demonstrations and early applications of the new technology or product. Finally, iii). a demand driven stage in which buyers begin to have a better understanding of the technology or product and begin to articulate their needs. Balachandra et al. (2004) describe a similar model of technology development in terms of supply and market driven stages. According to these authors, this process is not linear. Instead a new technology and applications of the technology co-evolve and go through several cycles of technology push and market pull. Based on a case study of the personal computer industry, Balachandra et al. identify cycles of technology application in which technology development and the development of applications interact. In each cycle a company goes through an exploratory phase, a transition phase and a market driven phase. In an exploratory phase, applications are sought for the technology. Many applications are tried out, but few succeed. Subsequently, a phase of transition follows, from a technology driven to a market-driven stage in which there is a growing responsiveness to external inputs from the market. Finally, there is a phase of technology variation, refinement and market growth. Balachandra et al. (2004) argue that it takes several cycles of technology application in niche markets before large scale application is achieved.

The models of technology development suggest that the period after the discovery of a new technology and before widespread commercial applications is particularly challenging. The 'fluid' phase or 'era of ferment' prior to the emergence of a dominant design is characterised by uncertain decisions on a diversity of alternatives, as the technology develops and early applications are pursued. According to Van de Ven et al. (1999), innovations terminate at higher rates in proportion to the time required for their implementation. This can at least partly be explained by the required investments and low return on investments. Consequently, most entrepreneurial firms fail in this period (Olleros 1996).

Several things can go wrong throughout the 'pre-dominant' phase of technology application. Jolly (1997) specifies five independent sub processes for the commercialisation of a new technology: i) imagining a technological innovation in combination with a potentially attractive market opportunity, ii) incubating the technology to define its commercial potential, iii) demonstrating the technology in the products, iv) promoting the adoption of these products and finally, v) sustaining commercialisation. These sub processes proceed in dynamic cycles and there are multiple intermediate applications, such as 'proof of concept' applications, demonstrations of the technology, prototypes and applications in early markets. Jolly (1997) argues that each sub process requires a mix of various disciplines and skills. For example, both basic research and marketing research is required in order to link a technological discovery to market opportunities. For demonstrating, development, engineering, manufacturing and marketing disciplines are required. From this perspective, Jolly describes the commercialisation of new technologies as cyclic and multi-disciplinary process. This model contrasts with 'traditional' linear models of technological innovation, starting with basic scientific research, followed by development and then on to production and marketing. Nevertheless, the intensity of each discipline will vary over time. The intensity of the scientific research effort is likely to decrease relative to the technology development effort as an innovation moves towards markets. Day et al. (2000) distinguishes a period of scientific discovery, in which scientific research prevails, a period of probing and learning in which viable applications and market concepts emerge through technology and market development effort. Finally, Day et al. describe a period of commitment and competitive development to support commercialisation (fig. 4.5).

With the objective of gaining a better understanding of technology application decisions, this study will focus on the phase of technology development. This phase has been described as an 'era of ferment', the 'pre-dominant' design phase or the fluid stage of development in which choices have to be made from multiple alternatives under a high degree of uncertainty.

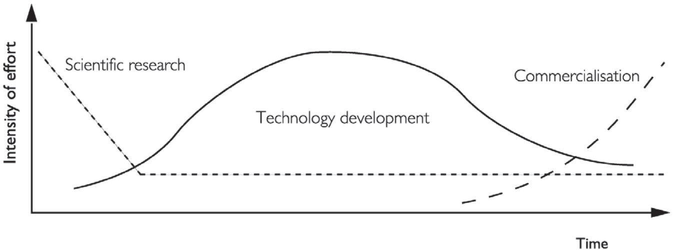

Figure 4.5 Relative intensity of effort in innovation process. Source, Day 2000

4.3.2 Niche Market Accumulation

Prior to the widespread commercialisation of a new technology, there is a phase of technology and market development in which early applications and niche markets are pursued. A niche market is a market portion that may accept the relative high costs and low performance of a new technology because the technology fulfils a demand that is not addressed by mainstream technologies. The emergence of niche markets is described from two different theoretical perspectives. From a multi-level perspective, Geels (2002) describes the process of 'niche accumulation' within technological transitions. Departing from theory on the diffusion of technologies, Rogers (1995) describes how a technology primarily penetrates small markets segments.

First, the market penetration perspective is discussed, in which early niche applications are modeled as specific customer segments. In the case of computer technology Balachandra et al. (2004) describes several cycles of small scale applications prior to large scale market adoption. Primarily a small number of hobbyists and specialists adopted computing technology, gradually larger professional markets followed and finally personal computing technology was widely adopted by consumers. This case illustrates the 'technology adoption life cycle' model introduced by Rogers (1995). This model represents the market penetration of a new technology in a bell shaped curve, segmented into several types of customers that adopt an innovation over time. Typically a small number of innovators, enthusiasts for new technologies, primarily adopt the technology. They are followed by a (larger) number of early adopters, attracted to an added value of the technology. Adopters in this segment are often found in specialised niche markets with specific requirements. A larger group, the early majority, subsequently adopts the technology, but only if the benefits of the technology are well proven and the risks are tolerable. The late majority adopts the technology only after many people have tried it and finally a number of 'laggards' decide. The different customer segments have distinct identities, behaviours and requirements.

High technology marketing strategies have largely been based on the market penetration model. It is assumed that initial and early adopters can be used as a reference base for targeting subsequent segments. However, scholars have argued that this strategy may be flawed because the segments often have almost nothing in common with each other (e.g. Von Hippel 1988, Moore 2002). Additionally, Moore (2002) questions the assumption that market adoption will develop sequentially. According to Moore, there are 'cracks' in the bell curve: the adoption of a customer segment does not readily follow the adoption of earlier segments. Moore observed two minor cracks and a major chasm. The two minor cracks are observed between: i) innovators and early adopters and ii) between the early majority and the late majority. The major chasm Moore describes divides the early adopters from the early majority. According to Moore, technologies often fail to be adopted beyond early adopters because the early majority is not prepared to accept high costs and low performance. Consequently, technologies often remain in niche markets.

That brings us to the second perspective. Moore (2002) suggests that technologies often fail to grow past niche markets. However, in the case of multi applicable technologies, niche markets may be found in a diversity of market segments. Geels (2002) suggests that new technologies are applied in several niche markets, then in other niche markets and eventually move towards mainstream markets. It is thereby assumed that the various niche markets contribute to the adoption of the technology in larger markets. Scholars argue that niches provide a market entry point that enables an innovative firm to gain a foothold before facing the fierce competition of mainstream markets (Dalgic and Leeuw 1994, Kotler 1991, Raynor and Weinberg 2004). Niche markets enable learning and the development of a social network, such as supply chains relationships (Rosenberg 1976, Von Hippel, 1988; Lundvall, 1988). Thereby niches enable firms to improve their technology and become competitive. From this perspective, niches in different market segments and sectors contribute to the transition of a technology. The term 'Strategic niche management' has been introduced, referring to a concentrated effort to develop protected spaces for certain applications of a new technology (Kemp et al. 1998, Kemp et al. 2001, Hoogma 2000). In these 'protected spaces' a technology with relatively low technical performance and high costs can be applied in an environment protected from commercial pressures. These scholars have described the development of 'protected spaces' shaped through policy measures.

Thus, there appears to be a general consensus that technology application begins in small niches, characterised as specialized market segments in which the technology provides an added value. However, scholars refer to niches differently. Niche markets have been described in terms of the early adopters of a new technology. Niche markets have also been described in terms of multiple small market applications that contribute to technological transitions. Finally, niches have been described as non-commercial protective spaces, necessary for the socio economic transition of a new technology. In the case of a multi-applicable radical technology, various niche market applications are likely to be pursued prior to large scale application. For the purpose of this study, niche markets are referred to as early applications in various small markets, prior to large scale applications.

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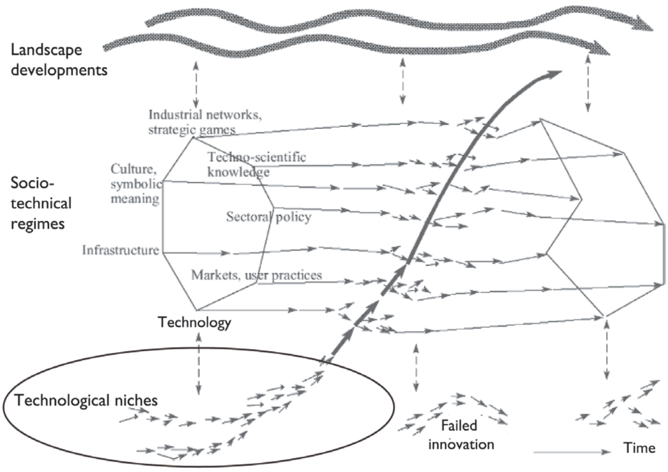

Figure 4.6 Niche market accumulation in technological transitions. Based on Geels 2002

The process of niche accumulation assumes that niches can contribute to the development of subsequent markets. From this perspective, niche markets are considered to be intermediate steps in the process of learning, development and demonstration. However, some niches fail and do not contribute to development, as illustrated in a model of technological transitions presented by Geels (2002) (fig. 4.6). Apparently, there is a risk in choosing niche markets that do not grow into larger markets or contribute to the growth of other markets. The difficulty, described by Moore (2002), to transfer experiences and feedback from early adopter markets to mainstream markets emphasises this risk of selecting niche markets that do not contribute to subsequent growth. Despite the apparent relevance of managing niche markets, literature on niche market accumulation does not address how niche markets are identified and selected in firms.

Given the risks and the role of niche market applications in the development of technology and markets, it is relevant to understand the process of selecting niche markets. The selection of niche markets is particularly relevant for a study on how firms manage early applications of their technology.

4.4 Matching Technology to Market Opportunities

The previous paragraph described how the commercialisation of a new technology involves multiple applications in niche markets prior to widespread adoption. This section addresses how such market applications are identified and developed. The market application of a new technology requires some kind of 'match' between technology and market opportunities and the success of a new product or technology is strongly related to this match (e.g. Balachandra et al. 2004, Coombs et al. 2001)[3]. Given the technical and market uncertainties of radical innovation, the identification and development of profitable markets is challenging. As Jolly (1997: p.9) states, *"the challenge of marrying a new technology's function with market worthy end products lies behind many of the delays in commercialisation"*. Assuming that successful innovation requires a match between technology and market, then what is considered to be a match? Literature on innovation and NPD argues that innovations are more likely to be successful when a technology fulfils a need with a significant product differential advantage and meets customer requirements (e.g. Cooper and Kleinschmidt 1987). In this section, technology-market matching is described in two ways: i) matching a technology's function to a market opportunity to identify potential applications and specific customers, ii) matching technological specifications to customer requirements, to develop the opportunity for application. Subsequently, research question 2a is addressed: how do FC firms develop market insight to identify and develop market applications?

4.4.1 The Identification of Market Opportunities

The initial stages of NPD and innovation models are concerned with the identification of 'market' opportunities and 'needs' for innovation. Howells (1997) has criticised the lack of clarity regarding terms such as 'markets' and 'needs' in innovation studies. The process of opportunity identification becomes more comprehensible with a clarification of these terms. Mowery and Rosenberg (1979: p.229) propose the following definition of market demand:

"(Market) demand expressed in and mediated through the marketplace, is a precise concept, denoting a systematic relationship between prices and quantities, one devolving from the constellation of consumer preferences and incomes".

Departing from this economic perspective, Howells (1997) describes 'needs' as the willingness of users to shift spending to an innovative product. In line with these definitions, there are 'opportunities' for market application where customers are willing to adopt a new technology.

Entrepreneurship literature addresses the identification and development of market opportunities. However, there are conflicting theoretical approaches to how entrepreneurs discover market opportunities, initially driven by Kirzner (1973) and Schumpeter (1942). In a highly simplified summary of this dispute, Kirzner argues that opportunities emerge, whilst Schumpeter argues that opportunities are created. Scholars in line with Kirzner (1973) argue that opportunities emerge from the environment. It is assumed that markets

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[3] According to Cooper (1987) the three most important new product success factors are i) a unique product with differential advantage in the market, ii) having strong market knowledge, undertaking market research and marketing iii) having technological production synergy and proficiency. These success factors for new product success emphasise the relevance of achieving some kind of match between technology and markets.

have errors arising from over-optimism and over-positivism and that these errors provide opportunities. According to Kirzner (1999: p.6), the identification of opportunities is matter of noticing these opportunities: *"the entrepreneurial role is that of alertly noticing (discovering) where these errors have occurred and moving to take advantage of such discoveries".* From this perspective, entrepreneurs must be alert to recognize the opportunities. Therefore, differences between entrepreneurs are explained by the differences in information available to the entrepreneur. By contrast, scholars in line with Schumpeter (1942) argue that an entrepreneur creates market opportunities. It is assumed that existent opportunities are already fully and familiarly exploited and that an entrepreneur generates disturbances in this market place. The identification of opportunities is seen as a creative process requiring individual qualities. Differences between firms are therefore attributed to differences in the fundamental character and qualities of an entrepreneur. From this perspective, Dougherty and Heller (1994: p.201) state, *"linking market and technology possibilities is a creative process in which product innovators must experiment with different attributes, work closely with customers, pursue multiple development paths at once and at times make discontinuous leaps in imagination".*

These theoretical perspectives are reflected in the discussion of factors influencing the identification of opportunities. On the one hand, factors related to the qualities of an entrepreneur are argued to be influential, on the other hand, the information available to a firm is expected to influence opportunity identification. The experience of a founder, prior to firm formation, is repetitively emphasised as a prominent factor influencing the identification of market opportunities (Shane 2000, Ardichivili 2003). However, Kakati (2003) argues that technological and market capabilities are more influential than entrepreneurial qualities for the success of new venture. Similarly, innovation literature emphasises the importance of firm capabilities on the success of an innovation. However, this emphasis on firm resources instead of individual qualities and character is biased: a majority of innovation studies have focused on established firms. Among others, Bond and Houston (2003) suggest that customer orientation is vital to linking technologies and markets successfully. Additionally, technical and market experience in prior market applications is argued to be determinant for new product success. Moreover, the interaction between technical and market experience is found to be highly important (Nerkar and Roberts 2004, Song et al. 2005). If the identification and assessment of opportunities requires a match between technology and markets, then it seems obvious that both technological and market experience is required. Yet, innovation literature provides a limited understanding of how firms develop these capabilities and how they influence the innovation process at different stages of opportunity identification and development.

The identification, assessment and development of opportunities are described as 'pre-development' activities in the NPD process, or FFE activities (see paragraph 4.2.3). Multiple success factors are described to manage these pre-development activities, including product strategy, product definition and organisational factors (Khurana and Rhosenthaal 1998). Among others, the relevance of marketing strategy, application expertise and interactive development are emphasised. Thus, multiple factors are argued to influence the success identifying opportunities. Again, literature provides limited support in identifying which factors are most important in which stage and time. What factors influence the timing and prioritisation of opportunities appears to be relevant when there are diverse opportunities to choose from. According to Klofsten (1997), is usually easy for young firms to identify relevant customer categories, but more difficult to set priorities and select specific opportunities. Similarly, in a case study of an YTB firm, Danneels (2002: p.1107) observes that the prioritisation and selection of customers was particularly problematic: *"the technology is applicable in so many different areas that we have a tendency to want to go after everything".* Apparently, with limited market information, a high degree of uncertainty and multiple alternatives to choose from, it is difficult to prioritise and select specific market opportunities.

Therefore, identifying, evaluating and selecting market opportunities for radical innovations appears to require learning about markets and extensive information gathering in order to make decisions such as: which needs the product will target, what function it will embody and what the general product architecture should look like. Multiple factors influence the success of these activities. Literature suggests that a firm's level of technical and market experience is likely to have a strong impact on either 'noticing' or 'creating' opportunities, however, there is a limited understanding of how these factors influence the prioritisation and selection of opportunities as a firm gains experience.

Table 4.1 Factors from the literature review that influence the identification of opportunities

Factors	Authors
Experience prior to firm founding	Shane 2000, Ardichivili 2003
Market related competences / Customer orientation	Bond and Housten 2003, Kakati 2003
Combination technology / market competences	Song et al. 2005 Nerkar and Roberts 20004

4.4.2 Development of Market Opportunities

The development of an opportunity refers to the specification and testing of a product concept, associated with product development. However, unlike other products Jolly (1997: p.8) explains, products derived from a new technology require *"walking a tightrope between conceiving something customers will buy and being able to implement it with the technology at hand".* The successful development and specification of an opportunity requires a match between technology specifications and customer requirements. However, in the case of radical technologies, early applications are characterised by miss-alignments between the new technology and the user environment.

Leonard-Barton (1988) argues that applications almost never fit the requirements of an application directly. A new technology may not be aligned to customer requirements in terms of cost and performance. Additionally, the technology may not be compatible with its application context. These misalignments stem from the complexity and uncertainty of a radical innovation. Typically, developers lack information about customer requirements and customers lack an understanding of the technology. Innovation studies suggest different approaches to achieve alignment. The classic approach is to modify the technology according to user preferences. By contrast, Von Hippel (1988) argues that user preferences will change in response to the technology. According to Leonard-Barton (1988), the alignment of technology and market is best viewed as a process of mutual adaptation. Similarly, Coombs et al. (2001) describe technology application as a co-evolutionary process between technology and users. Not surprisingly, the interaction between developer and customer is central to this process of mutual adaptation and co-evolution. Interaction between developer, customer or user and producer is argued to be an important condition for developing and marketing new technologies[4]. For example, Rosenberg (1992) addresses the value of user involvement in technology development. Similarly, Nebeker et al. (1998) argue that successful new technology products are best developed through early and in-depth involvement of customers, a process described as 'co-development'. Based on the integration of findings from industrial marketing and innovation management literature, Frambach (1993) argues that the rate of adoption is directly related to the extent of interaction and involvement of potential adopters in the development process. However, the early involvement of end users in the development of radical innovations is not evident. Some level of cost and performance achievement is likely to be necessary to attract the interest of end users. It can be argued that interaction at an earlier stage of development is particularly relevant in the case of OEM customers. Interaction enables a developer to learn about a customer's product requirements and align the technology to these requirements. Vice versa, interaction enables a customer to learn about the technology and develop the capabilities to integrate the technology. Consequently, as Tidd et al. (1997) suggest, the relationship between developer and adopter is likely to change throughout the process as information and resources are exchanged. However,

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[4] Lundvall (1988) further describes the user-producer perspective of the innovation process.

relatively little guidance is available for managing the interface between the developers and adopters of a technology. Teece (1986) suggests that firms should produce a number of prototypes and expose a variety of designs to customers to enhance interactive development. Innovation studies have also addressed the relevance of interaction between the disciplines of basic research, product development and marketing, to align technology and market requirements. Moenaert et al. (1995) suggest that within large firms, the level of communication between R&D personnel and marketing personnel influences NPD success. Similarly, Mc Grath and Eldred (1997) argue that interaction between product and technology developer is necessary to bridge the various goals, approaches and characteristics of the different disciplines. In the case of YTB firms, the interaction between disciplines is more likely to involve inter-firm collaborations. Therefore, in addition to inter-disciplinary alignment and communication, the development of opportunities with customers is likely to involve a balance between generating interest and being able to meet expectations. As Jolly (1997: p.79) describes, *"generating pull without hype".*

The development of market opportunities appears to require customer interaction and learning. Considering the misalignments and the process of mutual adaptation, the specification of a radical technology is likely to require multiple cycles of adaptation. In addition to intensive dialogues, these cycles of adaptation may require intermediate applications such as prototypes and demonstrations to enhance interaction. Thereby, the product concept emerges out of an interactive learning process. Thus, the specification of a product with a radical technology appears to require a process of mutual learning and mutual adaptation through cycles of designs and early applications.

4.4.3 Developing Market Insight

The above paragraphs suggest that technology-market matching requires learning to gain an understanding of market and customer requirements, for example, to learn about a market's potential, the suitability of an application and what customers really want. However, innovation literature rarely describes how firms develop these market related competences. Technology marketing literature suggests that traditional market research methods are not reliable for identifying, evaluating and developing market applications of radical technologies (e.g. Lynn et al. 1996, Von Hippel 1988, Shanklin and Ryan 1987).

Conventional market research methods include techniques such as concept testing, customer surveys, conjoint analysis, focus groups and demographic segmentation. These marketing tools and techniques have been developed on the basis of existent products and are most applicable to relatively mature products and markets (Tidd et al.1997). Besides, Shanklin and Ryan (1987) explain, traditional approaches to marketing are not designed to accommodate rapidly changing environments where the potential applications seem endless. Moreover, Deszca et al. (1999) found that for radically new products, market research questions are less specific and more difficult to answer than traditional market research questions. Firms apply conventional market research techniques for new products and technologies and some of this information is useful. However, scholars have found that most of the market information gained through conventional techniques is misleading and in hindsight strikingly inaccurate (Lynn et al. 1996, Leonard-Barton 1988). For example, Lynn et al. (1996) observed that information from traditional market research methods pointed some of the case firms away from the most significant market opportunities. To develop market insight for the application of radical technologies, traditional market research appears to be unreliable.

According to Von Hippel (1988) consumer perception of new products explains the inappropriateness of traditional market research techniques for radical innovations. The author states that a user's perception of a new product and its preferences are constrained and shaped by the user's real-world experience with existing products. Consequently, consumers cannot comprehend what a new technology or product will be like or how it will function. A consumer's unfamiliarity with the technology causes unreliable responses to conventional research techniques based on the assessment of consumer demand (Shanklin and Ryan 1987). However, it can be argued that in the case of 'technological innovations', there is some information on consumer demand from the requirements of established products and markets. This implies that traditional demand based techniques may provide some useful information, but it is not clear to what degree this market information is reliable. Tidd et al. (1997) provide suggestions: in the particular case of 'technological innovations', developers have to actively promote their technology and identify why a customer may be interested in an alternative to the existing solution.

Developing market insight for radical technologies evidently requires a different approach than conventional market research methods. According to Day (2000), available methods for market research have to be adapted and new approaches for radical innovations have to be developed. Literature suggests that market assessment approaches for new technologies require the use of more anticipatory and exploratory methods (Hersttat and Lettl 2004, Deszca 1999). For technological innovations, or replacement technologies, a balance appears to be required between conventional and new approaches to market research.

4.4.4 High Technology Marketing

The application of radical technologies is also argued to require different approaches to marketing. Literature on high technology marketing addresses how firms can move people closer towards adopting new technologies. The marketing methods assume that customer perception influences the rate of technology adoption and are typically based on factors that influence the rate of customer adoption, described by Rogers[5] (1995), i) perceived relative advantage, ii) compatibility with existing values of customers, iii) the ease of understanding the technology and iv) the possibility to try out and experiment with the technology. Thereby, high technology marketing aims to reduce a customer's perceived risk of adoption. In the case of 'replacement' technologies, developers are largely responsible for educating and convincing customers. Therefore, in contrast to conventional marketing methods, Shanklin and Ryan (1987) suggest that high technology marketing is characterised by a supply side approach. Conventional marketing wisdom is demand driven: the identification of buyers and preferences is central to marketing new products. In the case of radical innovations:

- The dynamic environment of a co-evolving technology and market requires a loose linkage between the firm's R&D and marketing functions (Shanklin and Ryan 1987).
- It is necessary to lead existing customers and identify potential new customers, placing a greater burden on developers to educate and convince potential customers (Tidd et al.1997).

A supply side approach implies that developers are responsible for stimulating primary or basic demand for a new technology, for example, by educating customers and generating interest. Early applications and experiments, such as prototypes and demonstrations are instrumental in this process. As Betz (2003: p.314) suggests, *"the more radical the innovation, the more experimental must be the marketing approach.*

4.4.5 Conclusions on Radical Technology Application

The novelty of an innovation, radical or incremental, influences the process of technology application and diffusion. In the case of a radical technology, the innovation process will proceed differently than an incremental product development process. The innovation process involves multiple intermediate and parallel developments instead of a single development towards a final result. The development of multiple intermediate 'niche market' applications illustrates how firms manage the pre-dominant phase of technology application. Furthermore, experimental logic and learning prevails over the analytic assessment of available information. Additionally, it has been argued that the application of a radical technology requires alternative methods of market research that are more anticipatory and exploratory than traditional methods. Finally, marketing radical technologies is characterised by a supply side approach instead of a demand driven approach, involving activities to proactively stimulate market demand. Thus, successful management practices for the development and application of radical innovations are described as relatively experimental and explorative compared to more incremental innovations.

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[5] Rogers takes a communication perspective on the diffusion of technologies. Brown (1981) presents a typology of perspectives on technology diffusion literature: i) communication perspective, ii) economic history perspective, iii) development perspective and iv) a market infrastructure perspective. These perspectives have typically focused on the adopters instead of the developers of a new technology. Diffusion research largely fails to address how and why entrepreneurs can influence the diffusion of new technologies (Brown 1981, Miller and Garney 2000).

Successful opportunity identification and development is derived from understanding and meeting customer needs. In the case of radical technologies this process involves a continuous learning for both developer and customer. Firms are challenged to reduce uncertainty to a manageable level and gain insights ahead of others. In the context of uncertainty, successful technology application primarily depends on a firm's ability to absorb uncertainty and anticipate opportunities faster (Day et al. 2000). Consequently, in the process of radical technology application, competitive advantage is likely to come from informed anticipation.

4.5 Effective Management Practices

The above sections have addressed the identification and development of opportunities, the uncertainties associated with radical technology application and the implications for the innovation process. This section is about how firms have learned to manage radical innovation. Various effective management practices described in literature are discussed. These practices are all characterised by experimentation and learning. Subsequently, examples from practice are described to illustrate such demonstration and market research experiments.

4.5.1 A Process of Experimentation and Learning

If advantage comes from informed anticipation and uncertainty reduction, then learning plays a central role in the selection of early applications. Learning to understand where potential markets may arise, learning about the suitability and limitations of a market application and learning about what customers really want. Cooper and Kleinschmidt (1986) find that prototype testing with customers has a positive impact on the launch of a new product. Similarly, Tidd et al. (1997) suggest that firms should learn as quickly as possible through experimentation with real products and customers. Jolly (1997) describes the relevance of a demonstration phase in which prototypes are developed to demonstrate and test the technology. Prototyping, demonstrations and market experimentation appear to be common techniques in novel development projects (Tidd et al.1997, Tidd and Bodley 2002). For example, in 'expeditionary marketing', developers learn as quickly as possible by experimenting with real products (Hamel and Prahalad 1994). Pisano (1994) found that 'learning by doing' was advantageous in the rapidly changing bio-tech industry. Another technique described in NPD literature is rapid prototyping, where functioning models are produced early in the NPD process to test customer reactions (Thomke 1998). From a study of several successful organisations, Schager (2003: p.3) found that creative improvisation through modelling, simulation and prototyping is related to successful innovation: *"how organizations play with their models and prototypes determines how successfully they manage themselves and their markets"*. Leonard-Barton (1998) argues that the primary activities spawning learning in companies are experimentation and prototyping. The findings of these scholars point towards a similar message: the application of a new technology involves experimentation with multiple prototypes and iterative loops of learning.

According to Van de Ven et al. (1999), this experimental learning process is typically described as a 'trial and error' process: trying out, adapting to the response and trying out again. However, the term 'trial and error' has a negative connotation and assumes that projects will fail. The practice of 'trial and error' appears to contradict NPD literature that is largely focused on avoiding failure and 'getting it right' the first time, to increase efficiency and the speed of getting products to markets. By contrast, Leonard-Barton (1995) argues that 'failure' can be beneficial and necessary for an organisation to learn in a dynamic and uncertain context. In a study of high technology companies, Maidique and Zirger (1984: p.299) similarly found that *"the knowledge gained from failures was often instrumental in achieving subsequent success"*. These arguments do not imply that failure from avoidable mistakes is beneficial. Rather, Leonard-Barton (1995) argues that learning is derived from 'intelligent failure', or creative experiments. Although it is questionable if firms can 'fail' intelligently, the message is likely to be that 'trial and error' does not imply simply thrashing about and wasting resources on avoidable mistakes. 'Intelligent failure' appears to suggest a conscious process of learning from failure instead of ignoring failure or results that fail to meet initial objectives (Leonard-Barton

1995). In the case of simulation models and prototypes, Schager (2000: p.3) argues that *"the unexpected results of a simulation may prove far more valuable than the reason the model was built in the first place…... model surprise can be even more important than model affirmations. The challenge is recognizing and exploiting that unanticipated value".* Radical technology application appears to involve learning from unanticipated results and experiments that may fail.

A trial or experiment literally means trying something new, a venture into a new domain. The novelty implies a more risky undertaking than an application in a familiar domain. Experimentation, by engaging in multiple alternatives, is also described as a common strategy to compare alternatives and facilitate selection (Eisenhardt 2000, Pisano 1994). Although several scholars refer to experimentation, different types of experimentation are described. Leonard-Barton (1995) describes how companies experiment with a variety of product functions and performances. Different strategies of product function experimentation were observed including, the introduction of a variety of models at the same time, the iterative improvement of a new product variation with feedback from pervious trials and finally, the companies that learn from other companies and 'wait' to introduce models. In contrast to experiments with different product functions, Friar and Balachandra (1999) describe experiments in different customer segments of a market. Finally, Lynn et al. (1996) describe how firms experiment in diverse markets. In a case study research of technology based firms, Lynn et al. found that successful case firms applied immature versions of their technology in a series of market experiments, referred to as a process of 'probing and learning'. This strategy is expected to be a successful management practice for multi-applicable technologies, when there is a high degree of uncertainty about which markets to pursue at which point in time. It can also be argued that 'probing and learning' through various applications is not necessarily a management practice, but represents the process of parallel developments and applications that characterises radical innovation models.

Assuming that YTB firms experiment in various niche market applications prior to large scale markets, the process of technology application is likely to proceed in small steps. From an analysis of the development of wind turbine technology, Garud and Karnoe (2003) found that a 'bricolage' approach was more effective than a 'breakthrough' approach. 'Bricolage' refers to an approach of moving ahead on the basis of small steps and adapting to feedback signals at each step. By contrast, a breakthrough approach takes leap frog advancements, introducing a radical technology to the market in one big step. It is argued that a bricolage approach lowers the risk and increases the likelihood of success (Garud and Karnoe 2003, Berchichi 2005). However, the effectiveness of a bricolage approach is disputable. A bricolage approach may be a more costly and a lengthier process than a breakthrough approach and it does not guarantee the realization of original project goals. Moreover, for the purpose of studying the application of radical technologies, the concept of bricolage is less suitable than the concept of probing and learning, as it describes the development of one product in a sequence of experiments instead of various parallel developments.

The experimentation strategies have in common that users respond to a real application of the technology in real time, providing feedback on customer requirements and preferences. Prototypes are a physical realisation of a technology that enables prospective users to experience the technology. Lynn et.al. (1996) suggest that firms learn about markets and prospective users through a process of probing and learning. Vice versa, Rosenberg (1982) introduced the term 'learning by using' to describe how users learn about a new technology by using and experiencing prototypes. Apparently two types of learning can result from experimental applications: developers learn about markets and customer requirements and customers learn about the technology.

4.5.2 Experiments in Practice

Experimental applications are developed for various purposes. In demonstration projects, immature versions of a technology are applied to demonstrate and explain a new technology and generate awareness. Large demonstration projects are often supported by government funds and are characterised by the involvement of various stakeholders. The larger demonstration projects provide 'temporary protected spaces' or 'incubator rooms' for technology development and application, as described by literature on strategic niche management. There are a limited number of studies on demonstration projects, considering the significant investments typically involved. Regarding energy technology demonstration projects, Sagar and Gallagher (2004: p.16) suggest that *"there is a need to better understand the factors affecting successful demonstration and deployment".* Lefevre (1984) has questioned the role and value of demonstration projects to commercialize and diffuse new technologies. Based on the experience from various demonstration projects, the author provides practical recommendations for conducting demonstration projects more effectively:

- Clarify the cost and risks involved. The stakeholders must be willing to accept the costs and risks of the project.
- Enable the adopters to try out. Prospective adopters should be able to try out and experience the innovation.
- Identify the audience. Perception of success and expectations to be met will depend on the audience. Therefore, the audience(s) should be clearly defined.
- Select a target audience that is favourable towards novelty.
- Present inducements beyond the demonstration project. Although stakeholders must be willing to accept that the demonstration will, in most cases, not be profitable or commercial in the short term, there should be incentives for longer term commitment.

Like all experiments, demonstration projects may fail despite significant investments. Major difficulties stem from a tendency to overestimate the ability for technical problems to be resolved within the demonstration setting (Lefevre 1984, Hellman 2007). Moreover, stakeholders are often reluctant to learn from failure. Although the effectiveness of learning and demonstration is variable, demonstration projects typically enable various stakeholders to learn about the technology and its potential.

Experimental applications in practice are also conducted to provide potential customers with the opportunity to try out a new technology. Providing a new technology on trial to customers is a high technology marketing strategy observed in practice by Easingwood and Beard (1989) to reduce a customer's perceived risk of adoption. Additionally these authors observe a positioning strategy in which a new technology is positioned in early adopter segments.

4.5.3 Market Research Methods in Practice

Traditional methods of market research were argued to be unreliable for radical innovation. In practice, the use of multiple market research methods in experimental applications enables firms to absorb uncertainty and anticipate opportunities faster. Market research techniques applied in practice are focused on obtaining a deeper understanding of a customer's current and future usage needs. Additionally the techniques are aimed a accelerating a customer's interaction with a new product or technology. In general, there is a greater burden on developers to educate potential users than in the case of traditional techniques. Deszca et al. (1999) reviews methods to conduct market research for new technologies, including diffusion models, visualisation techniques, information acceleration, lead user analysis, empathic design, experimental marketing and customer immersion sessions. The lead user method is further described.

Market research for new technologies has to overcome the constraint that the users' perception is determined by products familiar to them. To gain representative information on customer preferences, Von Hippel (1988) proposes the 'lead user method'. He argues that for accurate market research of new and complex technologies, this lead user method should be applied. Lead users are users that do have real life experience with novel product or process needs. They are also constrained by the familiar, but have insight into future conditions. Lead users face needs that will be similar to general needs in the market place, however, they face them months or years before the bulk of the market place encounters them. Additionally, lead users can benefit significantly from the solution proposed. This group of users who experience a strong need prior to the general market place can therefore be used as a 'laboratory' for market research. Lead user involvement in the development of a product concept is thereby argued to positively influence user satisfaction. However, Von Hippel's work is based on two assumptions. First, that new needs flow slowly across markets and market segments instead of simultaneously. Second, that the perception of relative advantages emerges in a time sequence. It is thereby assumed that the needs of lead users are representative for markets thereafter. It is questionable if the needs and preferences of lead users can be generalised. Additionally, although Von Hippel describes the characteristics of lead users, his work does not explain how to identify and select lead users. Furthermore it can be argued that the description of lead users is similar to early adopters and early niche market users. Experimental applications with early customers are likely to provide a similar result. Thus in practice various market research methods are applied and early applications are pursued to generate feedback from customers.

4.6 Describing Technology Application

The above paragraphs have described key differences between a 'classic' NPD process for incremental innovations and a process for radical innovations. Different management practices are proposed to successfully identify, develop and diffuse radical technologies. These practices share similar characteristics, i.e. exploratory methods, experimentation and learning. With these insights, research question 2b can be addressed: how can the process of FC technology application be described? 'Probing and learning', introduced by Lynn et al. (1996), appears to be a particularly suitable concept to describe the application of multi-applicable technologies.

4.6.1 Probing and Learning

The process of 'probing and learning' has been observed as a successful management practice for the application of radical technologies, to manage the problem of developing and understanding a market for radical innovations. 'Probing and learning' has the characteristics of a radical innovation model, as the following comparison with the stage gate model of NPD illustrates: the logic of probing is far more experimental than the rational assessments of the stage gate model. The emphasis is on probing and learning instead of analysis and prediction. Additionally, the stage gate process describes product implementation towards a single launch whilst the process of probing and learning describe parallel and successive experimental applications. Moreover, in the stage gate model, efficiency is the main objective, whereas probing and learning is more about gaining experience and valuable information (Lynn et al. 1996).

The Oxford Dictionary defines *probing* (v) as 'an investigation into unfamiliar matters' or an 'exploratory action to investigate or obtain information. A probe (n) is defined as 'an investigation', synonymous to 'an enquiry, examination or an exploration' (Oxford Dictionary 2001). These definitions imply that probing is aimed at gaining information and an understanding, to reach new conclusions and find out the nature of things. The word 'probe' originates from the Latin word 'proba' referring to proof. In the context of applying a technology in an uncertain market environment, a probe is aimed at learning about the market and technology to gain some degree of 'proof' about the potential of a market application.

Through case study research, Lynn et al. (1996) have observed that firms who developed their product by 'probing' potential markets with early versions of their product or technology, learned from these probes and subsequently tried again in new probes. The study comprised of four case studies: i). cellular phones by Motorola, ii) optic fibres by Corning, iii) a new technology for CT scanners by General Electric and iv) NutraSweet by Searle, a new type of chemical sweetener. Lynn et al. illustrated the case study histories with circles for the probes and arrows to illustrate the learning between probes (fig. 4.7). The authors conclude that the probes are used as a vehicle for learning, enabling firms to modify and improve their technology in response to customer feedback. The process of probing and learning can therefore be described as an iterative process of multiple experimental applications and feedback loops.

Lynn et al. (1996) describe probing as the introduction of prototypes into a variety of market segments.

According to the authors, experiments into new market domains enable firms to learn about the potential of that market segment for technology or product application. Beforehand, a firm has ideas about potential market opportunities. By probing in these market segments, a firm can find out which applications and market segments are most receptive to the value and functions of the technology. The application of a physical prototype into a market segment elicits response from customers and the feedback enables firms to asses the suitability and limitations of the market segment. Developers may, for example, learn about the problems and needs of customers, find out if they are receptive to alternative technologies and gain an understanding of customer requirements. Thus, probing in a variety of market segments enables companies to learn about markets and communicate with potential customers in different market segments.

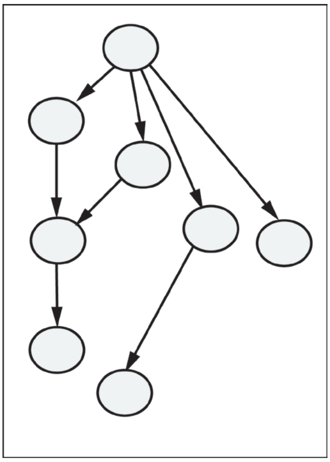

Figure 4.7 Example of probing and learning process of case firms in Lynn et al. (1996)

In addition to probes in different market segments, the case studies of Lynn et al. show successive probes, integrating the feedback and improving the next 'generation' of probe in the same market segment. Successive probing is an iterative process of consecutive approximations, moving closer to a match of technology functions and market requirements as firms learn about the technology in operation and specific customer requirements. Meanwhile, customers learn about the technology and are better able to express their requirements and preferences. As iterative development proceeds and the potential of the market application becomes more analytically predicable, the application can move into a phase of product development.

The concept of probing and learning embodies the characteristics of radical technology application. Additionally, the concept emphasises early applications and the selection of early application over time. Concluding from the literature review, this study finds that the application of radical technologies can be described as a process of probing and learning. Therefore, the concept of probing and learning will be used as a construct to analyse the process by which firms pursue and learn from early applications. Lynn et al. have described four case study firms in an historic analysis. For each firm Lynn et al. describe the probes conducted over time spread over the vertical axis. The learning is represented with connecting arrows between the probes. However, Lynn et al. have not defined the horizontal axis of variation. Additionally, the representation illustrates singular cases. Van de Ven et al. (1999) have also described an historic case study analysis of product development, represented on a time axis. Again, the opposite axis is not defined. Although the illustrations primarily serve to present the case study data, these scholars have not generalised patterns of development. This study believes that there is potential to analyse the process of probing and learning in order to derive general patterns and a more general manner of representation. Considering the above distinction between probes in a variation of markets and a sequence of iterative probes, probing and learning appears to vary in two dimensions: i) variation in market segments to learn from engagements in new markets, ii) variation in the sequence of iterative probes, to learn from successive probes in the same market.

4.6.2 Probing and Learning in Young Technology Based Firms

The concept of probing and learning has been identified as a construct to describe the application of radical technologies. This study has chosen to focus on the young firms of the FC industry, therefore, what particularities can be expected for probing and learning in young technology based firms (YTBF)? In section 3.4, young FC firms where characterised by challenges common to YTB firms: limited resources to allocate, limited legitimacy and developmental in terms of competences and partnerships. These characteristics will determine the degree to which the research findings on probing and learning can be generalized beyond YTB firms. Although Van den Ven et al. (1999) argue that the innovation journey follows a similar pattern for different organizational settings, the case studies described in their work suggest variation. Van de Ven et al. (1999: p362) observed that the young technology based case firm, Qnetics, was strongly influenced by 'liabilities of newness' and a dependence on external resources: *"although Qnetics managers had numerous ideas, they were never able to implement any of them fully because they could not convince customers, alliances, partners and new investors that Qnetics had significant prospect"*. This quote illustrates that for YTB firms, challenges of technology application are largely an issue of legitimacy. Applying the concept of probing and learning to this characteristic of YTB firms, probe applications are expected to play a significant role in the communication and education of customers, partners and investors. In comparison to large established firms, where probes may be developed internally, YTB firms are more likely to publicize and demonstrate their technology in probe applications. YTB firms are under especially severe pressure to develop legitimacy in the formative years of an industry. Aldrich and Fiol (1994) suggest that new industries must also gain legitimacy and that the entrepreneurs of an emerging industry should generate interest and build trust collectively. The probe applications of YTB firms are, therefore, likely to influence the development of new industry legitimacy and trust.

Furthermore, YTB firms are characterised by limited resources and a dependence on external sources of funding. Yet, the realization of probes typically requires costly investments. Consequently, the selection and development of probe applications will, at least partly, depend on the availability of external resources and opportunities for funding. Probing and learning in YTB firms is, therefore, likely to be influenced by external sources of funding. On the other hand, the growth of YTB firms is also characterised by the formation of partnerships, supply chain relations and networks. In this process, probe applications may help to develop legitimacy and thereby help to attract external resources, partners and customers. In comparison to large established firms, probing and learning is more likely to cross the boundaries of YTB firms, in collaboration with customers and partners. Moreover, in contrast to established firms with dedicated marketing departments and personnel, YTB firms are typically challenged to develop market related competences to complement their technological core competences. Scholars argue that many technical start-ups fail due to a lack of marketing skills and a lack of attention to market assessments (e.g. Klofsten 1997, Shanklin and Ryan 1987). If probing is a vehicle for learning then YTB firms are expected to learn and develop market competences through experience in probe applications. Thus, for YTB firms, decisions on which probes to engage in at which point in time are related to multiple interests, such as access to resources, the formation of partnerships and the development of internal competences.

Finally, when a YTB firm's technology is multi-applicable, application decisions are central to the commercialisation of its technology. Whilst large firms are typically established in a particular sector, YTB firms are challenged to select which markets they want to be in at which point in time. As Shanklin and Ryan (1987: p.4) state, *"possibly the ultimate frustration for many high-tech companies is deciding where to begin the commercialisation process. Which products, in fact which industries, should be pursued first becomes a standard question for high-tech firms when their products and processes have multiple applications"*. Lynn et al. (1996) suggest that firms should probe in a series of market experiments to learn which markets have most potential. When there are multiple applications and markets to choose from, firms are expected to engage in various market segments. Probing and learning in YTB firms, is therefore likely to show probe applications in a 'breadth' of market segments, however, this breadth depends on a firm's probing strategy. Concluding, the selection of probes and probing strategy appears to be particularly relevant for YTB firms, as probing and learning is strongly related to firm growth and development.

4.6.3 Latent Questions on Probing and Learning

The concept of probing and learning will be applied in this study as a point of departure for case study research on the application of radical technologies. Lynn et al. (1996) present a preliminary study in which it is observed that a process of probing and learning occurs in successful cases. However, Lynn et al. (1996: p.33) conclude that *"this analysis raises more questions than it puts to rest"*. The authors argue that there is a need for an entirely new product development methodology based on the logic of experimentation, to provide developers with adequate control over the process. Questions for further research, proposed by Lynn et al. include: i) how companies should select their probes, ii) how they can minimize the cost of probing and maximize learning within and between probes and iii) how the companies can compress the time of probing. Thus, questions remain on how 'probing and learning' can be conducted effectively with fewer resources. Considering these 'latent' questions on probing and learning, this study will focus on the selection of probes and the process of learning from probes.

A study on the selection of probe applications and the learning output is relevant because 'probing' is generally a time and resource consuming activity. The realization of probe applications, such as prototype testing, field trials or demonstration projects, require significant investment. Besides, Schager (2000) argues that new technologies for modelling, simulating and prototyping are more of a threat than an opportunity if mismanaged because they are 'expensive exercises', ultimately disconnected from reality. Therefore, Schager (2000: p.6) argues, *"there is an urgent need to explore where and why model building and playful prototyping degenerate into pathological behaviour whose costs consistently outweigh benefits"*. Considering the risks of probing applications, what determines probe effectiveness? Effective probing appears contradictory because experimentation by definition is more prone to failure than regular developments. An effective probe would require minimal cost and time, yet derive maximal learning. Effective probing is not a blind 'trial and error' process, it requires intelligent selection to filter the avoidable mistakes and maximize learning from failure. Lynn et al. provide a number of recommendations. First, firms should design a probe by observing the site or customer prior to probing and observe the effect of the probe. Additionally, Lynn et al. (1996: p.33) suggest that *"adequate control comes from selecting sites where it is possible to specify the who, when and what"*. If effective 'probing' is considered to be a vehicle for developing market insight, further research should consider the selection of probes, the experience gained in probes and the influence of experience gained in probes on subsequent probe decisions.

There is little understanding of how firms select probe applications. When there are multiple applications to choose from, there may be multiple market opportunities to pursue. However, multi-applicability also complicates decision making on which probes to engage in at which point in time. With diverse applications to choose from and limited resources to allocate, the selection of probe applications is particularly challenging for YTB firms. Although Lynn et al. (1996) describe the process of probing in a variety of market experiments, the authors do not address how firms select probe applications from a wide range of possibilities. In the process probing and learning, firms must decide where to probe, with whom to probe, when to probe and which probe applications to develop. This study will address decisions on the pursuit of market segments and the continuation or abortion of probe applications. Thereby, this research will focus on **probe decision making.**

Finally, the preliminary findings by Lynn et al. (1996) require further study to gain more insight into the process of probing and learning and to derive a more general understanding of the concept. Lynn et al. do not describe how probing and learning is similar or different for various firms and innovations. To gain a better understanding of this innovation process it is relevant to compare different strategies of probing and learning, such as probing with a technology and probing with a product or probing in various market segments compared to focused developments. Thus, with a focus on probe decision making, this study aims to identify patterns of probing and learning among firms and to derive a more generally applicable manner to represent the pursuit of probe applications over time.

4.7 Conclusions on Probing and Learning

The application of a new technology, in the phase prior to widespread commercial sales, is characterised by uncertainty, rapid change, variations of technological options and niche markets. A new replacement technology is a case of technological innovation that can disrupt existent supply chains. This type of innovation is radical in terms of the unfamiliarity and required learning for actors external to the technology based firm. Besides technical uncertainties, developers face uncertainties about if and when markets will adopt their technology. The novelty and uncertainties influence the process of technology development and application: the innovation process involves multiple intermediate and parallel developments characterised by experimental logic and continuous learning.

Innovation studies widely acknowledge that success is derived from understanding and meeting customer needs and requirements. The literature review suggests that a firm's experience, competences and customer interaction influences the success of the identifying and developing opportunities. Therefore, among others the following factors are likely to influence the process technology application:

- Experience of the firm's founders, prior to the firm's formation.
- Market competence, a firm's level of market insight and understanding of customer requirements.
- The combination of technology and market related competences: the match between a firm's technology and market needs/customer requirements.
- The interaction between developer and customers.

Multiple factors influence technology application, however, literature provides limited insight into the relative influence of these factors over time.

In the case of radical innovations, customers are typically unfamiliar with the new technology and the impact of the innovation on a customer's capabilities and skills causes resistance to change a perception of risk. This customer unfamiliarity strongly influences the process of technology application. First, due to customer unfamiliarity, development of market insight requires experimental methods of market research. Secondly, marketing radical innovations requires a supply side approach to generate interest, educate and convince prospective customers. Given these challenges and characteristics, 'probing and learning' is described as successful management practice (Lynn et al. 1996). This concept embodies the characteristics of a radical innovation model. Therefore, for the purpose of this study, applications of a new technology will be described and analysed as a process of probing and learning. On the basis of this concept, this study identifies the following constructs for further research:

- Probing: the application of immature versions of a technology into markets.
- Learning: the experience gained in probing and the effect on subsequent probing decisions.

The preliminary research by Lynn et al. calls for further research on probing and learning. Probing into new and unfamiliar markets is often a costly and time consuming undertaking. Yet, there is a limited understanding of how firms manage or should manage this process. This study will focus on the selection of probe application and the influence of experience gained in probes on subsequent decisions. Thereby, this study introduces the following construct:

- **Probe decision making:** the probe applications a firm chooses to pursue over time.

This study will focus on how and why firms select probe applications throughout the process of probing and learning. Through a comparison of probe decision making strategies, patterns of probing and learning may be derived.

Probing in a variety of markets involves decisions on which markets to engage in, at which point in time and whether or not to continue with probes in a market. With a focus on YTB firms, probe decision making is related to the development of firm legitimacy, the formation of partnerships and the development of competences. Given that YTB firms have limited resources to allocate, there is a risk of choosing the 'wrong' probes, and 'wasting resources' on probes that do contribute to profit, learning, or marketing. Besides, probe applications may damage or enhance a firm's legitimacy. To better understand how probing and learning is conducted and managed, this study will focus on probe decision making in YTB firms.

The concept of probing and learning assumes that probing is a vehicle for learning in the innovation process. Van de Ven et al. (1999) find that much further study is necessary in order to explain the innovation process as a learning process. The following chapter will discuss concepts from organisational behaviour and organisational learning to conceptualise probe decision making, the factors that influence probe decision making and learning from probe applications.

Chapter 5: Concepts from Organisational Behaviour

"Theory, as an interpretive lens, profoundly influences our capacity to understand phenomena."

Aldrich and Martinez 2001

5.1 Introduction

Chapter 5 reviews relevant concepts from theory on organisational behaviour and organisational learning to better understand how firms manage the process of technology application. This theoretical perspective complements innovation studies with a more in-depth look at the behaviour of firms: what explains firm behaviour, what drives firms and how do firms learn. The concept of 'probing and learning' has been chosen as a point of departure to describe and analyse the early applications of a new technology. Within this process, this study focuses on 'probe decision making' in YTB firms. Theory can provide an interpretive lens to better understand the factors that influence probe decision making. A number of organisational behaviour and learning concepts are reviewed to further explore the selection of probe applications and the process of learning from probe applications. Thereby, the following research questions are addressed:

- What theory is most suitable to explain the selection of early applications in young technology based firms? (RQ 3a)
- How does experience gained in early applications influence subsequent decisions? (RQ 3b)

First, models of organisational behaviour are discussed to determine which 'theories of the firm' are most suitable to explain the process of probing and learning in FC firms (5.2). A 'dynamic capabilities' perspective is subsequently described and applied to the concept of probing and learning. On the basis of this theoretical perspective, various factors are discussed to explain the selection of probe applications in section 5.3. In the second part of this chapter, concepts of organisational learning are described to better understand the influence of learning from probe applications on subsequent decisions (5.4).

5.2 Firm Behaviour

There are various theoretical perspectives to model the organisational behaviour of firms. These theories differ greatly in their assumptions, objectives and beliefs. Consequently, there are disagreements about why firms differ, what firms should do, what drives firms, what explains decision making etc. Applied to strategic management, these models differ with respect to their rationality of decision making and the degree to which the influences on a firm's behaviour are external or internal to the firm. Theories of the firm either assume economic rationality or normative rationality in decision making and factors that influence the behaviour of the firm are either assumed to be strategic and internal to the firm or institutional and external to the firm. This section describes various paradigms of decision making and discusses the most suitable theory to explain probing and learning and probe decision making in YTB firms.

5.2.1 Paradigms of Decision Making

From a multitude of theoretical streams, rational actor models, institutional models and cultural models of organisational behaviour are described to address the question how firms make strategic decisions. The classic debate that shapes perspectives of strategic decision making is based on two paradigms: rationality and bounded rationality. In rational actor models, firms are assumed to be rationally capable of anticipating the consequences of a decision and evaluating preferred outcomes. From this theoretical perspective, firms are economically rational and carefully analyse and plan decisions to maximize profit. Information is assumed to be available and complete. With this information, the 'best' decisions to serve a firm's interests can be calculated and predicted. The models assume that firm behaviour can be explained by assessing the interests of firms. Rational actor models include economic models, strategic management theories (Porter 1985) and the resource based view of the firm. The resource based view (RBV), focuses on costly-to-copy attributes of the firm as the main driver of competitive advantage (e.g. Amit and Schoemaker 1993, Wernerfelt 1984, Peteraf 1993). From this perspective, firms choose consciously to be different by acquiring unique and sustainable competences and resources.

By contrast, cultural theories and institutional theories of the firm argue that firm behaviour cannot be explained by firm rationale. The theories assume that firms have incomplete information and are rationally bounded. Instead, cultural and institutional models focus on routines and norms in a firm to explain firm behaviour and decision making. Cultural theories of the firm argue that firms have strong internal cultures that influence decision making (e.g. Schein 1988, Swidler 1986). Firm culture is built up historically and engrained in an organisation in the form of traditions, routines and rituals. The routines and norms of a firm's culture evolve. Institutional theorists focus on how the norms, standards and rules of organisational structures become institutionalised (e.g. Scott, 1987; Zucker, 1987). According to institutional theory, firms make normatively rational choices instead of economically rational choices (Oliver 1997).

In addition to the debate on the rationality of decision making, there is a debate on whether the behaviour of a firm is primarily influenced by factors internal or external to the firm. From a RBV, firm decisions are primarily shaped by a firm's resources and the economic context of a firm. By contrast, institutional theorists argue that organisations are embedded in an institutional environment and that firm decisions are shaped by the social context of a firm (e.g. DiMaggio and Powell 1983, Scott 1995). From this perspective, the institutional environment constrains firm behaviour by prescribing the appropriate and legitimate firm behaviour. Three aspects of institutions shape organisational behaviour (Scott 1995): i) regulative aspects such as rules and laws that constrain firm behaviour ii) normative aspects, emphasising normative rules and values and iii) a cognitive pillar of socially constructed rules. The latter implies that the beliefs and expectations of a sector or industry influence firm decisions, causing mimicking behaviour among firms in the industry[1]. Resource dependence models stem from institutional theory, suggesting that a firm's decisions are steered by resource dependent factors external to the firm (e.g. Ulrich and Barney 1984, Pfeffer and Salancik 1978). Resource dependency theory looks into the social context of an organisation and its relationship with the environment. From this perspective, organisations depend on their relations to other organisations in order to survive.

Applied to technology application decisions, rational actor models suggest that firms comprehensively search for unexploited or under-exploited market niches, set goal priorities and choose to optimise and analytically asses alternative strategies and markets for application (Prahalad and Hamel 1991). Critics argue that rational actor models ignore the limits to rationality, the emotions of humans and alternative logic (e.g. March and Olson 1976). It can be argued that in practice decision making is neither entirely rational nor entirely non-rational. According to Eisenhardt and Zbaracki (1992 p.32), whether decision making is rational or boundedly rational is no longer a very controversial debate: *"most scholars believe that people are boundedly rational and that decision making is essentially political and that chance matters"*. Eisenhardt and

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[1] Van den Hoed (2004) reviews institutional theories to explain homogeneous and heterogeneous firm behaviour

Zbaracki suggest that decision making is not only boundedly rational but that politics within organisations is the most powerful mechanism determining decisions. The authors' empirical research supports the existence of cognitive limits to rationality. Eisenhardt and Zbaracki argue that a more realistic view of strategic decision making should be developed that incorporates both the way decision makers feel and behave and the normative concerns of complex organisations into the rational view of decision making. Oliver (1997) also calls for a combination of resource based views and institutional theories to better understand sustainable competitive advantage.

March (2006) summarises the difficulties associated with rational actor models. First, uncertainties resulting from inadequacies of information make future consequences of decisions obscure. Second, complex systems, with a multitude of variables and interactions can be difficult to comprehend analytically. Third, many variables are difficult to measure. Fourth, preferences based on values and wants are often unclear, inconsistent and not entirely rational. Finally, the choices of a firm are often interdependent with the choices of other firms. Particularly in the highly uncertain and dynamic environment that characterises new technology application, scholars argue that rational models alone fail to explain decision making (Bourgeois and Eisenhardt 1998, Eisenhardt 1989). A purely analytic evaluation of alternatives on the basis of inadequate and incomplete information may lead to mistakes, mis-specification and misjudgement. Bourgeois and Eisenhardt (1988) argue that in rapidly changing environments, in which firms are limited in information and resources, the entirely rational analysis of decisions has to be abandoned. The authors observe that in this context of uncertainty and change, firms discover their goals in a process of searching. Additionally, strategy is shaped by adaptation and small increments instead of comprehensively in large steps. Apparently, decision making in rapidly changing environments involves learning and discovery.

5.2.2 An Evolutionary Perspective

'Evolution' refers to building a new form on the basis of prior forms in a process of gradual development. When applying an evolutionary view to decision making, firms go through cycles of learning, in which prior experiences influence subsequent decisions. From an evolutionary perspective, strategic decision making is influenced by environmental conditions, learning and adaptation. Nelson and Winter (1982) have presented influential work on evolutionary theory in the field of economics, based on Darwin's theory of biological evolution[2]. Central to this approach are three fundamental processes: variation, adaptation, and selection and retention. From a variation of routines, firms adapt to changing environments, select the most effective routines to generate competitive advantage. The most successful approaches are retained. This evolutionary approach assumes that environmental factors have a strong influence on organisational behaviour and development. Within evolutionary organisational theory, Hannan and Freeman (1977) introduced 'population ecology' to study the dynamics of populations and how these populations interact with their environment. Scholars have taken a population ecology approach to learn more about how organisations evolve (e.g. Aldrich and Reuf 2006, Aldrich and Martinez 2001). The population ecology approach is applied to study entrepreneurial actions and their outcomes in the creation of new organisational structures. From this approach, a firm's strategy and the environment interact in a recursive continuous process (Low and MacMillan 1988).

An evolutionary sequence of events, constituting a self-reinforcing process, can result in 'path dependence' whereby firms become locked into a trajectory (e.g. Arthur 1988, David 1985). The concept of 'path dependence' stems from this evolutionary perspective where chance and historical events shape the choices of a firm instead of the rationally strategic choices. Theorists departing from such closed evolutionary cycles, assume that strategic choice is not possible. In contrast, Garud and Karnoe (2000: p.25) argue that although firms evolve, entrepreneurs follow a process of 'mindful deviation' and path creation rather than the logic of consequentiality and path dependence: *"path creation, then, is the binding of objects, relevance structures*

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[2] The theory of evolution presented by Darwin (1859) holds that variability exists in the inheritable traits possessed by individual organisms of a species. Since the work of Darwin, evolutionary theory has been applied to a broad range of situations involving change processes.

and time into an overall co-evolutionary process". Similarly, critics of the ecological or Darwinian view of evolution argue that the process of natural selection should be complemented by principles of self-organisation, where the development of an organisation also takes place through targeted activities by the organisation itself (e.g. Kauffman 1993)[3]. So although extreme evolutionary perspectives rule out strategic choice, there appear to be opportunities to apply the evolutionary perspective to more rational perspectives of decision making and firm development. Recently, scholars have proposed an evolutionary version of the RBV to combine these apparently opposing perspectives of strategic decision-making. According to Barney (2001), these evolutionary versions of the RBV are applied to understand how the capabilities of firms change over time and what the implications of those changes are. Makadok (2001) refers to these theories as 'capability building theories'. Teece, Pisano and Shuen (1997) have presented influential theoretical work on the combination of resource based and evolutionary views, described as the 'dynamic capabilities' perspective.

In conclusion, there are different evolutionary views of the firm: i) evolution as an uncontrollable process that takes place external to a firm and ii) an evolutionary process by which firms develop competences and capabilities. In each approach, evolution implies that a new form builds on prior forms in a process of gradual development. The degree to which an evolutionary process results in a 'lock in' and path dependence, limiting strategic choice, depends on how closed the evolutionary model is. Considering the role of learning in innovation and firm growth and the context of uncertainty and continuous change, an evolutionary view appears suitable to describe and analyse the process of probing and learning. It is thereby assumed that firms can 'mindfully' deviate from evolutionary paths in the selection of probe applications.

5.2.3 Applied to Fuel Cell Technology and Probe Decision Making

The applicability of organisational theories to firm behaviour depends on the phenomenon under study and the case at hand. Considering the focus of this study, FC technology and radical innovations have been characterised by a highly dynamic and rapidly changing environment in which firms face a high degree of technical and market uncertainty in decision making. In addition, this study has focused on YTB firms that have been characterised as developmental and limited in resources and legitimacy. What theory of organisational behaviour is most suitable to explain how YTB firms select probe applications? This paragraph discusses the degree to which the selection of probes is a choice variable of the firm.

In a context of uncertainty and rapid change, it is difficult to predict and calculate the outcome and profitability of decisions through rational assessments as information is often inaccurate, unavailable, or obsolete. Technological innovations, replacing established technologies, allow for some comparison with the established technologies and their market requirements. Nevertheless, it is difficult to predict and systematically plan how customers will behave in reaction to the new technology and what external events and developments will constrain or facilitate market adoption. This uncertainty of decision making does not appear to fit rational models. Yet according to Lynn et al. (1996), the process of probing and learning and the selection of probe applications are based on quasi-experimental logic, suggesting some degree of rationality in the selection of probes. Additionally, probing is described as a vehicle for learning and according to Leonard-Barton (1995), firms can only learn from probes through the deliberate and rational integration of the experiences gained. Nevertheless, the process is characterised as experimental, in which outcomes are beyond the control of the firm. The process of probing and learning appears to require a combination of rational choice and bounded rationality models.

Regarding strategic intent, YTB firms are typically driven by the profit potential of commercialising a new technology. This drive appears to suit rational actor models driven by profit maximisation and the economic context, in contrast to institutional models in which firms strive to comply with norms and rules. For example, from an institutional perspective, decisions to pursue environmental technologies are driven by compliance with environmental regulations. However, in the case of YTB firms pursuing the commercialisa-

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[3] This approach refers back to Lamarckian evolution. In contrast to the Darwinian evolution approach, individual efforts during the lifetime of the organisms were considered to be the main mechanism driving species to adapt andevolve.

tion of an environmental technology, firms are more likely to be driven by a moral ambition and commercial potential. It can also be argued that for YTB firms, attaining minimal requirements and compliance is insufficient to survive the period prior to widespread commercial sales. Moreover, in the case of emerging industries, the institutional factors such as regulations, norms and beliefs are still developing. It can, therefore, be argued that these non-institutionalised factors have limited impact on a firm's strategic decision making. Therefore, the strategic intent of YTB firms appears to fit rational actor models in which firms derive their own strategies and strive for optimal decisions. Institutional models appear to be more suitable for studying established firms in mature industries. However, considering the high degrees of uncertainty and the rapidly changing environment, the social context of firms is likely to have some influence on their strategic intent. For example, the emerging industry may provide a social context in which firms share beliefs and follow each other's beliefs to manage the uncertainty of technology application.

Furthermore, YTB firms typically have limited resources to allocate. Given the resource limitations, firms may be driven by opportunities for funding and show opportunistic behaviour, i.e. taking advantage of incentives and opportunities without being conscious of their advantage or disadvantage. From this perspective, the resource dependency model may explain firm behaviour where the firm's resource limitations drive strategic decisions. YTB firms are also in the process of developing competences. It can be argued that the pursuit of applications in order to develop competences is a rational act. Both strategic intent and a degree of opportunistic behaviour are expected to influence probe decision making. Early applications may not be conducted for profit, but to learn and develop valuable competences. The process of learning is likely to influence decision making over time and puts emphasis on how firms develop their competences. An evolutionary view appears suitable to model such developments and their consequences.

The cultural models of the firm, described in paragraph 5.2.1, suggest that firms are shaped and influenced by their history. In the case of YTB firms, this perspective is useful to explain how the experiences and network prior to founding have shaped and constrained a firm. The historic antecedents of YTB firms are expected to influence and shape strategic decision making and the evolution of a firm. On the other hand, it can be argued that due to their relatively young age, YTB firms have limited established routines that standardise decision making. Additionally, the rapidly changing environment does not permit firms to follow a standard procedure for decision making. From this perspective, it can be argued that cultural theories are less suitable for studying immature industries and YTB firms.

Rational actor models appear most suitable for a firm level analysis of 'probe decision making' as a strategic choice variable of the firm. YTB firms, at least partly, decide which probes to pursue, however, their strategies are prone to changes and events in the external environment. YTB firms depend on developments and resources in their external environment such as regulatory support and the emergence of market demand. In addition, the process of probing and learning and firm development appears to require an evolutionary view. A combination of views would best fit probing and learning in the context of a new industry. The dynamic capabilities perspective, introduced by Teece et al. (1997), appears to provide a suitable integration of the RBV and evolutionary models.

5.2.4 Dynamic Capabilities Perspective

A dynamic capabilities perspective is an evolutionary approach that builds on the RBV to explain how firms develop valuable assets in highly volatile environments. Dynamic capabilities scholars argue that in rapidly changing environments, external pressures force firms to build and reconfigure their competences to remain competitive (Teece et al. 1997, Eisenhardt and Martin 2000).

It has been argued that a RBV emphasises the role of unique competences in competitive advantage, but does not explain how firms get to possess these valuable competences (Priem and Butler 2000, Teece at al. 1997). The RBV attempts to fit in the 'perfect market' of an economic perspective, assuming that the resources and information are available to a firm and that there are no unknowns. Therefore, the 'classic'

RBV is not very useful to explain how a firm grows and develops competences to become competitive in a highly volatile and uncertain environment (Eisenhardt and Martin 2000). The dynamic capabilities perspective attempts to address these issues by integrating opposing perspectives: the strategic intent approach (Penrose 1959) of the RBV and the more deterministic approach (Porter 1985) of institutional models in which firms are constrained and shaped by their social context. To model the identification and development of valuable and appropriate competences, Teece et al. (1997) have complemented the RBV with an evolutionary approach in which 'history matters' and external factors are influential. From a dynamic capabilities perspective the competitive advantage of a firm is determined by its:

- Position, the current assets of a firm with respect to its environment.
- Processes, the patterns of current practice and learning.
- Paths, the strategic alternatives open to a firm, given the constraints of previous choices and external influences.

From a dynamic capabilities perspective it is assumed that firms rationally evaluate and select applications with reference to their 'position', i.e. the assets of a firm including resources, competences and capabilities. A firm's position and strategic intent is, however, shaped and constrained by a firm's path, i.e. its history of prior decisions and experiences. In addition, a firm's position is constrained and shaped by its external environment. From this perspective, the history of a firm, its prior experiences and the external environment influence firm decisions and performance, limiting the strategic options a firm can choose and pursue. From a dynamic capabilities perspective, competitive advantage is derived from a firm's level of dynamic capability, described as a firm's capacity to renew, integrate and reconfigure its competences in order to respond to rapidly changing environments. However, there are disagreements on what exactly dynamic capabilities are. Dynamic capabilities have been described as, *"high-performance routines operating inside a firm that are shaped by the processes and positions of the firm* (Teece et al. 1997: p.528). However, Eisenhardt and Martin (2000) argue that in high velocity markets, dynamic capabilities are simple, highly experimental processes with unpredictable outcomes. In this context, the authors argue that firms must learn quickly and renew their competences through experimental actions. Eisenhardt and Martin suggest that in practice, dynamic capabilities are processes such as product development, strategic decision making and the formation of alliances.

It can be argued that the dynamic capabilities perspective, as a combination of theoretical views and a multitude of factors, has become too generic to derive valuable findings on strategic decision making. Besides, the RBV and dynamic capabilities have been criticized as 'vague' and 'tautological' (e.g. Priem and Butler 2000). The perspective is relatively new and it is uncertain how and if the perspective will develop. Nevertheless, the basic presumption that firms have to develop, renew and reconfigure their capabilities to respond to the dynamic environment, appears to be highly suitable to study developmental YTB firms in a volatile, uncertain and rapidly changing environment.

Competences and Capabilities

Before proceeding, the terms common to a dynamic capabilities perspective require clarification. The definitions for resources, capabilities and competences are broadly applied, but their definitions vary. Whatever a firm possesses, tangible or intangible such as machinery, stocks and patents, are referred to as firm assets. To undertake activities, a firm requires resources, which comprise all the assets, the capabilities and competences of a firm (Teece et al. 1997). Dynamic capabilities have been described as the firm's ability to integrate reconfigure and develop resources to achieve new forms of competitive advantage in rapidly changing environments (Teece et al. 1997, Eisenhardt and Martin 2000). The terms competences and capabilities are often confused. The following definitions provide clarification (Oxford Dictionary 2001):

- Capability is defined as the ability to do something.
- Competence is defined as the quality of being competent, i.e., having the necessary skill or knowledge to do something successfully.

With these definitions as the point of departure, capabilities are processes that a firm is able to conduct, such as product development and marketing or a firm's ability to match its technology to markets. Competences are the knowledge and skills necessary to conduct these processes such as technology and market related competences. Prior research has applied various classifications and typologies of capabilities and competences. Teece (1986) provides a useful distinction between core and complementary competences.

- Core competences are the competences that define a firm's fundamental business. It is the knowledge that fundamentally underlies and is required to create a firm's product or service. For example, the core competence of an YTB firm is its technology.
- Complementary competences are the resources and capabilities needed to profit from core competences. Technological innovations require the use of complementary competences of, for example, markets and sales to produce and deliver new products and services. A complementary competence of YTB firms is an understanding of customers and markets.

5.2.5 Probing and Learning from a Dynamic Capability Perspective

Various models of firm behaviour and decision making have been discussed. The dynamic capabilities perspective appears to be most suitable for studying the process of probing and learning in YTB firms. Probing applications for experimenting, prototyping and demonstration are processes by which firms learn and develop new competences in the context of radical innovation. Therefore, considering the above definitions, 'probing and learning' can be viewed as a dynamic capability in rapidly changing and uncertain environments. The dynamic capabilities perspective suggests that probing and learning, as a unique and valuable capability, is a source of competitive advantage. It is assumed that firms strive to be different through their unique capabilities, therefore from this perspective, firms are expected to pursue different probing strategies. Lynn et al. (1996) observed probing and learning as successful management practice in a number of cases. However, further research is necessary to determine if probing and learning, as a dynamic capability, is a source of competitive advantage. Moreover, the study by Lynn et al. did not compare strategies in the same industry. Therefore, to analyse if probing and learning causes differences between firms, further research is required.

The dynamic capabilities perspective is additionally suitable to describe how YTB firms select their probe applications. The perspective suggests that probe decisions are made with reference to a firm's competences and that these competences evolve over time through learning and experience gained in probes. Moreover, from a dynamic capabilities perspective it is assumed that YTB firms are rationally bounded in probe decision making by uncertainties of and a dependence on the external environment. The scope of options for selection is influenced by the firm's prior experiences and constrained and shaped by its external environment. Viewing the process of probing and learning through a dynamic capabilities lens, it is assumed that probe decisions are not only influenced by learning from probes but also by external pressures and events.

5.3 Probe Decision Making

Lynn et al. (1996) have described probing and learning as 'quasi-experimental', i.e. the applications are experimental, but probe decision making does not proceed as a process of blind trial and error. From a dynamic capabilities perspective, it is assumed that firms are able to exert some level of control and conduct assessments on the basis of firm competences and experience gained in probes. This section discusses the factors that may explain the selection of probe applications in YTB firms. The dynamic capabilities perspective suggests that both factors internal and external to the firm influence probe decision making. First firm internal factors and subsequently external factors are addressed.

5.3.1 Firm Internal Factors and Probe Decisions

From a dynamic capabilities perspective, the applications a firm chooses to pursue are partly determined by a firm's position in terms of resources and competences. Evidently, an innovation process can only proceed if a firm has the resources or can acquire the resources to do so (Van de Ven et al. 1999). As Jolly (1997) suggests, mobilizing resources is a key activity to proceed from an idea to demonstrations of the idea in an application context. Application decisions involve resource allocation decisions. A firm's decision to engage in a probe is likely to be influenced by the availability of financial resources or the possibility to obtain these resources from external sources. In addition to financial resources, a firm's competences are likely to influence probe decision making.

Firms are likely to select probes in which they can apply their proprietary technology. However, firms may also have the objective to develop their technological capabilities. Den Hond (1996) describes the relation between a firm's competences and resources and the activities it chooses to pursue. According to Den Hond, firms evaluate whether or not to take on a new activity on the basis of three criteria:

- The complementarity of the new activity with the firm's current resources and activities.
- The existence in the new activity of technological options, to improve a firm's capabilities.
- The appropriability, the degree to which the firm can generate profits from the new activity.

Activities are complementary when they enhance each other's value adding (Den Hond 1996), and fit a firm's core competences (Teece 1986). From a RBV it is assumed that firms derive a business strategy around unique competences, therefore, the strategic fit between a new activity and the firm's strategic objective is an important determinant for whether a firm will engage in a new activity or not. Technological options refer to the potential of new activities to improve a firm's technological capabilities. Den Hond (1996) suggests that in the fluid stage of a technology's life cycle, firms may perceive multiple options for developing and renewing their technological competences. The criterion of appropriability refers to the possibility to profit from the new activity. In an early stage of a technology life cycle, appropriabilty from R&D efforts are, for example, derived from patent protection (Teece 1986). Regarding probe applications, initial revenues may be derived from early adopters or governmental grants. However, the commercial profitability of the market is typically further away, beyond the decision to engage in a probe application. Decisions may, therefore, be based on expectations of market adoption that may contribute towards profit in the future.

The decision criteria suggest that firms seek a fit between their competences and resources and the characteristics and potential of the new activity. Helfat and Lieberman (2002) argue that the difference between the capabilities a firm has and the capabilities a firm needs to enter a particular market, influences the decision to enter that market. This rational decision assumes that firms have an understanding of their proprietary competences and detailed information about the resources required to conduct the new activity. However, scholars suggest that entrepreneurial firms may suffer from cognitive biases, i.e. the firms may be overly optimistic about their capabilities and fail to recognize their level of skill (e.g. Dosi and Lovollo 1997, Kahneman and Lovollo 1993). Additionally, Jonvaic (1982) argues that firms only learn about their cost efficiency subsequent to market entry. From the dynamic capabilities perspective it is assumed that firms base decisions not only on the information they have, but also the need to respond to changes in their environment. The concept of probing and learning is based on experimentation as a vehicle for learning. Firms select probes to further develop their technology through applications in real life probes, similar to the criteria of technological options described above. Additionally, Lynn et al. (1996) assume that probes are conducted to acquire (new) market information.

A dynamic capabilities perspective assumes that a firm's competences and capabilities will at least partly influence the activities a firm chooses to pursue. Which competences and capabilities are likely to be influential? The review of innovation literature in section 4.2 suggests that firms require both technology and market related competences to identify and develop market opportunities.

- Danneels (2002) describes technological competences as the ability to make a certain product. According to Teece et al. (1997), developing technological knowledge enables firms to make things better than the existing state of the art. The technology is the YTB firm's core competence.
- Market related capabilities are those that provide links with customers. Danneels (2002) describes customer competences as the ability to serve certain customers. Developing market related competences enable firms to compete by meeting customer needs, preferences and providing access to customers (Day 1994).

The level of market related and technology related competence is likely to influence the opportunities a firm sees and decides to pursue. However, innovation studies fail to explain the relative influence of the competences on the identification and development of opportunities. Recent studies argue that in rapidly changing environments, the interaction between technology and market-related competence is more important than simply having the competences separately (Song et al. 2005, Nerkar and Roberts 2004). This observation can be explained by a dynamic capabilities perspective: a firm's ability to link technology to markets, as both technology and market develop, is a dynamic capability that may provide competitive advantage. Consequently, the level of a firm's 'linking' ability is likely to influence probe decision making. From a dynamic capabilities perspective, a firm's technological and market related competences largely determine its dynamic capability. Therefore, this study expects that the selection of probes can at least partly be explained by a firm's level of competences and dynamic capability. Furthermore, a dynamic capabilities perspective implies that firms are able to develop, renew, integrate and reconfigure their competences.

Finding the balance between acquiring new knowledge and building on prior knowledge is a classic debate in models based on rational decision making: the decision to explore new possibilities or to exploit prior certainties (March 1991). March introduced the terms exploration and exploitation to distinguish between these two types of activities (table 5.1). Exploration refers to activities such as experimentation, play, flexibility, discovery and innovation that provide new knowledge. Exploitation refers to activities such as refinement, implementation and the optimization of production that builds on prior knowledge and competences. A firm may select a probe on the basis of the competences is has (exploitation) or on basis on the competences it needs (exploration). Thereby, exploration and exploitation represent different modes of learning that will be further discussed in section 5.3 on organisational learning. Smulders (2006) applies the concepts of exploration and exploitation to design and manufacturing and describes a gap between explorative NPD and exploitive manufacturing. Thereby, NPD aims to renew a company's product portfolio and manufacturing aims to exploit the present portfolio. Smulders expects 'prototyping' to be an important interface bridging activity between these explorative and exploitive activities. The experimental nature of probing and learning is likely to involve both exploration and exploitation: probing to explore new markets and acquire new knowledge and probing in prior market segments, building experience from prior probes. A firm may choose to explore new and unfamiliar markets or decide to further develop applications within a prior market. However, the balance between exploration and exploitation is likely to vary over time. Explorative and exploitive activities may explain variable probe decision making behaviour over time.

Tabel 5.1 A comparison of exploration and exploitation. Source: March 1991

	Exploration	Exploitation
Activities	Experiments	Optimisation
Learning	Develop new competences	Build on prior competences

YTB firms are typically founded with a new technology and limited experience in markets. With limited experience, firms are likely to choose applications to explore and learn in an early phase of application. Firms are expected to gain experience through probe applications. A dynamic capabilities perspective suggests that learning from probe applications influences a firm's position, on the basis of which subsequent decisions are made. Therefore, experience gained in probes is likely to influence subsequent probe decisions. With the experience and information gained, a dynamic capabilities perspective suggests that firms may develop the (dynamic) capability to link their technology to markets. Consequently, increasingly decisions are based on the opportunities the firm has identified and the ambition to further exploit these opportunities. Therefore, the level of a firm's competences and capabilities over time is likely to influence the type of probe activity a firm chooses to pursue.

In addition to the influence of competences and capabilities, other firm internal aspects of YTB firms may influence the selection of probe applications. Literature on the emergence of new businesses, suggests that the origins, prior experiences and inherited relations influence the foundation and development of a new firm (e.g. Bhidé 2000, Shane 2000). According to Alvarez and Besenitz (2001), firm specific history at founding is likely to influence the growth of a firm. In line with these scholars, the dynamic capabilities perspective suggests that a firm's position is shaped by its history and prior experiences. Therefore, a firm's history in terms of prior experiences, ambitions and inherited network relations is likely to influence decision making in YTB firms. Furthermore, the norms, culture and beliefs of YTB firms are developing and are likely to be at least partly shaped by the firms' histories prior to founding. Van den Hoed (2004) argues that in addition to a resource and competence fit, firms seek a fit between a new activity and a firm's norms and beliefs. From this perspective, a firm's history and prior experiences influence decision making through cultural norms and beliefs. There are diverse aspects shaping the foundation of firms. Therefore, if decisions are driven by firm history, then firms can be expected to show a diversity of probe decisions and strategies. Likewise, differences are expected if decisions are based primarily on unique competences and capabilities gained through probing.

In conclusion, probe decision making can partly be explained by firm internal factors, including a firm's resources, competences, capabilities and history. The review suggests that firms may select probe applications to exploit the competences a firm has. Additionally, firms may select probe applications to explore and develop new competences. March (1991: p.71) suggests that firms require both exploration and exploitation: *"maintaining the balance between exploration and exploitation is a prime factor in survival and prosperity of firms"*. Explorations can be costly, without direct profit and perhaps, without gaining useful knowledge. On the other hand, exploiting an uncertain market application may cause a firm to become trapped in a market without potential and with a limited set of competences. However, the process of learning suggests the level of a firm's competences and capabilities is likely to influence the probe applications a firm chooses to pursue at a particular time. The influence of firm internal factors on probe decision making is expected to be variable throughout the process of probing and learning. .

5.3.2 External Factors and Probe Decisions

In addition to firm internal factors, there are factors external to the firm which are expected to influence probe decision making. As the paradigms of strategic decision making suggest (5.2), these internal and external factors may provide conflicting explanations. A dynamic capabilities perspective assumes that external factors influence a firm's strategic position. Teece et al. (1997) summarise the external factors that shape a firm's strategic position: i) institutional factors including the regulatory environment ii) market structure factors including the emergence of market demand and iii) structural factors including external linkages and partnerships. This paragraph will also describe the emergence of industry expectations.

Development of Regulatory Environment

Institutional and policy settings are important in enabling and constraining what firms can do. YTB firms, targeting the commercialisation of an environmental technology, typically depend on regulatory support. The availability of government grants is likely to influence the probe applications a firm can pursue. The development of regulations and policies will also influence the development of market demand for a new technology. Additionally, opportunities for market applications are shaped by local regulations. In the case of FC technology, market opportunities have emerged from local emission regulations, as illustrated in section 3.3. As the dynamic capabilities perspective suggests, the options open to a firm are shaped by its regulatory environment. Thereby, the regulatory environment at least partly drives strategic decision making in YTB firms. It can also be argued that although firms depend on how regulations, incentives and support will develop, they can play a role in shaping the institutional environment of a young industry. Nevertheless, the regulatory environment is likely to at least partly enable and constrain firms in probe decision making.

Development of Market Structure

According to Teece et al. (1997: p.522), *"product market position matters but is not all determinative".* Rather, the authors argue that strategy should be formulated with regard to competences and capabilities. However, in the context of radical technology application, when market demand is yet to emerge, firms are in the process of market positioning and this position is typically extremely fragile. In this context, YTB firms largely depend on the emergence of market demand and the adoption decisions of customers to strategically position themselves in a market. The review of technology marketing literature suggests that adoption is strongly related to a customer's perception of the new technology (section 4.3). To some degree YTB firms can stimulate customer interest and market demand through supply side marketing techniques. On the other hand, firms depend on a customer's level of understanding and their ability and willingness to change. Developing customer interest and trust is a matter of firm legitimacy in which firms depend on the degree to which customer's are aware of the company and trust the company. This study will refer to this external factor as 'customer familiarity'. This study argues that 'customer familiarity' influences a firm's path, i.e. the options a firm can choose from for technology application, and constrains a firm's strategic plans and intent. Therefore, probe decision making is expected to be influenced by a customer's familiarity with the technology and the firm.

Development of Partnerships

From a dynamic capabilities perspective, the external linkages of a firm influence the direction of an innovation and how competences and capabilities evolve (Teece et al. 1997, Teece 1996). It can be argued that this influence of external partnerships and relations prevails in the developmental years of a firm. YTB firms have been characterised by a dependence on external stakeholders to acquire resources and develop legitimacy (section 3.5). Opportunities for the formation of partnerships are likely to influence probe decision making. However, partnerships may also constrain and influence a firm's internal decision making process. Particularly in partnerships with large established firms, an YTB firm may find itself in an 'underdog' position in which decisions are driven by stakeholders external to the firm. Similarly, external investors may overrule the strategic intent of a firm. Therefore, partnerships also appear to be a factor that influences the options a firm can choose from and the probe applications it chooses to pursue.

Development of Industry Expectations

As an industry emerges, it develops its own set of socially constructed norms and rules (Scott 1995). Garud and Rappa (1994: p.344) describe how a shared reality emerges in a new industry through a *"process of institutionalisation at the macro level of shared cognition".* In the case of new technologies, the norms and beliefs of a new industry develop through, for example, professional conferences, journals and technical communities where dominant problems and solutions are discussed (Van den Hoed 2004). These socially constructed beliefs and rules dictate 'the way things are done' in an industry. Although the dynamic capabilities perspective does not describe the influence of this external factor, this study expects that the formation of industry beliefs and norms influences a firm's perceived set of options to choose from. With a focus on the beliefs and expectations for technology application, this study will refer to this external factor as 'industry expectations'.

It can be argued that in a young industry, expectations about potential markets and the timeline for market adoption will emerge before the formation of rules, norms and routines that characterise established industries. In the context of uncertainty, firms may choose to follow such industry expectations and mimic best practices rather than pursue decisions driven by internally derived beliefs and strategies. In the case of an industry in its formative years, Aldrich and Fiol (1994) suggest that collective marketing and learning should be prevalent above competition to build trust in a new industry. Irrespective of the desirability of a collective process, the influence of industry expectations implies that firms will follow each other and show homogeneous behaviour. Industry expectations are expected to at least partly influence the selection of probe applications in an emerging industry.

In the case of radical technologies, the highly uncertain environment is influence probe decision making. Regulatory development, industry expectations, customer familiarity, the emergence of market demand and partnership formations are expected to influence the alternatives open to a firm. Venkatarm and Van de Ven (1999) present a model of how the relative influence of managerial choice and environmental determinism directs the evolution of a firm. Eventually, environmental disturbances are expected to decrease as customers and investors become familiar with the firm and the regulatory environment takes shape. However, Van de Ven et al. (1999: p.363) suggest, *"it is through the adolescent stage that start ups are most vulnerable to environmental disturbances".* According to the authors, it is in this period that environmental selection dominates managerial choice.

In conclusion, a multitude of internal and external factors influence probe decision making in YTB firms. The role of these factors throughout a company's process of probing and learning is expected to change. Nevertheless, it is not apparent which factors are most important in explaining the selection of probe applications over time. This problem provides a theoretical opportunity for further study.

5.4 Organisational Learning in the Innovation Process

The process of innovation can be viewed as a learning process (e.g. Buijs 1984, Van de Ven et al. 1999). There is a reciprocal relationship between innovation and the development of a firm's competences. In a study of new product success and failure, Maidique and Zirger (1985: p.299) found that firms learn through product innovation, *"in which commercial successes and failures alternate in an irregular pattern of learning and unlearning".* Similarly, Danneels (2002) argues that product innovation can be used as a vehicle for organisational learning. According to McKee (1992), different types of organisational learning skills are involved in incremental and radical innovations. In section 4.5 radical innovations were characterised by a process of experimentation, adaptation and 'trial and error', in which firms learn and benefit from failure. The process of probing has been described as a vehicle for learning about radical innovations, whereby firms learn through 'probing' their technology in market applications. Section 5.3 suggests that firms engage in probe applications to gain new competences and to further develop prior competences through explorative and exploitive applications respectively. Concepts from theories on organisational learning help to understand how firms gain experience from probe applications and the consequences for subsequent decisions. This section will describe a number of organisational learning concepts and apply the concepts to the process of probing and learning.

5.4.1 Learning by Discovery and Adaptive Cycles of Learning

To conceptualise the problem of decision making in the absence of concrete information, scholars have applied adaptive processes of organisational learning to the innovation process (e.g. Levitt and March 1988, Cohen and Levinthal 1990). March (2006) summarises three theories of adaptive processes based on the reaction to feedback. First, experiential learning, the outcomes associated with previous uses, being successful or not, influences the tendency to continue or abort the procedure respectively. Second, a process of variation and selection in which the procedures followed are unchanged, but the procedures of successful users are more likely to be reproduced than the procedures of less successful users. Third, a process of learning from others in which successful procedures are reproduced by other firms. The innovation process in highly novel and uncertain situations is typically based on the first theory: an experiential adaptive learning process of 'trial and error' and experiments in practice (Van de Ven et al. 1999). Kolb (1974) introduced an experiential learning model. This model emphasises the role that experience plays in the learning behaviour of individuals and is based on the process of adaptation. Thereby the theory differentiates from cognitive theories of the learning process where learning is assumed to follow rational and analytic decisions. Carlson et al. (1976) applied the experiential learning model to the innovation process, resulting in the following four phases:

1. Concrete experience, a divergent phase in which experience is gained and alternatives are considered.
2. Reflective observation, an assimilating phase in which the alternatives are compared.
3. Abstract conceptualisation, a convergent phase in which a selection is made of alternatives.
4. Active experimentation, a phase of accommodation in which the selected experiment is realised and new goals are formulated.

With the experience gained in the active experimentation phase, the learning cycle continues with the first phase of concrete experience. The product innovation model described in section 4.2 is based on this learning model and incorporates the divergent and convergent phases of learning.

The experiential learning model suggests that experience gained in applications influences subsequent decisions. To understand the consequences of experience gained on subsequent decisions, a focus on the internal loop between actions and outcomes is useful. This type of learning has been described as a process of trial and error: firms undertake a course of action, there is some outcome response from the environment, firms interpret and evaluate the response and then adapt their course of action to increase the propensity of the desired response (March and Olson 1976). The theory of experiential learning posits that outcomes associated with success are more likely to survive and replicate then outcomes associated with failures. Based on the process of adaptive learning, Van den Ven et al. (1999) describe a learning model to conceptualise decisions in an innovation journey (fig. 5.1). The model assumes that people are adaptively rational. An innovator's decision and the outcomes are related as follows: a course of action is chosen with the intention of achieving a positive outcome. If a positive outcome is experienced, the course of action will be continued. If the outcome is negative, the course of action will be changed. Examples of positive outcomes are successful technical accomplishments or positive feedback from customers. Examples of negative outcomes are technical failures or customers rejecting the innovation. External to this internal loop, events in the environment of a firm disrupt the adaptive learning process by influencing the perceived outcome of an action. External interventions are described as environmental incidents that occur beyond the control of the innovator, such as the shift of priorities in external groups, new information about competitors, natural or political news. Additionally, resource controllers from top management may intervene in decision making in response to positive and negative outcome. Through the cycle of adaptive learning, a firm learns how to perform better and better. However, this adaptive model of learning does not incorporate learning from failure: changing the course of action will reset the learning clock back to zero.

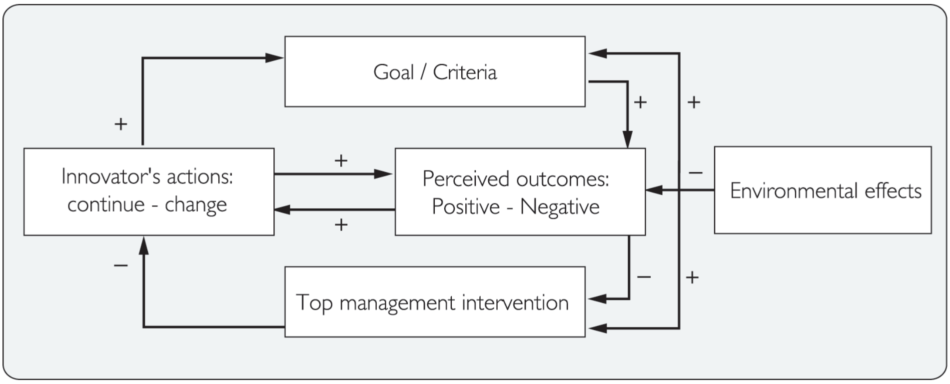

Figure 5.1 Adaptive learning cycle. Source: Van de Ven et al. 1999

The theory of adaptive learning has been criticised as inadequate to explain explorative activities. Adaptation cycles are biased against uncertain and risky alternatives that are more likely to result in negative outcomes. Experimental and explorative activities will be phased out in adaptive cycles based on positive outcomes. Exploitation is favoured and will ultimately eliminate exploration. However, according to Argote (1999) mechanisms such as repeated practice and mistakes contribute significantly to learning. Therefore, March (2006) argues that if a model is purely adaptive, it is not suitable to explain exploration, pursuit of new strategies and learning from failure. Considering that exploration and experimentation characterise radical innovation in YTB firms, the adaptive model appears inappropriate to understand probing and learning.

Apparently a different type of learning takes place in explorative activities. On the basis of an in-depth case study of innovation developments, Van de Ven et al. (1999) argue that adaptive learning does not occur during the beginning period of innovation development. Rather, action and outcome events follow a chaotic pattern and innovators learn by discovery. Learning from discovery is different from adaptive learning: it is an expanding and diverging process of discovering possible alternatives, whilst adaptive learning is a narrowing and converging process. In contrast to adaptive learning, action and outcome events follow a chaotic pattern and are not directly related. In such a chaotic system, a model of learning is dynamic, non-linear and sensitive to initial conditions. Huber (1991) observes a similar type of learning in the early period of innovation: learning through a process of searching and noticing instead of adaptive learning. In comparison to the adaptive process of learning, the concept of learning by discovery suggests that external events, ideas, and expectations have more influence on decision making. Thereby, the concept of learning by discovery is applicable to the dynamic capabilities perspective: the renewal and reconfiguration of firm competences in response to changes in the environment.

Van de Ven et al. (1999) argue that before adaptive learning cycles can occur, firms must set their preferences, goals and plans through learning by discovery. From this perspective, learning by discovery, or the exploration of alternatives, is a necessary condition for adaptive learning. The authors suggest that the transition from chaotic to orderly and adaptive learning patterns occur when external disturbances subside and actions and outcomes become more tightly linked. Considering that YTB firms are particularly sensitive to external pressure and events it can be argued that the transition from more chaotic to stable learning will take longer than for established firms. Applied to innovation models, the difference between learning by discovery and adaptive learning cycles is reflected in the difference between the more experimental radical innovation models and the more analytic and iterative NPD models (4.6). Thereby, product development is likely to follow an experimental phase of probe applications once the uncertainty of technology application has been reduced to a manageable level.

5.4.2 Organisational Learning Applied to Probing and Learning

The previous paragraphs have addressed two types of learning. Applied to probe decision making a firm can decide to probe in a new market and decide to continue in a prior market. These decisions are related to two different types of learning: i) explorative learning about new markets and ii) exploitive learning, building forth on prior market engagements. These decisions can be represented along two axes: a variation of new markets on the horizontal axis and time on the vertical axis to represent iterative learning in the same market (fig. 5.2).

The application of learning by discovery to the concept of probing and learning, suggests that in an early phase of probing firms will primarily explore new markets. In this divergent process of probing in alternative markets, there are likely to be ‘failures’. Explorations are notorious for their low success rates. The value of these explorations is likely to lie beyond their immediate outcome. March (2006) suggest that for exploratory activities to endure, the positive and negative outcome of a single exploratory activity should not be discriminated crudely. Instead the attributes from various explorative activities are intermixed with attributes from explorative activities, enabling ‘effective’ learning irrespective of the success or failure of a single explorative probe. According to March (2006), the outcome of explorative applications can be used to make subsequent decisions through 'feedback-based adaptive intelligence'. Applied to probing and learning, this concept suggests that after initial explorative probes, there is a transitional period in which experience is gained in both explorative probes in new markets and exploitive probes in prior markets.

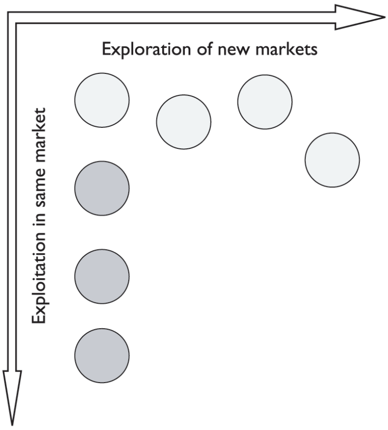

Figure 5.2 Two models of probing and learning, exploration and exploitation

On the basis of organisational learning concepts described by Van de Ven et al. (1999) and March (1991, 2006), probe decision making is expected to pass through three phases of organisational learning: i) learning by discovery ii) a transitional phase of feedback adaptive intelligence and iii) adaptive learning. Applying these organisational learning concepts to the process of probing and learning, three phases are proposed:

1. Exploration: primarily probing applications in new markets.
2. Experimentation: probing applications in new markets and the development of applications in prior markets.
3. Exploitation: adaptive development of applications in a select number of markets.

The experimental phase suggests that experience from various explorative probes contributes to subsequent decisions. These explorative probe applications may 'fail' and not find continuation, yet the experience gained may 'cross-over' to probe applications in other markets. This study suggests that a process of 'cross-over learning' occurs during an experimentation phase of probing and learning. Thereby, technical cross-over learning or market cross-over learning may occur for the development of technology and market related competences respectively. The concept of cross-over learning may help to explain how firms can learn effectively from experimenting in various market segments.

5.4.3 Experience from Probing

Firms gain experience in probe applications. To understand the impact of this experience on subsequent probe decisions, organisational models of learning have been described. However, learning from probes is not evident: it requires effort to integrate knowledge and information into the competence base of a firm, whilst firms tend to ignore failure (Leonard-Barton 1995). Schager (2000), describes 'dishonest prototyping': how people avoid what their models are saying or manipulate models and prototypes to convey a different message. Schager argues that dishonest prototyping results in self-deception and misrepresentation instead of competence development. An additional problem in understanding the impact of experience on subsequent decisions is measuring competence development. Competence development is difficult to measure. In this paragraph the 'value' of probe experience and measures of competence development are discussed.

From a dynamic capabilities perspective, the most 'valuable' capabilities are those that come about over time through a gradual evolutionary process (Teece et al.1997). Through experience with applications and markets, firms develop complementary competences that enable a firm to manufacture, market and distribute its products. Barnett and Hansen (1996) similarly find that a firm's complementary competences develop as a result of participation in market applications. But how unique are these competences? Complementary competences may be necessary, but not particularly unique. From the theoretical perspective of an 'accumulation process', a firm's complementary competences are inherently unique and inimitable because imitators would need to replicate the entire learning path to achieve the same competences and capabilities (e.g Dierickx and Cool 1989). On the contrary, Eisenhardt and Martin (2000) argue that although firms travel unique paths of experimentation and development, firms can end up in the same position because the paths are shaped by well known learning mechanisms. From this perspective, firms may choose highly different probing and learning processes and end up in the same markets. Instead, Eisenhardt and Martin argue that sources of competitive advantage are found in the details, generated through situation specific knowledge. Thereby, a distinction is made between specific experience of a particular market and experience generally applicable to other markets. Furthermore, is a firm's own experience more valuable than the experience of other firms in the industry or the expectations and beliefs of the industry? A distinction has been made between a firm's own experience and the shared beliefs of an industry (section 5.3). Ingman and Baum (1997) argue that there are risks associated with building on a firm's own experience because firms may fall into 'competency traps' and fail to compete in a changing environment. These authors suggest that learning from the experience of others, such as competitors in the industry, is just as, if not more valuable than experiences gained by the individual firm. There are conflicting views on the value of experience gained in probe applications. This discussion on the competitive advantage of probing and learning requires further research.

A recurring problem in studies from a RBV and (dynamic) capabilities perspective is how to measure competences and capabilities and particularly, how to measure the development of these competences. Few methods have been proposed. Branzei and Vertinsky (2006) conducted a survey in which firms were asked to scale and value their competences. Dutta (1999) measures capabilities as the efficiency by which a firm uses the inputs available to the firm and converts them into what ever output it desires. These measures of competence and capability do not address their development. Knudsen (2005) addresses technological competence development and measures both the level and the change in technological competence level with patent data. For the purpose of this study, these measures are unsuitable. In this study, the source of competence development is the experience gained in probes. Moreover, this study is focused on the influence of experience on subsequent decision making. Therefore, measures of experience will be considered and to understand what the experience is, primarily qualitative measures will be used. Different types of experience will be identified and the influence of this experience on a firm's subsequent decisions will be observed. Quantitative measures of experience can be derived from data on the realization of applications, such as the number of probe applications realized or the number of hours of experience in practice. In a comparison between firms, these measures provide an indication of a firm's experience in market applications relative to other firms.

5.5 Conclusions Probe Decision Making

A dynamic capabilities perspective provides a suitable 'lens' to study the concept of probing and learning and explain probe decision making. The perspective is applicable to: i) decision making under uncertainty and limited information ii) a process of learning, iii) dynamically changing environments and iv) firm level analysis. From this perspective, it is assumed that the selection of probes is at least partly a decision variable of a firm. This rationality is, however, bounded by prior experiences and influenced by factors external to the firm. From a dynamic capabilities perspective, probe decisions are made under influence of multiple firm internal and external factors. The role of these factors in a firm's probing and learning process is expected to change over time, however, the dynamic capabilities perspective does not suggest which factors are most important in driving probe decision making at which point in time.

An objective of this research is to provide an overview of these factors and how their relative influences change over time. Explanatory factors of probe decision making internal to the firm include a firm's resources, history, and technological and market related competences. External to the firm, the development of industry expectations, the regulatory environment, partnership and customer familiarity are likely to influence the strategic alternatives open to the firm. The relative influence of these factors represents the conflicting models on strategic decision making. Probe decision making may be explained by:

- Strategic intent, competitive positioning on the basis of a firm's unique competences and capabilities.
- The institutional environment, following the expectations and beliefs of an industry.
- Opportunistic behaviour, the pursuit of resource and partnership opportunities primarily for immediate benefit, irrespective of strategic intent.

From a dynamic capabilities perspective, probing and learning is argued to represent a firm's (dynamic) capability to renew and reconfigure competences in response to the rapidly changing and uncertain environment of radical innovations. However, it is not clear if competitive advantage can be derived from the process of probing and learning or from the experience gained in probes. This problem also provides a topic for further discussion.

Finally, concepts from organisational learning appear to be useful to describe how probing and learning proceeds over time. A firm can decide to engage in two models of learning: i) explorative, learning about new markets and ii) exploitive, learning more about a specific market. The application of learning models to the innovation process suggests that probing and learning will go through a phase of learning by discovery and subsequently make a transition to a phase of adaptive learning. From this perspective, the process of probing and learning will make a transition from a highly experimental phase to the more focused iterative developments of product development cycles.

Chapter 6: Conceptual Model and Research Methodology

6.1 Introduction

In chapter 6, findings from the previous chapters will be brought together to describe and conceptualise the process of radical technology application. Fuel cell technology and the phase of applications prior to widespread commercial sales have been introduced and characterised in chapters 2 and 3, clarifying the challenges of FC technology application. Literature on innovation processes and management practices has been reviewed in chapter 4, identifying the concept of probing and learning to describe and analyse technology applications. With this concept as the point of departure, this study has focused on better understanding probe decision making and patterns of probing and learning. Chapter five introduced theoretical constructs that may explain probe decision making and concepts from organisational learning to better understand the process of probing and learning. The previous chapters have enabled the further specification of the research problem and the phenomenon under study. In addition, relevant theoretical constructs have been identified. As Eisenhardt (1989) suggests, the findings will be brought together and conceptualised in preparation of the case study research. On the basis of prior findings this chapter will conceptualise the process of radical technology application by YTB firms.

The objective of conceptualisation is to develop a mental configuration of a phenomenon to, on the one hand, extend and integrate existent theory, and on the other hand to help structure and analyse the empirical domain. This chapter first describes the construct central to this research: probe decision making (6.2). Taking the literature on ‘probing and learning’ and the theory of organisational learning as points of departure, a descriptive model of probing and learning (6.3) is proposed. Sections 6.4 to 6.6 discuss the theoretical constructs that are expected to drive probe decision making, on the basis of which a conceptual model is presented in section 6.7. The conceptual model leads to propositions and new research questions on the selection of early market applications over time. Finally, in section 6.9 the case study research design is described.

Constructs and Models

Conceptualising is the act of forming a mental configuration or an abstract idea about a phenomenon. Theoretical ‘constructs’ describe these abstract ideas (Bacharach 1989). Eisenhardt (1989) suggests the identification of relevant theoretical constructs prior to case study research enables more accurate measures of the phenomenon under study. In this research, the phenomenon under study is the process of probing and learning. Chapter 4 concludes that this study will focus on *probe decision making* to better understand how and why firms select probe applications throughout the process of probing and learning. In the following paragraph this construct will be further defined. Probe decision making is described as the ‘central construct’.

The previous theoretical chapter concludes that a multitude of factors may influence the selection of probe applications. Various factors have been discussed that need to be translated to 'explanatory constructs'. An objective of study could be to provide an overview of all the factors that may influence probe decision making. However, this study finds that although innovation studies and a dynamic capabilities perspective point to a multitude of factors, they fail to explain the relative influence of these factors over time. Therefore, this study will focus on the relationship between a selection of explanatory constructs and probe decision making over time. The selection of explanatory constructs is based on three criteria:

- The constructs are important determinants in the process of new technology application,
- The constructs are supported by the empirical data,
- There is a limited understanding of the construct or its relations.

The clarity of constructs is critical to the validity of research findings. According to Bacharach (1989), constructs should have convergent validity and discriminant validity. Kerlinger (1973: p.463) explains: *"in determining convergent validity the theorist must confirm that evidence from different sources gathered in different ways all indicate the same or similar meaning of the construct… In determining discriminant validity, the theorist must confirm that one can empirically differentiate the construct from other constructs that may be similar".* This study has compared and contrasted the proposed constructs with similar constructs in literature. Additionally, the constructs have evolved by looking back and forth between literature and the case study data.

Furthermore, the relationship between the central construct of probe decision making and explanatory constructs will be described in propositions (6.8). Propositions are predictive statements that should be defendable yet opposable, enabling scientific discussion on topics that are not well understood. Propositions are suitable to answer questions of how, when and why. Propositions communicate a relation between constructs and help to integrate and extend theory. Additionally, propositions are useful to focus and organize research. Where theory fails to support the formulation of propositions, further specified research questions help to focus the study of construct relationships in case study research.

6.2 Definition of the Central Construct

Probing: *1. to physically explore or examine, 2. to investigate closely, 3. investigation into unfamiliar matters, 4. an exploratory action to investigate or obtain information.*

The central construct of this study revolves around the applications of a radical technology prior to widespread commercial sales. It has been recognised that applications of new technologies start in small niche markets and go through numerous niche markets prior to large scale commercial markets However, prior to the emergence of commercial niche markets, this study expects to find probe applications. Probe applications are not self sustaining and function as a vehicle for developing the technology, product and market. Innovation scholars characterise radical innovation as a process of experimentation and learning, and recommend early applications of a new technology in real world settings (section 4.5). Lynn et al. (1996) observed this process in successful cases of new technology application, introducing the term 'probing and learning' to describe series of market experimentations, with early immature versions of a product into a variety of market segments. Eisenhardt and Martin (2000) have similarly observed that in high-velocity environments, firms are able to learn quickly through experimental activities such as prototyping and simulations. Experimentation is observed to be a more effective decision making process in this context (Eisenhardt 1989, Judge and Miller 1991). Thereby, *experimentation is defined as a new course of action adopted without being sure of the outcome* (Oxford Dictionary 2001).

Experimental applications include prototypes, demonstration projects and field trials and are conducted for various reasons. Demonstration projects generate awareness and are argued to reduce uncertainty by testing the technology and learning about the drivers and barriers that the new technology will face (Harborne 2005). Larger demonstration projects enable new technologies to be further developed and tested in a protected environment in which commercial considerations do not apply (Kemp 1998). In some NPD models, prototypes, simulations and 'proof of concepts' are an integral part of the development process. The varieties of experimental techniques show a commonality: early applications of the technology and learning from the feedback and experience gained. Thus, the literature review in chapter 4 suggests that various terms are used to describe similar concepts of early and experimental applications of a new technology.

6.2.1 Selection of Central Construct

From the various terms, 'probe decision making' is chosen as the central construct for this study. This construct is shortened to 'probe decisions' where necessary. The following definitions are applied:

- Probe(s): the application(s) of immature versions of a technology into market(s)
- Probe decision making: the 'probes' a firm chooses to pursue over time
- Probing: the act of realising probes
- Probing process: the series of probing, learning and probing again

The selection of this construct is based on the following assumptions. It is assumed that there are multiple options to choose from, therefore, firms face decisions on which markets to engage in, which to pursue and which to leave. It is also assumed that the application of a radical innovation involves a lengthy process of early applications. Finally, it is assumed that a firm level perspective is necessary to better understand how YTB firms manage technology applications. This paragraph compares the similarities and differences between 'probe decision making' and similar constructs of early and experimental applications. Table 6.1 summarises the constructs and the literature references reviewed in section 4.5. Probe decision making takes place within the process of 'probing and learning', whereby the first emphasises the decisions to engage or pursue a probe and the latter emphasises the process of learning from probe applications over time.

The construct 'probe decision making' is suitable for a firm level analysis of strategic decisions on early applications. By contrast, concept of niche market accumulation in strategic management literature primarily addresses the meso level developments of technological trajectories. Furthermore, these scholars study shifts of technological trajectories that may involve numerous innovation processes whilst this study focuses on a single technological innovation. In contrast to the concept of niche market accumulation, demonstration projects and 'proof of concept' refer to the development and analysis of single projects. Demonstration projects, proof of concept and prototyping are activities conducted within a probing process and belong to the scope of probes to choose form. Such activities are also conducted in a New Product Development (NPD) process. Although 'probe decisions' and decisions in NPD both address the generation and development of innovations, the constructs differ in their timing and approach. An NPD process typically begins after the experimental activities, when the uncertainty of an innovation is reduced to a manageable level. The NPD process is analysis driven and is geared towards the 'launch' of a new product. By contrast, the probing process is characterised by uncertainty and requires a more experimental logic in decision making. Additionally, the probing process involves multiple successive and modified launches to apply a new technology or product. The concept of experimentation is based on experimental logic in which alternatives are tried out and tested. Experimentation is similar to the concept of probing and learning, however, with an emphasis on the pursuit of new applications the process of learning and iterative development are not addressed. The probing process is similar to a bricolage approach, considering the process of several steps and modifications on the basis of feedback. However, the bricolage approach typically revolves around a single product and puts emphasis on gaining input from various actors instead of various different market alternatives. Learning from a diversity of market probes is central to probing and learning with technological innovations.

Table 6.1: Comparison of the 'probe decision making' with similar constructs

Concepts	Definition	Similarities / differences to probe decision making
Probe decision making	The 'probes' a firm chooses to pursue over time. Probes: applications of immature versions of a technology into markets	Firm level decisions. on early applications prior to widespread commercial sales
Probing and learning	A series of market experimentations, with early immature versions of a product into a variety of market segments, as a vehicle for learning (Lynn 1996)	Puts emphasis on learning. Terms may give the suggestion of learning through trial and error. Concerns firm level activities.
Experimentation	Experimental actions by creating multiple alternatives. Early testing characterised by parallel considerations and often partial implementation of multiple options. Learning by doing (Pisano 1994, Eisenhardt 2000)	Describes a phase of pre-commercial application characterised by a breadth of activity. A phase in the probing process.
Niche market acumulation	The technology is applied to a number of different 'application domains' until the performance of the technology improves to reach a point where it makes sense to use it more extensively (Geels 2002)	Higher level perspective of technology development process. Suggests markets are self sustaining. Probes are not, although niche markets are sought in the process of probing
Strategic niche management	The creation, development and controlled phase out of protected spaces for the development and use of promising technologies by means of experimentation with the aim of learning (Kemp 1996)	Describes a particular type of pre-commercial application for learning. Field of research is particularly concerned with decisions and learning at institutional level.
Demonstration project	Demonstrations of technology and products, and learning from the outcomes (Harborne 2005)	Puts emphasis on function of demonstration. Often concerns subsidised projects by consortia. A part of the probing process
Demonstration phase	Stage of demonstrating a new technology in marketable products or processes, associated with product development (Jolly 1997)	Seen as a stage in new product development process. Part of probing process
Proof of concept	Part of the development process, justifying continuing interest by potential buyers and investors (Garfinkel 2003)	Puts emphasis on the function of proofing. An activity within the probing process
Prototyping	Creative improvisation through modelling, simulation and prototyping (Schager 1999)	Prototyping represents probe activities within the probing process. Simulations and modelling do not take the form of physical applications
Bricolage	A process of moving ahead on the basis of small feedback signals, accumulating inputs from relevant actors (Garud and Karnoe 2003)	Technology entrepreneurship perspective, input from diverse actors instead of diverse market alternatives
NPD	A multi phase linear process within the innovation process (Cooper 1994)	After early probing. Analysis driven, towards the launch of a product versus experimental logic and multiple launches. of probes

There are various constructs to describe and analyse early applications at different levels of analysis and from different perspectives. The concepts of probing and learning (Lynn 1996) and bricolage (Garud and Karnoe 2003) have been observed in cases of successful technology application. Scholars have described the occurrence of niche market accumulation and value of demonstration projects (Kemp 1998, Geels 2002). However, prior research has not addressed the firm level selection of experimental applications in the innovation process, such as decisions on which probes to pursue, which probes to continue and which to abort. The construct probe decision making is significantly different from other constructs, yet there is sufficient evidence that indicates the same meaning, thereby, confirming the validity of this construct. The following paragraph will further define this central construct and describe a model of the probing process.

6.2.2 Characteristics of the Probing Process

Probe decision making has been defined as the probes a firm chooses to pursue over time. Literature does not provide a general model of probing or a model to explain probe decisions. On the basis of findings from chapter 4 and 5, characteristics of a probing process are proposed.

Probe decision making is based on the concept of probing and learning, introduced by Lynn et al. (1996). The principles of probing and learning can be described as: i) engagement in a variation of new markets and ii) feedback and learning for further development. This study applies concepts from organisational learning theory, described in section 5.4, to this process of probing and learning. From this perspective, probing in a variation of new market segments can be described as process of learning by discovery (Van de Ven et al. 1999). This process is characterised as a divergent process. As firms learn and gain experience in probes, a firm's probe activities are expected to converge to a select number of market segments through a process of adaptive learning (March and Olson 1976). Probing and learning involves multiple iterations and feedback loops. Throughout this process, probe decision making can be characterised by the following decisions: i) the variation of new probes a firm decides to engage in and ii) the probes a firm decides to continue.

Variation of Market Probes

When there are diverse market applications to choose from, this study expects firms to pursue probes in a variety of market segments. Firms can decide to pursue probes in a variable breadth of market segments over time. This study expects that this breadth of market segments is related to different phases of probing and learning. What phases of probing and learning can be identified? On the basis of the explorative and exploitive learning modes introduced by March (1991), this study suggests that phases of probing can be characterised by: i) exploration, activities that lead to the addition of new resources and ii) exploitation, the use and further development of existing competences. Applied to the process of probing, explorative probes are conducted in new markets to gain new competences and exploitive probes are conducted in line with prior probes to further develop existent competences. Similarly, Leonard-Barton (1995) categorises experiments on the basis of learning and competence development. This author suggests that experimentation and prototyping create two kinds of capabilities: a diverse portfolio of technological options or a virtuous cycle of innovation optimisation. Defining phases in terms of learning and development, Karlstrom and Sandén (2004) identify two phases: first, demonstration projects in an experimental phase to maximize learning and second, demonstration projects in the diffusion phase to enable market growth. The experimental phase is characterised by experimenting with multiple applications. The development phase is characterised by focused development towards market growth.

Firms may conduct experimental probes to explore new alternative courses of action in a divergent process of learning. The opposite of experimenting in new market segments is exploitation and optimisation, implying focus. Exploitive probes refer to the development of an application through linear iterative development cycles. Applying the concepts of learning by discovery and adaptive learning, exploration is conceptualised as a divergent process of learning by discovery and exportation is conceptualised as a convergent process of adaptive learning for iterative development.

Continuation of Probes

In addition to decisions on which probes to engage in, the probing process involves decisions on which probes to continue with. This study will refer to this continuation as a 'probe path'. Probes may be one-off, but most probes are expected to find some form of continuation. Probes may be continued in a linear path of development, i.e. a next generation of the same application in the same market. Section 5.4.2 suggests that experience gained in probes may cross-over to other probe applications. Furthermore, probes may lay dormant until they are picked up in later years. A commonality of these different modes of continuation is that lessons from prior probes are used to develop the next probe. The output from one probe is used as the input for the next.

Linear probe paths are characterised by iterative cycles of optimisation, refining versions of the application. Leonard-Barton (1989) describes this type of development as an iterative process of alignment between technology and customer requirements. This process has been characterised by exploitation, in which firms build on the experience gained in prior probes, and adaptive learning cycles: if the outcome is positive, the path is continued, if the outcome is negative, firms will abort or change that path of activity. Nevertheless, the concepts of intelligent failure (Leonard-Barton 1995) and feedback adaptive intelligence (March 2006) suggest that firms can also learn from aborted paths. This study expects that the effectiveness of probing and learning depends on a firm's ability to transfer experiences in aborted probe paths to other probes. This transfer of experience will be referred to as 'cross over learning'. This study expects that in the case of a replacement technology, a 'technology platform' enables cross over learning.

Probe Objectives

Probe applications have been characterised as experimental and a vehicle for learning. High technology marketing literature suggests that probes are also pursued for other reasons (section 4.3). The characterisation of Young FC firms suggests that probes are conducted to develop legitimacy and access external resources. Probes are expected to be conducted for a variety of functions and objectives such as generating awareness, demonstration, validation and the education of customers. Over time, the motivations for engaging in probe applications are expected to change. Moreover, firms are expected to set different priorities. For example, a firm may choose to invest in the development of demonstrations, whilst another may choose to focus on reliability tests. The relative investment provides some indication of a firm's probing strategy.

6.3 Descriptive Model of Probing

A descriptive model is proposed to represent the probe applications a firm has pursued over time (fig. 6.1). This model is expected to be useful for describing and analysing the probing process in firms. Based on the characterisation, the probing process is described as a series of experiments, involving explorative learning and exploitive development. Firms may choose to explore alternative applications for their technology and choose to exploit their technology in specific markets. Therefore, the probing process is characterised by the following probe decision making variables: i) the breadth of market probes, the number of different market segments a firm chooses to pursue ii) the length of probe paths, the decision to continue with a probe on the basis of a prior market probe.

The breadth of market segments is placed on the horizontal axis, measured in the number of different market segments a firm pursues. The length of probe paths is placed on the vertical axis, measured in time. The breadth of market segments is associated with the pursuit of new markets. The length of probe paths is associated with development within a market segment. The vertical axis enables the observation of variable breadth over time. The probes are illustrated by circles. The circles vary in diameter to indicate the degree of relative investment. Technology platforms, i.e. a technological subsystem applicable to various market segments, are illustrated by squares. Furthermore, different types of probe paths are represented:

i) linear probe paths for probes in the same market segment; ii) paths with limited probes for some time, followed up at a later time; iii) cross- over paths in which the output of one probe is used as the input for probes in different market segments.

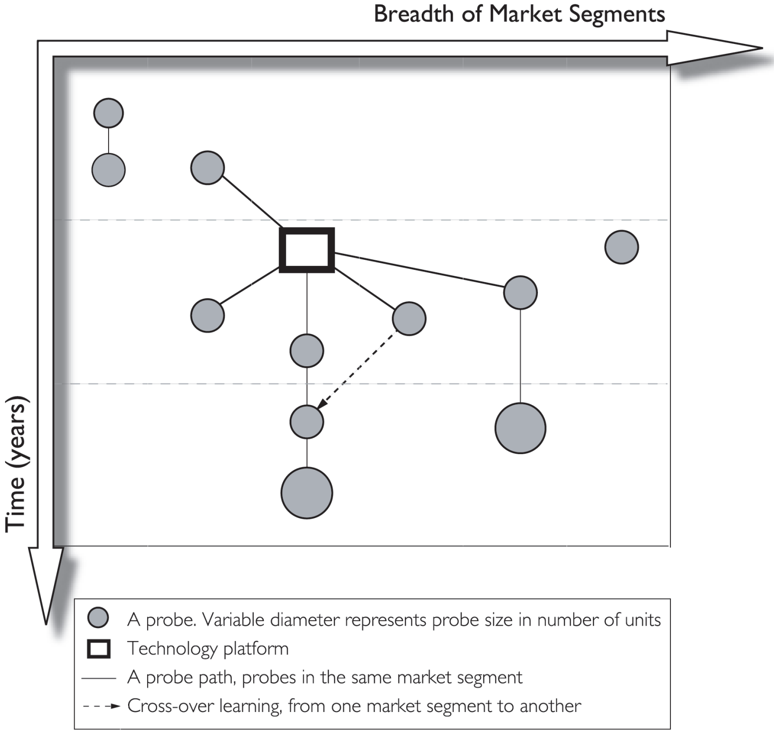

Figure 6.1 Descriptive model of the probing process

This descriptive model is expected to provide a useful tool i) to describe the history of a firm's probe applications ii) to generate an overview of a firm's probe decisions iii) to compare the probing processes of different firms.

6.3.1 Patterns

The descriptive model is expected to enable the analysis and comparison of probing processes. This study expects to find similar and different patterns of probing in firms. The probing process illustrated in the descriptive model (fig. 6.1) represents a pattern of probing that this study expects to observe in the case study research. The pattern is characterised by a variable breadth of market segments over time and three phases of probing. On the basis of the concepts of learning by discovery and adaptive learning, three phases of probing have been proposed (section 5.4). Over time, the probing process is characterised by three phases: an explorative, an experimental and finally a developmental phase. The explorative phase is characterised by initial explorative probes in new market segments. A second experimental phase is characterised by explorative probes in new market segments as well as exploitive probes, building on prior probes in a market segments. Finally, a developmental phase is characterised by pre-dominantly exploitive probes in the form of product development cycles to optimise the product prior to commercial roll out. The phases also represent different stages of probe decision making: over time different factors are likely to influence the probes a firm chooses to pursue or abort. The descriptive models provide a framework for analysing patterns of probe decision making in firms.

A dynamic capabilities perspective suggests that firms will choose different strategies on the basis of their competences, histories and prior experiences. From this perspective, this study expects to find different probing strategies among YTB firms. These probing strategies are expected to vary along the variables of the descriptive model: variation in the breadth of market segments and length of probe paths. To analyse different probing strategies and what drives these differences, the selection of case studies should be based on a variation of probing strategies.

6.3.2 Operational Measures

The descriptive model requires operational definitions to observe and measure a firm's probing process in practice. Operational definitions of a 'probe', the breadth of market segments, the length of probe paths as well as the horizontal and vertical axes are described (table 6.2).

A Probe

A probe has been described as the market application of immature versions of a technology as a vehicle for learning. However, in practice, what does a probe encompass? Activities such as market assessments and conversations with potential clients contribute to learning about market applications, however, they are not considered to be probes. Lynn et al. (1996) refer to a probe as a physical object, such as a functioning prototype. This characteristic is relevant for studying probe applications because it is the physical application of a technology in practice that elicits feedback from markets (section 4.5). Additionally, the realisation of physical probes has been described as costly and time consuming, emphasising the relevance of understanding how probe decisions are made. However, a firm may be involved in a multitude of physical applications. Which physical applications are 'counted as probes' and how can the probes central to a firm's probing process be determined?

A dilemma of probe decision making has been observed: decisions typically involve the allocation of resources and competences under a high degree of uncertainty (section 3.4). Considering this dilemma, the probes relevant to a study on probe decision making include the activities in which a firm decides to invest. From this perspective, a probe is counted as a probe based on a firm's level of investment, in terms of time, financial resources or personnel. The relative investments indicate which probes are central to a firm's probing process. Financial resources are not always an appropriate measure to apply. YTB firms may not posses or invest proprietary financial resources in probes. For example, a demonstration project may be largely funded by subsidies or early adopters. Nevertheless, a YTB firm has to decide to which activities to allocate its time and personnel. The relative level a probe investment in terms of time invested or number of personnel dedicated to a project, provide a measure of firm's level of commitment to a probe. Considering this definition, the supply of technology to customers without significant investment in time and personnel will not be considered as a probe. This study is primarily concerned with probes that have characterised a firm's investments in a particular period and have been determinant for learning and subsequent probe decisions. To identify the probes central to a firm's probing process, the following data is used: i) the centrality of probes in interviews, ii) the applications described in press releases and other publicity materials, and iii) the number of patents related to the probe.

Furthermore, the size of a probe is a relevant and variable characteristic. A 'probe' may involve a single application or include various applications, such as a field test with multiple units. The number of physical units in a probe reflects the objective of a probe and the scale of investment. The number of units also influences the type of experience gained. In the descriptive model, the size of a probe is represented by the diameter of a probe circle. A technology platform differs from a 'probe' in that the technology has been designed for application in multiple markets. Technology platforms are found in a firm's product portfolio and their application can be observed. Technology platforms are represented in the first probe and in the first market segment where it is applied.

Table 6.2 Operational measures of the proposed probing characteristics

Characteristic	Operational measure
Probe	Physical applications in which a firm invests time and/or resources, represented at the time the probe is publicly announced
Probe size	Number of units in a probe application
Horizontal axis	Breadth of market segments, number of different market segments a firm engages in
Vertical axis	Absolute time in years
Probe path	Begins when plans to develop probes in a market segment are announced. Continues when a new probe follows a prior probe in same market segment.
Cross-over learning	The transfer of operational and reliability data to other market segments
Phases	Dominance of either explorative or exploitive probes

Horizontal Axis Defined

A 'breadth of market segments' is represented on the horizontal axis of the descriptive model, however, how can a firm's breadth be measured? The variation in breadth refers to probes in different market segments. To describe this variable in operational terms, it is necessary to define observable categories of market segments. What are criteria for the categorisation of market segments?

Lynn et al. (1996) suggest that firms probe in different markets to develop market insight and learn about which applications and markets have most potential. Explorations into new markets have been described as activities that lead to new information about an application, market and technology. Market segments can be categorised in terms of different product categories, characterised by product functions and requirements. In the case of a replacement technology, applications are found in existent markets and product categories in which established technologies determine the benchmark requirements. The technological requirements of these product categories differ. For example, the stationary and automotive categories have contrasting requirements and characteristics (section 2.3). The existent markets for a product are also associated with the characteristics of an established market sector and industry in terms of customer specific requirements and adoption behaviour. Therefore, in addition to product categories, a market segment can be categorised by the characteristics of a market sector. Within each market segment, sub segments may be identified as a specific customer segment within the same product category.

The breadth of market segments is measured as the number of different market segments a firm pursues at a particular time. The market segments are categorised by the key product categories, differentiated in terms of product requirements and market sector characteristics.

Applied to the case of FC technology, the technological requirements mainly vary between stationary and transportation (fig. 6.2). Within this differentiation, market segments are further categorised by the benchmark requirements of a product category, arranged in order of power level decreasing from the centre outward. The market segments are further segmented according to the market sectors. Subcategories are found in different customer segments within a market segment, illustrated as a branch within the main categories.

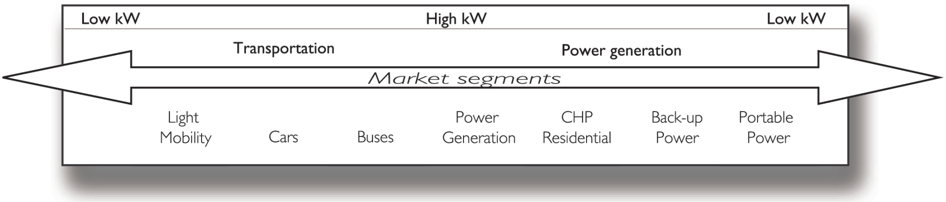

Figure 6.2 Market segment categorisation in product category and power level

Vertical axis defined

The vertical axis of the descriptive model represents time in years, enabling a historic account of the probes a firm has engaged in over time. For comparison between firms, the same time scale in years is applied. In this manner, the timing of probes and the phases of probing can be compared. For the individual analysis of case firms, a focus on the period relevant for that particular case may be necessary. The year time scale will indicate variance in the timing of initial probes. Another option for the operational measure of time could be to begin with each probing process at 'zero'. In that case, the duration of probe paths and the firms' total probing processes is measured on the vertical axis. The total duration of the firms' probing process will vary. This approach may indicate the comparative amount of probe experience. Finally, the vertical axis could also represent the percentage of time. This measure may provide an indication of the relative duration of probe applications and phases throughout the process of probing. Cooper (1983) and Buijs (1984) have applied this scale to measure the relative duration of stages or steps in the design process. For the purpose of this study, the vertical axis is defined as a timescale in terms of years in absolute time. This option is considered to be most suitable for an historic account of probing processes and their comparison.

With the aim of understanding probe decision making, a probe is ideally represented at the time the decision is taken to invest in a probe application. However it may not be possible to gather data on the exact time of investment. Therefore, the public announcement of an agreement or plan to develop a probe will be used to measure the timing of a probe decision. This decision is represented by the start of a line. The circle itself indicates the time at which a physical probe is demonstrated to the world. The announcement of a demonstration is utilised to measure this timing demonstration. The path line is continued for the period of operation. Probe paths are represented as vertical lines when a new probe follows a prior probe in same market segment. When a probe path is conducted with the same customer or partner, the probe path line is solid and represents a 'customer path'.

The length of path is measured in terms of duration of probing activity in a market segment. The path density refers to the number of probes conducted in that length of time. A 'postponed path' is characterised by a low path density, in which probes are followed up after a period of in-activity. When a probe path stops and the firm has not continued with subsequent probes in that market segment, it is defined as an 'aborted' segment. Cross-over learning is observed when technical learning from one probe is applied to a probe in a different market segment. This cross over learning can be measured by the transfer of operational and reliability data to other market segments.

Phases Defined

A probing process is expected to go through three phases characterised by different approaches to probe decision making and learning. The operational definitions of these phases are derived from the concepts on organisational learning described in section 5.4. These phases are characterised by their degree of experimental versus analytic logic in decision making (Lynn et al. 1996) and the degree of learning by discovery versus adaptive learning (Van de Ven et al. 1999). The link between action and outcome is primarily chaotic, subsequently changes from chaotic to periodic and finally proceeds to a periodic adaptive cycle.

Applied to the probing process, the phase of exploration refers to a firm's engagements in initial probes. Decisions on initial probes are sensitive to initial conditions and are expected to follow a chaotic pattern of learning in which outcomes are not directly linked to actions. By contrast, the development phase refers to the iterative development of probes towards commercial applications, characterised by a convergent process of optimisation. Probe decision making follows a periodic cycle of adaptive learning, in which outcomes are directly related to subsequent actions and outcomes can be analytically predicted. Between the phase of exploration and the phase of development, a transitional phase of experimentation is identified. This phase is characterised by a combination of explorative and developmental probes: trying out new market probes as well as iterative developments within a market segment. The phase is primarily characterised by a divergent process of exploring alternative market segments and subsequently makes a transition to convergent cycles of more focused development.

Translated to the variables of the descriptive model, the phases can be measured in terms of the breadth of market segments and the length of probe paths. Based on concepts of probing and learning by discovery, the explorative phase can be identified by a breadth of probes in new market segments and multiple aborted paths. The development phase can be identified by a select number of linear probe paths characterised by iterative developments and an increasing number of units within each probe. The experimental phase can be identified by probes in a breadth of market segments as well as linear probe paths. The divergent process of learning by discovery can be observed by a dominance of explorative probes in new market segments above exploitive probes in linear probe paths. By contrast, the transition to a convergent process of adaptive learning can be observed by a dominance of exploitive paths compared to explorative probes in new market segments. In addition to the pattern of probing, an event may characterise the transition from one phase to another. For example, the presentation of a technology platform may signal the beginning of the experimental phase in a variety of new market segments and a significant customer order in a particular market segment may signal the end of experimentation and the beginning of selective development.

6.4 Explanatory Constructs of Probe Decision Making

The descriptive model, proposed in the previous section, will be used to describe the probe applications a firm pursues over time. Subsequent conceptualisation will focus on *explaining* probe decision making. This paragraph provides an overview of factors that may explain probe decision making, as derived from the literature reviewed in chapters 4 and 5. The dependent construct of this study has been defined as probe decision making: the probe applications a firm chooses to pursue over time. Decisions include the selection of market segments, the decision to pursue probes and the decision to continue, abort or change probe paths. This section will summarise the constructs that may explain why these decisions are made: the factors that drive probe decision making. A dynamic capabilities perspective has been chosen as a theoretical lens in chapter 5. From this perspective, the factors that may explain probe decision making include rational and non-rational factors as well as factors internal and external to the firm. The firm level perspective of this research puts emphasis on firm level factors, however, influential constructs external to the firm are also discussed. This section describes the constructs that may influence probe decision making from a dynamic capabilities perspective.

Resource Position

From a dynamic capabilities perspective it is assumed that probe decisions are at least partly rational, made with reference to a firm's resource position. A firm's resource position comprises its assets, including resources, competences and capabilities. Assuming rational decision making, section 5.3 suggests that a firm will choose to pursue a probe application when: i) the firm has the resources to do so. Does the firm have the resources to engage in the probe? ii) the probe complements the competences and strategy of the firm. Is the firm capable of conducting the probe and does the probe fit the competences a firm aims to develop? iii) the probe provides an opportunity to gain revenue. Does the firm expect the market probe to be a market opportunity for revenue generation in the short, mid or long term? From this perspective, firms are expected to select different probing strategies on the basis of different resources positions, competences and capabilities. It has been argued that there are limits to this rational model in the dynamic and uncertain context of radical innovation. In this context, the information to make rational decisions is often unavailable and incomplete, limiting the role of rational assessment and strategic planning in probe decision making. Moreover, YTB firms are expected to depend on external resources and events. It is, therefore, assumed that firms are rationally bounded in the selection of probe applications. From a dynamic capabilities framework, probe decisions are not only influenced by a firm's resource position and strategic intent, but also by prior experience and external factors.

Firm History and Legitimacy

A dynamic capabilities perspective suggests that a firm's position is shaped and constrained by a firm's history of prior decisions and experiences. Prior experience has been described as an influential factor on the growth and performance of new businesses (5.3).This study will refer to this construct 'firm history' as the decisions and experience prior to firm founding. Inherited networks, ambitions, technological core competences and experiences are likely to shape and influence the probe decisions of YTB firms in the years after founding (figure 6.3). Furthermore, Alvarez and Busenitz (2001) suggest that firm specific history and skills may have long term implications for firms in terms of development paths and strategic focus. Probe decision making is expected to be sensitive to initial conditions at firm founding. Firm history is argued to be a source of differences between firms and expected to result in heterogeneous probe decisions.

The particular characteristics of YTB firms likely to influence probe decision making include their limited legitimacy in the early years of firm growth and typically, their dependency on external resources. Aldrich and Fiol (1994) distinguish between the cognitive legitimacy and the socio-political legitimacy of a firm and an emerging industry. The cognitive legitimacy, referred to as the level of knowledge about a new business, is likely to influence the probing alternatives open to a firm. The socio-political legitimacy, referred to as the degree to which key stakeholders accept the new business, is likely to influence a firm's strategic options to continue developing probe applications. The level of resource dependence and firm legitimacy are likely to influence probe decision making. In turn, YTB firms are typically highly dependent on external relationships and the formation of networks and partnerships in order to acquire resources and develop legitimacy. 'Partnership formation' as a construct that may influence probe decision making, requires further specification. Firms may approach potential partners or be approached by firms for partnering. In YTB firms it can be argued that the formation of partnerships may be driven by strategic intent or opportunistic behaviour. From a dynamic capabilities perspective, partnerships are considered to be firm assets that may influence probe decision making (fig. 6.3). Partnerships are variable in strength and function. The following types of partnerships are expected to be influential for probe decision making:

- Customer partnerships, including agreements to supply, for example, to OEM customers.
- Joint or co-development partnerships, including agreements to jointly develop technology and/or probe applications.
- Distributor- marketing partnerships, including agreements for the distribution and marketing of a firm's products or technology.

External Constructs

On the basis of a dynamic capabilities perspective, this study expects that various factors external to the firm will influence probe decision making. Chapter 4 described how technology adoption strongly depends on a customer's understanding and perception of a new technology. Chapter 5 described how firms depend on changes in the regulatory environment and are likely to be influenced by the evolving expectations of an emerging industry. The regulatory environment, the emerging industry and potential customers are likely to influence probe decision making. The following external constructs are expected to at least partly explain the selection of probe applications in YTB firms (figure 6.3):

- Regulatory factors, such as the development of legislation, financial support for R&D and tax incentives for early adopter markets. In the case of FC technology, the development of zero emission legislation will influence the opportunities open to FC firms. These are institutional factors, likely to cause homogeneous behaviour among firms.
- Industry factors refer to the development of norms and shared beliefs in an industry. In an emerging industry, primarily industry expectations of technology development and timeframes for market adoption are expected to be influential. These are institutional factors that are likely to cause 'mimicking' behaviour.
- Market factors include the development of customer familiarity and market demand. The level of customer familiarity and market demand is expected to influence the type of probes a firm decides to pursue and the opportunities open for development. In the case of FC technology, demonstrations are necessary to generate public and customer awareness.
- Competing technologies, refers to the relative advantage of the new technology compared to other new and established technologies. The existence of competing technologies is likely to influence the perceived desirability of the new technology in the regulatory and market environment. Consequently, competing technologies are a source of uncertainty in the environment of a firm.

External factors are expected to influence the uncertainty of probe decision making and the scope of probing alternatives open to a firm. In particular, industry expectations are expected to influence probe decision making in YTB firms, considering the context of uncertainty and the small size of the industry. Industry factors can influence probe decision making in two ways: first, by determining the boundaries within which a firm searches and selects probes and secondly, by influencing specifically which probes a firm selects.

Firm Competences

From a dynamic capabilities perspective, the resource position of a firm is also influenced by learning processes. YTB firms, such as young FC firms, are in the process of developing complementary competences necessary to profit from their technological core competences. These developmental competences, shaping a firm's resource position, are discussed in further detail. The review of innovation studies in chapter 4 suggests that the success of technological innovations is largely derived from meeting customer needs and requirements. Moreover, product innovation has been described as a process of linking technology and customers (Dougherty 1992). Hence, it is not surprising that scholars emphasise the importance of market and technology related competences to successfully identify, develop and sell market opportunities (section 4.3). A firm's ability to link its technology to market opportunities in the co-evolutionary context of radical innovations has been described as a dynamic capability (section 5.2). A firm's level of technology and market related competences and its capability to combine these competences are expected to have an impact on which probes a firm chooses to pursue. Technology-related competences are those that develop and produce technology, such as manufacturing plant equipment and know-how and engineering skills (Danneels 2002, Song et al. 2005). By definition, technological competences are the core competences of a technology based firm. A firm's level of market related competences includes an understanding of market dynamics and information to predict if and when a market will adopt a technology. Additionally, market competences include a firm's understanding of customer requirements and preferences (Song et al. 2005, Danneels 2002). In the case of radical technologies, firms are expected to develop market insight by probing with early versions of their technology in market applications (Lynn et al. 1996).

Throughout the probing process, firms are expected to develop their technology and gain an understanding of potential markets and customer requirements. Firms gain the competences to identify and evaluate the 'match' between their technology and potential markets. Gradually firms develop an understanding of the potential, adoption timing and suitability of alternative markets and the limitations of their technology in these markets. It is assumed that as firms gain experience in probing and develop their competences, firms are better able to identify and develop compelling 'value propositions'. A firm's value propositions are shaped by the firm's ability to combine its technology and market related competences.

*A firm's **'value proposition'** is defined as a firm's ability to identify and asses a 'match' between a firm's technology and market opportunities / requirements.*

A firm's value propositions are measured by the degree to which:
1. The firm has identified specific market opportunities for its technology
2. The firm's technology is aligned to customer requirements and preferences
3. Uncertainty is reduced on the timing and size of market adoption

The construct 'value proposition' varies between high or low. A high value proposition represents a firm's ability to identify and select cost effective market applications that are compelling to customers. Two different types of compelling value propositions can be identified:

- A problem solving value proposition, when the firm's technology has the potential to solve (urgent) problems that customers have with their current technology.
- An economic value proposition, when the firm's technology has the potential to save costs for a customer compared to the current situation.

A firm has a low value proposition if it does not have the ability to identify or asses such market opportunities or the ability to align its technology to customer requirements and preferences.

To clarify this construct it is relevant to distinguish between 'value propositions' as a firm internal factor and value propositions as the characteristic of a technology application in general. Each application has a value in terms of cost effectiveness and the possibility to solve customer problems. This value is determined by the added-value of a technology above the incumbent and competing technologies in a market segment. However, this study has focused on understanding firm level management challenges and probe decision making. For the purpose of explaining how firms select probe applications, this study focuses on value propositions as a firm capability. In turn, this capability depends on a firm's level of technology and market related competences. In addition to the above mentioned factors, the level of firm competences and capabilities are at least partly expected to influence probe decision making. If firms engage in probe applications primarily to learn about markets and further develop their technology, then probe decision making can at least partly be explained by the necessity to identify and develop value propositions. During the process of probing, firms are expected to develop their competences and their 'value propositions' on the basis of the experience gained in probe applications. The outcomes of probe applications and how these outcomes influence the explanatory constructs, is described in the following paragraph.

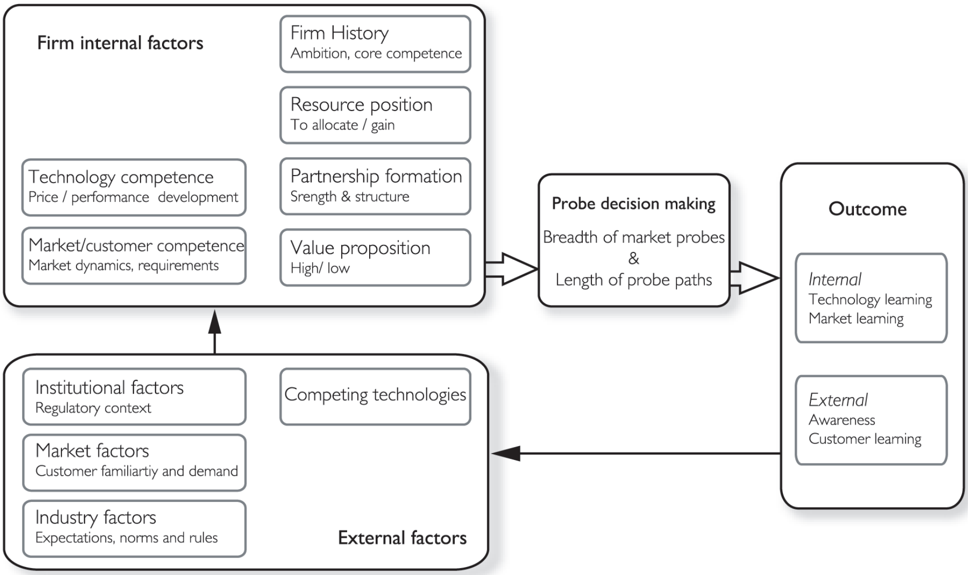

Figure 6.3 Overview of factors influencing probe decision making

6.5 Probe Outcomes and Consequent Changes

Considering technology application as a process of 'probing and learning', it is assumed that the outcomes of probes will influence learning within firms. Moreover, the outcomes of probe applications are likely to influence stakeholders in the external environment of the firm. Considering these changes throughout the probing process of a firm, the role of explanatory constructs in explaining probe decisions is expected to change over time. A conceptual model of probe decision making will, therefore, be based on the following assumption: the outcome of a probe and the constructs explaining subsequent probe decisions are, in some way, related. Although action and outcome are often not directly related, figure 6.3 illustrates possible probe inputs, probe outcomes and their relation. In this section the relationship between the probe outcomes and the explanatory factors is discussed, to better understand the changes that take place in a probing process over time.

6.5.1 Probe Outcomes

Probing includes various types of physical applications with early versions of a new technology such as demonstration projects, prototypes and field trials. Consequently, when a probe is realised, different types of outcomes can be expected. First, there is a physical product: a physical manifestation of the new technology. High technology marketing literature suggests that a physical product facilitates the communication with and the education of customers and other stakeholders (section 4.4). A physical product placed in a market environment elicits feedback and may stimulate market demand. Furthermore, the outcomes of the FC projects described in section 3.3 include publicity and stakeholder learning. The projects suggest that gradually the specifications and requirements of stakeholders were aligned. Probe outcomes appear to include learning and stimulants to change customer and public perception.

In support of these observations, Karlstrom and Sandén (2004) categorise the results from demonstration projects as: i) learning about markets and the technology in operation, ii) opening a market through increasing customer awareness and clarifying institutional barriers and iii) forming a network of actors to drive technology and policy change. Similarly, Harborne et al. (2005) have categorised stakeholder learning from demonstration projects as technical experiments and market trials. Sagar and Gallagher (2004) additionally argue that learning and generating awareness are important outcomes of demonstration projects: through probes customers learn about the technology. Literature suggests that on the one hand, real world operational data is gathered to test and validate the technology. On the other hand, market and institutional developments are stimulated through demonstrations in real world experiments. In conclusion, probe applications may provide the following outcomes: market feedback, application experience and operational data. In addition, probe outcomes include publicity and customer or public awareness that may stimulate market development and clarify institutional barriers (fig. 6.4).

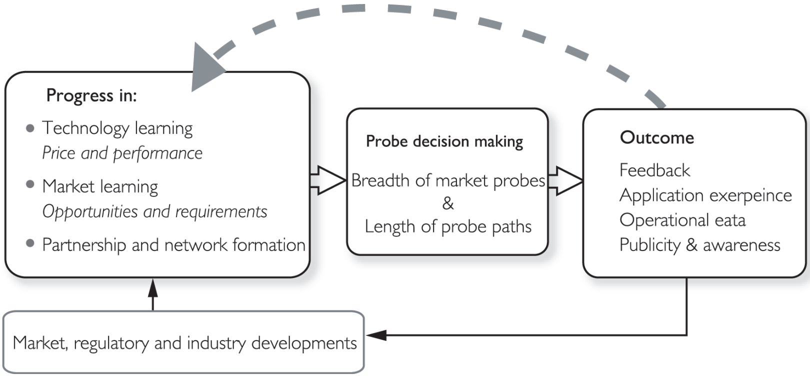

Figure 6.4 Illustration of in-put and output in probing and learning

6.5.2 Progress

A probe application has been described as a vehicle for learning. Therefore, a probe is not an end result but a trial application in a sequential process of development. As an ongoing part of the innovation process, it is difficult to say if the outcome of a probe is successful and positive or not in terms of innovation success. Rather, as a management approach to commercialising a new technology, a positive probe should contribute to progress in technology application. For the purpose of this study, a probe is considered to have a positive outcome when the firm and/or stakeholders in the external environment have gained experience that can contribute to progress in commercialising the technology. Hendry et al. (2007) applied a number of indicators to measure progress in PAFC technology. Borrowing three indicators for the purpose of this study, progress resulting from probe outcomes will be observed through the following indicators:

- Market learning and customer learning, on market opportunities, customer requirements and preferences
- Technical learning to achieve price and performance improvements
- The formation of relationships and partnerships

Through probe applications, firms are expected to gain experience about their technology in practice and develop their 'value proposition' in market segments. It is assumed that market feedback from probe applications influences the development of a firm's market related competences and ability to identify and evaluate market opportunities. The concepts of exploration and exploitation suggest that firms gain different competences from exploring new markets than from exploiting prior market applications. Learning about markets through probe applications is, therefore, expected to include:

- The exploration of new market segments results in new information on the potential of alternative market segments.
- The exploitive or iterative development of a market segment that builds on prior market information and experiences to align to customer requirements.

The development of a firm's 'value propositions' additionally depends the development of the firm's technological competences including price and performance improvements and manufacturing competences.

Through technology learning, from 'testing' the technology in practice, a firm's technology related competences and proprietary technological skills can further develop. Field test operations, for example, provide operational data to model system improvements.

In addition to firm internal developments, probe outcomes may influence and bring about change in the environment of a firm. For example, probe applications to validate and demonstrate the technology, are likely to influence a customer's familiarity and perception of the technology. Publicity of probes may evoke customer interest and operational data may validate the technology to potential customers, partners, policy makers and investors. A positive perception of probe outcomes by external stakeholders is expected to contribute towards the development of a firm's legitimacy and credibility. Thus, progress resulting from probe outcomes may include market development, partnership formation and regulatory change. Furthermore, the probe applications of individual firms are likely to contribute to a more collective process of learning in emerging industries, shaping the development of industry expectations. Probe applications are often demonstrated in public domains and presented at conferences and industry gatherings. Therefore, considering the small size of an emerging industry, firms are also expected to learn from each other's probes and shared experiences.

In conclusion, probe outcomes are likely to influence learning and developments within a firm and in the external environment of a firm. Consequently the explanatory constructs, summarised in section 6.4, and their role in probe decision making are expected to change over time. A model of probe decision making will therefore be modelled as dynamic, iterative, non-linear and sensitive to initial conditions.

- Dynamic implies that the value of an explanatory construct at a given time is a function of the values of that construct at an earlier time.
- Iterative implies that feedback loops influence the explanatory constructs.
- Non-linearity implies that the dynamic feedback loops vary in strength and direction.
- Sensitivity to initial conditions implies that small initial differences or fluctuations in constructs will grow over time into larger differences.

To model probe decision making over time, the following section describes how the outcomes of probe applications are expected to influence the explanatory constructs over time.

6.6 Explanatory Constructs over Time

Section 6.4 summarised the multitude of factors that may influence probe decision making. From various theoretical perspectives, the dominant influence of these factors is disputed. Furthermore, section 6.5 describes how probe outcomes elicit change within the firm and external to the firm. Therefore, the constructs and their influence is likely to change as firms probe in applications over time. As a company learns and the external context evolves, the input for probe decision making changes. This study suggests that a different set of constructs is likely to drive probe decision making throughout the probing process, characterising different phases of probing.

On the basis of organisational learning concepts applied to the process of 'probing and learning', this study proposed three phases of probing. Firms are expected to make a transition through three phases of probing, from a phase of explorative probes, through a transitional phase of experimental probes to a phase of developmental probes. The phases are characterised by different modes of learning and decision making, therefore, the relationship between probe outcomes and probe decisions is expected to change from chaotic to orderly over time. During the explorative phase, firms engage in their initial probe applications. In this phase, learning by discovery is expected to dominate due to the uncertainty and environmental turbulence. In the experimental phase, both explorative and exploitive probes are pursued. Primarily, explorative probes and learning by discovery dominates. Over time, a firm's competences are expected to develop as experience is gained in probes. Within the experimental phase, exploitive probes begin to dominate over explorative probes. Finally, as uncertainties reduce and the environment stabilises, firms are expected to show more orderly and predictable decision making behaviour, characterising the developmental phase of probing. Both internal and external constructs are expected to drive probe decision making throughout these phases.

Considering the multitude of factors that may influence probe decision making, this study will focus on a select number of constructs. Constructs are selected that are not well understood, yet important to explain probe decision making. Probing and learning has been observed as a management practice to solve the following key challenges of radical technology application: developing market insight and stimulating market development. With the ambition of gaining a better understanding of this process, this study will address the following constructs:

- The development of a firm's 'value propositions', a firm internal factor.
- The development of customer familiarity and demand, a firm external factor.

Moreover, this study has focused on YTB firms. Influential factors that characterise YTB firms will also be considered. The legitimacy of YTB firms is incorporated into the construct customer familiarity. In addition, the constructs firm history, external resources and partnerships are expected to influence decision making in YTB firms. Finally, in the context of an emerging industry, the construct 'industry expectations' is expected to be important for explaining probe decision making. Other institutional factors such as norms, rules and standards are not considered, as they are in development and expected to have limited influence in an emerging industry. Competition between FC firms is not addressed in detail for a similar reason: young industries are typically characterised by low levels of competition in comparison to collaboration. Moreover, although regulatory support may be described, this study does not specifically focus on developments in the regulatory context. In the context of an environmental technology, the development of legislation is assumed to primarily provide opportunities instead of constraints. Moreover, the study of regulatory factors requires an additional level of analysis, whilst this study has focused on a firm level analysis of YTB firms and their interaction with customers. On the basis of the theoretical constructs, this section characterises the context of each phase and suggests how both internal and external constructs are expected to influence probe decision making in each phase of probing.

6.6.1 Explorative Phase

The selection of the initial probes takes place under a high degree of uncertainty: the technology is immature and firms have limited market information and experience in applications. Due to the immaturity of the technology and a lack of market information, it is difficult for firms to evaluate the opportunities for and timing of technology application. In addition, the environmental context is characterised by uncertainties: market demand does not exist, customers are unfamiliar with the technology and the regulatory environment has not yet taken shape. At the same time, limited legitimacy characterises the early years of YTB firms: there is limited awareness of the company's existence and technology.

It is in this context of uncertainty that YTB firms select their initial probes. By definition, these initial probes are explorative undertakings into market segments that are new to the firm. What drives the selection of initial probe applications? YTB firms begin with their technological core competences and their expectations of market opportunity. Firm history, in terms of technological core competences, inherited ambitions, experiences and relationships, is expected to influence the initial probes a firm chooses to pursue. Firm history is likely to cause heterogeneous probe decisions among firms. In contrast, firms may choose to mimic other firms and follow the expectations and beliefs of the emerging industry. It can be argued that collective learning and developments prevail above competition in small and emerging industries. In this context, industry expectations are also expected to influence the selection of initial probe applications. Considering the high degrees of uncertainty, this study expects that industry expectations may overrule a firm's strategic intent and expectations.

Furthermore, given the resource constraints of YTB firms, the availability and access to external resources is also expected to influence the selection and pursuit of initial probes. Such external resources may include government grants, partnerships or early customers. In this explorative phase of probing, firms must attract and convince external investors, customers and partners that are typically unfamiliar with the technology and the firm. The pursuit of initial probes may, therefore, additionally be driven by the need to convince stakeholders and investors external to the firm. Therefore, the explorative phase of initial probe applications is characterised by a low level of:

- Firm internal resources, firm legitimacy and market competences. External to the firm, stakeholders are typically unfamiliar with the technology.

Firm internal factors that may influence initial probe decision making include:

- Technological core competences
- Firm history, inherited ambition

External factors include:

- Industry expectations
- The availability of external funding
- Unfamiliarity of external actors

6.6.2 Experimental Phase

Subsequent probe decisions in the experimental phase of probing are based on a modified point of departure: firms have gained experience in probes and this experience is likely to influence subsequent probe decisions. Firms face the decision to continue or abort initial probes and select new probe applications. With the feedback from initial probes, firms are expected to be more capable of evaluating their value propositions. The feedback from initial probes is expected to reveal a discrepancy between a firm's technology and potential market applications, i.e. low value proposition. To identify new value propositions, set preferences and goals and discover the environmental context, probe decision making is expected to be characterised by learning by discovery. Therefore, some initial probes may be continued, but the pursuit of explorative applications in new market segments is expected to dominate. Compared to the initial probes, this is a divergent process of probing in a broader range of new market segments.

The outcome from initial probes will additionally generate publicity and stimulate awareness in the external environment. Investors and potential customers and partners are likely to become more aware of the technology and the firm. The outcome of initial probes is expected to open up opportunities for probing, funding and partnering. Thereby, the possibility to form strategic partnerships is likely to have a strong influence on the selection of subsequent probes. Considering the resource limitations of YTB firms, the formation of partnerships is expected to determine the continuation of probes for longer term markets. In addition, in response to initial probes, customer interest is expected to grow. As customer interest emerges, YTB firms are likely to be approached with application requests. Moreover, developments in the regulatory environment may provide opportunities for projects and applications. Thereby, opportunities for short term revenue arise and may cause opportunistic behaviour in probe decision making. In the phase of experimental probing, firms are expected to face trade-offs between probes for short term revenue, the formation of partnerships and their longer term ambitions.

Furthermore, initial probes may have stimulated interest, but the level of customer familiarity is still expected to be low and the uncertainty in the external context is expected to be high. Under the influence of customer unfamiliarity and uncertainty, probe decisions in this experimental phase are also expected to be driven by the need to communicate, educate and convince customers. Firms may probe in various market segments to explain and demonstrate their technology to potential customers. It can be argued that this type of probing is driven by firm internal competences and strategies. Therefore, the divergent probing behaviour in the experimental phase is expected to result in heterogeneous probe decisions among firms, in contrast to the mimicking behaviour expected in the explorative phase. The influence of the construct industry expectations is expected to reduce in comparison to the initial phase of probing. Nevertheless, industry expectations will evolve during the experimental phase of probing as shared beliefs on market potential and adoption timelines shape over time.

As the experimental phase of probing proceeds, firms learn, customers learn and the technology and markets co-evolve. The more information a firm has gained, the better it is able to evaluate the suitability and feasibility of market applications and develop 'rules of thumb'. With the accumulating feedback, YTB firms will have more information to asses their value propositions and determine which probe paths to continue and which to abort. Consequently, firms are expected to reduce the number of probe applications in new market segments relative to the further development of prior engagements. In addition firms are expected to narrow down their scope of probe applications. This transition from divergence to convergence is expected to be driven by firm competences and capabilities as strategic decision making becomes less uncertain and firms are able to identify compelling value propositions. Customer familiarity with the technology and the firm is also expected to drive this transition in probe decision making.

Therefore, the second phase of probing is characterised by:
- A relative increase of firm legitimacy and market information and experience.

Firm internal factors include::
- The level of a firm's value proposition
- Proprietary technology, developing in cost and performance
- Partnership formation

External factors include:
- Customer familiarity with technology and firm.
- Evolving industry expectations

6.6.3 Developmental Phase

Probe decision making in a developmental phase is characterised by a lower degree of uncertainty compared to the earlier phases of probing. Internally, firms have more experience, competences and capabilities to asses and develop market opportunities. Externally, market demand begins to emerge, industry expectations and beliefs institutionalise and regulatory measures and institutional barriers take shape. This phase is characterised by a dominance of exploitive probes and probe decision making is expected to focus on the development of a select number of probe paths. On the one hand, firms are expected to make a transition to a developmental phase of probing when they have the competences and capabilities to do so: when compelling value propositions are identified and uncertainty about market adoption is reduced. The formation of structured and formalised partnerships is also expected to influence when and how a firm chooses to develop probe applications. On the other hand, Van de Ven et al. (1999: p.80) suggest that this transition depends on external developments. The authors suggest that learning will make a transition to orderly cycles of learning once, *"random environmental events occur with insufficient frequency or magnitude to provide a context that is stable enough to permit identifying relationships between actions and outcomes".*

Particularly in the case of OEM customers, YTB firms are likely to depend on customer orders to engage in developmental probing. Customer repeat orders validate the emergence of market demand and enable firms to move into a phase of development. Customer adoption is related to their perceived risk of adoption and hesitance to change and in turn, is determined by a customer's familiarity with and trust in a firm and its technology. The transition to developmental probing is, therefore, also expected to depend on the level of customer familiarity and trust. On the one hand, customer repeat orders may emerge in response to a firm's unique technology, value propositions and ability to convince customers. On the other hand, firms may have to wait: their transition to development may be delayed if customers are slower to adopt than expected. Probe decision making in a development phase is expected to be influenced by a firm's value propositions and a customer's familiarity. In addition, probe decision making is likely to be influenced by the emergence of market demand in other markets. Moreover, the expectations of the industry have become more institutionalised and may influence the selection of developmental probes. In this phase of probing, the emergence of market demand and industry expectations may overrule a firm's probe experiences and value propositions in probe decision making.

In the third period of development, the firm is characterised by:

- Compelling value propositions
- Partnership more structured and formalised

The external context is characterised by:

- Customer orders, market demand.
- More institutionalised industry norms and expectations

Table 6.3 Overview of construct in each phase

Phase	Characteristics	Internal factors	External factors
Explorative	Initial probes new markets	Experience low Market competence low	Industry expectations in formation Actors unfamiliar with the firm and the technology
Experimental	Predominantly explorative	Partnerships in formation Low value propositions	Opportunities for early revenue Industry expectations taking shape
	Predominantly exploitive	Firms develop compelling value propositions	Customer' become familiarity with the individual firms
Development	Selective iterative developments	Formalised partnerships Cost-effective value propositions.	Industry expectations formed Emergence of market demand

6.7 Conceptual Model of Probe Decision Making

As a company learns and the external context evolves, the relative impact of the explanatory constructs on probe decision making is expected to change over time. This section presents a conceptual model to explain probe decision making over time. The model represents the constructs that influence probe decision making in each phase of probing, as described in the above paragraphs (6.6). The internal-external duality presents conflicting explanations of probe decision making. This model will be used to study the relative importance of the selected constructs in explaining probe decisions throughout the probing processes of firms. This study expects different constructs to dominate decision making in each phase of probing. The constructs expected to dominate are represented by a bold typeface in figure 6.5.

The expectations illustrated in the conceptual model can be summarised as follows: the construct expected to primarily drive decisions in the explorative phase of probing are industry expectations. In the experimental phase of probing, the low level of a firm's value propositions is expected to drive divergent probing behaviour. Either the level of a firm's value propositions or the level of customer familiarity is subsequently expected to drive a firm's transition to development. Finally, the emergence of market demand is expected to outweigh a firm's experience and value propositions in other markets. The following paragraphs will propose predictions on the influence of these factors in the form of propositions and questions for further research.

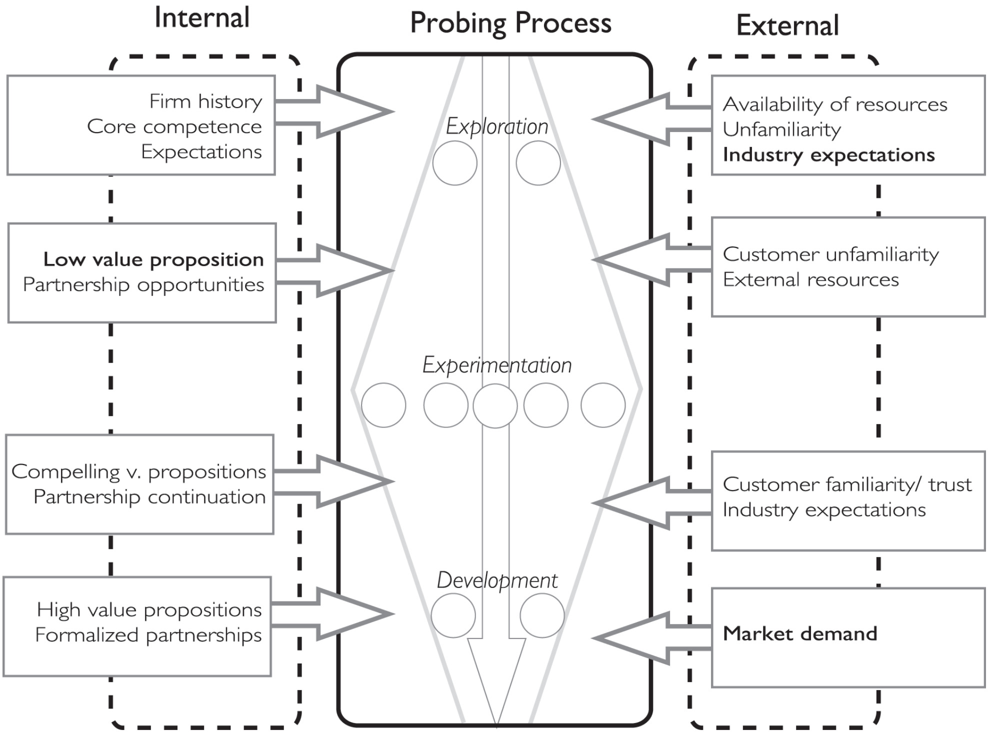

Figure 6.5 Conceptual model of probe decision making and a select number of constructs over time

The conceptual model will serve as a guide for the case study research in the following chapters. To apply the explanatory constructs of the conceptual model, operational measures for observation and data collection must be specified. The explanatory constructs are operationally defined as follows:

- The level of a firm's value propositions represents the degree to which a firm is able to identify and asses a 'match' between its technology and market opportunities/requirements. The level of a firm's value proposition can be measured by the cost and performance characteristics of a firm's technology in comparison to the requirements of the markets a firm has identified. Where the difference is large, the firm's value proposition is low. A high value proposition can be observed when a firm's technology can provide a cost effective solution to a customer's problem.
- Partnership formation and continuation. Publicly announced agreements with partners, to engage in the development of probes and subsequent publicly announced agreements to continue these developments.
- Customer familiarity with the technology and the firm. This construct is measured from the perspective of the YTB firm in terms of the relative effort necessary to demonstrate, explain and validate the technology to become a trusted supplier or partner. Ultimately a high level of customer familiarity is measured through customer repeat orders.
- Industry expectations represent the market focus and expectations for market adoption in the industry under study. Industry expectations at a particular time will be derived from sources such as conference proceedings and technical journals in which the expectations, views and focus of the industrial community are discussed.
- External resources refer to the availability of funding from external sources such as governmental grants, investors and customers. In public firms, these sources of funding are reported. In private firms, sources of funding are less likely to be publicised, nevertheless, supply orders, partnerships and venture capital may be reported in press releases.

The conceptual model will be applied to a case study research in the FC industry. Nevertheless, some degree of generalisation to other technologies is expected. Considering the characteristics of FC technology, the model is primarily expected to be applicable to radical replacement technologies with diverse potential market applications.

Propositions and Research Questions

The conceptual model highlights the relationship between a number of firm internal and external factors and probe decision making over time. This study questions the influence and weight of these factors over time. On the basis of literature reviewed in the previous chapters, expectations for the dominant factors driving probe decisions in each phase have been described. In the following paragraph, predictions are made about the dominant factors and probing behaviour in the form of propositions. For other constructs that are expected to influence probe decision making, limited theoretical support has been found to predict their influence. These relationships will be addressed in the form of new research questions to further guide the case study research and analysis.

6.7.1 Propositions

Propositions are casual relationships between two constructs, whereby certain conditions are shown to lead to other conditions (Yin 1994). Taking the conceptual model as point of departure, the following paragraphs will propose such propositions, predicting the influence of the explanatory constructs on probe decisions over time. The propositions are derived from theory discussed in chapters 4 and 5. As section 6.1 described, propositions are suitable to answer questions on how, when and why. The propositions address how and why firms engage in initial probes, experiment in new market probes, decide to continue or stop a probe path and shifts from one market to another.

Initial probes

- Proposition 1 addresses: how do firms select initial probes?
- Proposition 2 addresses: how does experience from initial probes influence subsequent probe decisions?

The breadth of experimental probes

- Proposition 3 addresses: when is probing alternatives necessary?
- Proposition 4 addresses: what explains the continuation of a probe?

Transition to development

- Proposition 5 addresses: how do firms select market applications for development?

To test formulate propositions through case study research, Bacharach (1989) explains that the propositions must comply with criteria of falsifiability. The concept of falsifiability is based on the scientific principle that propositions or theory can only be scientific if there is the possibility they may be shown to be false. Criteria of falsifiability include the logical and empirical adequacy of the relationships between constructs.

- Criterion for logical adequacy is that they must be non-tautological and the nature of the relationship between the antecedent and the consequent must be specified.
- Empirical adequacy implies that the statement should be supported by a variety of sources.

Initial Probes

Chapter 3 suggests that in the initial stages of technology application, FC firms are challenged to choose from numerous market applications whilst their outcome is uncertain. YTB firms are driven by a market potential but lack the market information to predict if and when markets will adopt the technology. Considering the limited market information and experience available to the firm, how do firms select initial probe applications and how does experience from initial probes influence subsequent probe decisions?

The Selection of Initial Probes

Considering the limited resources and uncertainty of success, YTB firms cannot permit themselves to select initial probes through blind trial and error or at random. Lynn et al. (1996) suggest that these probes should fit within a firm's strategic context, shaped by firm history and core competences. Similarly the RBV of the firm suggests that firms select activities complementary to their resources and strategy. Based on studies of entrepreneurial firms, it can be expected that firm's history, including experience prior to founding, influences a firm's initial market engagements. However, under a high degree of uncertainty when firms have difficulty to asses the potential and the risks of applications, a firm's proprietary market expectations and ambitions are likely to be overshadowed by factors external to the firm. External to the firm, emerging industries develop shared beliefs and expectations (Garud and Rappa 1994). To compensate for firm internal uncertainty, firms are likely to turn to the shared expectations of an emerging industry. Also, firms can be expected to learn from each other in this context. Aldrich and Fiol (1994) suggest that firms should engage in collective marketing and actions to develop trust for a new industry. Therefore, the development of shared industry expectations is expected to drive the initial decisions of YTB firms. In support of this proposition, Van de Ven et al. (1999) argue that early in the innovation process, when there is a high degree of uncertainty, external factors strongly influence decision making in firms. Driven by industry expectations, firms are expected to select similar market segments for initial probe applications at a particular time. Industry expectations develop over time and consequently, firms are expected to select different initial probes in different periods of industry development. This study proposes that the selection of initial probes is primarily driven by the expectations of an industry at the time.

P1 Industry expectations are more important than firm internal factors in explaining the selection of initial probes

The selection of subsequent probes

Feedback from initial probes provides a firm with information and experience to evaluate the potential of a market application. This experience is likely to influence subsequent decisions. Firms have expectations of their value propositions prior to initial probe engagements. Experience gained in initial probes enables reflective observation of these initial expectations. Literature suggests that in early phases of commercialisation there are multiple alternatives for technology development and market application and it is highly uncertain which options will become dominant at which time (e.g. Utterback 1997, Tushman and Anderson 1986). It can therefore be expected that firms have difficulty with selecting and predicting the outcome of initial probes. Moreover, Leonard-Barton (1989) suggests a technology almost never fits market requirements when it is first applied. Therefore, feedback from initial probes is expected to reveal a large discrepancy between a firm's technology and market requirements, providing a 'reality check' of a firm's initial expectations in terms of alignment and time to adoption. In hindsight, initial probes may even seem ill-chosen. Thus, the ex-post evaluation of initial probes is expected to result in a lower value proposition than initially expected.

March's (1999) concepts of exploration and exploitation suggests that when there are no prior certainties to exploit, firms will explore new possibilities. Moreover, in a product innovation process Buijs (1984) suggests that the phase of searching for innovation potential requires divergent thinking to derive alternatives. Firms are, therefore, expected to start diverging into new market segments after the 'reality check' from initial probes. In response to a firm's low value propositions, firms can be expected to adapt their strategy and engage in a modified scope of market segments and probe paths.

P2. Low value propositions, resulting from the evaluation of initial probes, will cause firms to search for alternative market applications.

The Breadth of Experimental Probes

If initial probes reveal discrepancy and uncertainty, then firms would need to redefine their value propositions. Probing and learning by experimenting in markets with immature versions of the technology, is argued to be a successful management practice to develop this market insight and identify opportunities (Lynn et al. 1996). In contrast to probing in diverse market experiments, firms may choose to engage in specific applications for development. It can be argued that focusing directly on the development of a specific application is more effective in terms of time and resources than probing in various market segments that may not be followed on. Considering the costly and time consuming nature of probe applications, is it necessary to probe alternatives? Innovation scholars suggest that radical innovation requires experimentation and learning (e.g. Tidd et al. 1997). Buijs (1984) found that divergence in the phase of strategy formulation is related to success of the innovation process. Moreover, studies on strategic decision making have found that experimental actions, like creating multiple alternatives, was related to more effective strategic decision making in high velocity markets (e.g., Eisenhardt, 1989, Judge and Miller, 1991). From a dynamic capabilities perspective, probing and learning may enable firms to develop, renew and reconfigure their competences in response to rapidly changing environments (5x). Furthermore, from an organisational learning perspective, Van de Ven et al. (1999) argue that learning by discovery is a necessary condition for setting preferences, goals and detailed planning. Probing with variations and learning by discovery are divergent processes of trying out alternatives, enabling a firm to discover opportunities and develop their ability to asses and select these opportunities. Therefore, in the context of uncertainty, it is proposed that probing alternatives by diverging into new market segments, is a necessary pre-condition for firms to develop their value propositions.

P3 .Probing alternatives is a necessary condition to develop a firm's value propositions.

Continuation of probes

There are likely to be short as well as long probe paths in an experimental phase of probing. What explains the continuation of probes or the length of probe paths? Firms have to distinguish between opportunities that are worth pursuing and those that are not and decide which opportunities to invest in and further develop. In the experimental phase of probing, probe continuation is likely to depend on external factors. Venkataraman and Van de Ven (1998) argue that once organisations and institutions have become aware of the firm's existence, environmental selection pressures increase and dominate above managerial choice. For example, Van de Ven et al. (1999) indicate that the continuation of innovation projects strongly depends on a firm's ability to convince customers, alliance partners and investors. Revenues from a new technology typically lie beyond the first probe applications and require longer term commitments. Particularly in the case of markets that are unlikely to provide short-term revenue, YTB firms are likely to depend on external sources of funding and commitment. Moreover, to shift from a product concept phase to production typically requires growth capital from external sources of funding (Wintjes 2004). The continuation of experimental probes is, therefore, likely to depend on the degree to which external actors such as customers, stakeholders or governments are willing to invest in the continuation of the probe.

P4 Availability of external resources dominates the decision to continue probes for mid and long-term applications.

Experimentation and Development

Throughout the probing process, firms gain experiences that are likely to influence the selection of applications for further development. However, at the same time, the emergence of niche markets and changes in the environment of a firm may drive the selection of probes for development. How do firms select market applications for development? Innovation studies suggest that as firms develop market insight through experiments and probing, uncertainty is reduced, decisions become more analytic and their outcomes become more predictable (e.g. Lynn et al. 1996, Van de Ven et al. 1999). From this perspective, the selection of probes for development is primarily driven by a firm's prior experiences in probe applications. However, the emergence of demand in other markets may overrule a firm's prior experiences. According to

Balachandra et al. (2004), firms grow increasingly responsive to external inputs from the market and make a transition to a 'market pull' phase. Considering that the survival of YTB firms typically depends on the emergence of niche market demand, firms are likely to shift to the markets where initial demand emerges, irrespective of prior probes. As a consequence, this study expects firms to show mimicking behaviour and the pursuit of similar 'emergent' markets. The emergence of market demand is likely to drive the selection of probes for development.

P5. The emergence of market demand is more important than probe experience in explaining probe selection

6.7.2 New Questions for Research

Innovation and high technology marketing studies provide limited theoretical support to formulate propositions on probe decision making and the conceptual model gives rise to further questions. The following topics are relevant to better understand the factors that influence probing behaviour and probe decision making over time:

- What explains the timing of initial probes?
- What explains the breadth of market segments?
- What factors determine when a firm stops probing variations and focuses on development?
- What factors determine the decision to shift to markets without prior probe experience?

In addition, the influence of customer familiarity and the role of partnerships in probe decision making require further research. This study will use these questions and constructs to focus the case study research and analysis. Guided by these questions, new propositions may be induced from the case study data.

Timing of Initial Probes

Probing involves the application of immature versions of a new technology. However, early probes can be a costly and risky undertaking: the technology may be too immature to demonstrate the potential and failure may damage a firm's credibility. The timing of initial probes appears to be a relevant decision. Some firms are expected to 'wait' until probing becomes more 'realistic' whilst other firms may choose to demonstrate immature versions of their technology. What explains at which moment firms decide to engage in initial probes? Literature fails to explain what factors drive the timing of initial probes.

The Breadth of Probing

Probing involves trying out alternatives. The descriptive model suggests that firms can probe in a variable breadth of market segments. Given the cost of 'probing' and limited resources available to YTB firms, what explains this breadth of probing? This study expects that there is a 'breadth limit' to probe and learn effectively. Firms may choose to engage in a select number of markets whilst other firms choose to engage in a broad range of probes. Assuming variable probing strategies in terms of market segment breadth, further research is necessary to understand what drives this variation.

Making a Transition to Development

March (1991) suggests that a balance between explorative and exploitive activities is necessary. At a certain point in time, explorative probes in new market segments are expected to become a 'distraction' from further development. The opposite of experimenting in new market segments is the development of an application through iterative development cycles to meet customer requirements. To make a transition to development and production, firms require less new information and more specific information for development. Gradually, firms are expected to make a transition from probing variations to a more focused development of applications. What factors determine this transition and the timing of convergence? Van de Ven et al. (1999) argues that the timing of transition to orderly cycles of development depends on the degree to which environmental uncertainty has decreased. However, further research is required to better understand what drives this transition. Is this decision determined by a firm's level of competences, and capabilities or by external factors such as resources and customer adoption?

Decision to Shift

Firms are assumed to gain market experience and competences, develop their technology and form partnerships through probing and learning. Firms may decide to change direction and shift between market segments and technological designs. Flexibility is likely to be advantageous for entrepreneurs in an uncertain and dynamically changing environment. However, innovation studies do not explain how the flexibility of firms is enhanced or constrained by probing and learning. Does probing cause path dependencies or does the experience gained enable flexibility? This study expects the concept of 'cross-over learning' to enable shifting between market segments. Further research is required to understand what factors determine a firm's ability to shift. Do a firm's technological or market related competences determine its ability to shift? Perhaps this ability is primarily determined by the availability of resources to shift.

Customer Unfamiliarity

The characteristic of radical technology is that customers are unfamiliar with the technology and typically perceive the new technology as a risky undertaking. This unfamiliarity is a key source of uncertainty in evaluating the value proposition of a market and predicting the timing of market adoption. In the case of a radical technology, supply side marketing is argued to be necessary. Customers are expected to learn and gradually become familiar with the technology and the firm through probe applications. However, there is a limited understanding of how customer familiarity influences probe decisions in the innovation process. To what degree are firms enabled or constrained by the level of customer familiarity?

Strategic Partnerships

Strategic partnerships are likely to influence probe decision making, particularly in YTB firms where probing and learning typically crosses firm boundaries. Innovation and high technology marketing literature address the importance of strategic partnerships, but not how they influence the selection and development of experimental applications. Therefore, this study will also question the role of partnerships throughout the probing process. On the one hand, firms may choose partners for probing. On the other hand, partners may constrain and shape the selection of probe applications.

6.8 Research Design

The conceptualisation in the previous sections has further specified the focus of this research. This conceptualisation is based on a preliminary study of the empirical domain and the literature reviews in the previous chapters. In section 1.7, the research methodology was briefly introduced: a case study research to gain a better understanding of how FC firms manage early applications of their technology. The previous chapters and the conceptualisation in this chapter have enabled a further specification of the case study research. This section will describe the research design in terms of i) revised research questions, ii) the case study methodology, iii) the case selection, iv) the data sources and v) the case study description and analysis.

6.8.1 Additional Research Questions

With a further specified research problem and focus, new research questions have been proposed. The first and second research questions on the challenges FC firms face and how FC firms manage the process of technology application, has been addressed in chapters 3 and 4. The concept of probing and learning has been chosen to describe and analyse a firm's early applications prior to widespread commercial sales.

Table 6.4 provides an overview of the research questions addressed in previous chapters.

Table 6.4 RQs adressed in chp. 2-5

Questions proposed in section 1.7	Addressed in the chapters:
1. What challenges do FC firms face in selecting and developing applications for their technology?	Chapters 3 provided insight into the management callenges involved. Provided focus: the selection of early applications in YTB firms. Chapter 4. reviewed literature on the uncertainties of radical innovations and the implications for the innovation process
2. How do FC firms manage the process of technology application?	Chapter 4, reviewed innovation and technology marketing literature and concludes that firms manage radical technologies through experimentation and learning. The concept of probing and learning is chosen to describe and analyse the process of technology application
3. What explains the selection of early market applications in FC firms?	Chapter 5, derived concepts from strategic decision making and organisational learning. A theoretical lens and relevant theoretical constructs were identified to explain the selection of early applications. Organisational learning concepts help to explain how experience gained in probes influences subsequent decisions
4. What characterises the process of FC technology application?	Conceptualisation proposed in this chapter. Phases of probing an diverse probing strategies expected

To address the third research question: "What explains the selection of early market applications in FC firms?", the central construct 'probe decision making' has been chosen for further research. This research question is therefore reformulated in terms of probe applications: "What explains probe decision making in young FC firms?" Chapter 4 and 5 addressed several explanatory constructs that may explain decision making. Decisions to pursue early market applications have been modelled as a process of probe decision making. This chapter has proposed a conceptual model of probe decision making and raised several new questions to better understand what explains probe decision making. The new sub questions of research question 3 include:
3c What explains the selection and timing of initial probes?
3d What explains the breadth of market segments?
3e What factors determine when a FC firm stops probing variations and focuses on development?
3f What factors determine decisions to shift to markets without prior probe experience?

The fourth research question proposed in section 1.7: "What characterises the early applications and diffusion of FC technology?", is reformulated for the process of probing: "What characterises a FC firm's probing process?" This chapter has proposed a descriptive model of probing and conceptualised patterns of probing. These predicted patterns will be compared to the case study data to characterise the process of probing and to derive patterns of probing and learning. In addition to the sub question 4a "What different patterns of probing can be identified?", the case study data will also address the following new sub questions:
4a Can the probing process be represented on the basis of breadth and length?
4b What phases of a probing process can be identified?
4c What explains differences in patterns of probing

6.8.2 Case Study Research

The case study research methodology was briefly introduced in chapter 1. This paragraph elaborates on the choice of this research methodology and further describes the specific case study approach taken. Yin (1994) suggests that case study research is highly suitable to study real world situations and particularly suited to identify multiple factors that influence a phenomenon under study. Likewise, this study aims to better understand the phenomenon of probing and learning in the real world settings of FC firms. Strauss and Corbin (1990) suggest that case study research is suited for exploring and discovering new areas that are not well understood. For the purpose of this study, case study research is used to explore the probing processes of FC firms. Furthermore, Eisenhardt (1989: p.534) explains that *"case study is a research strategy which focuses on understanding the dynamics present within single settings"*. In this case study, FC firms are the cases or single settings under study. Case study research is predominantly an inductive approach to better understand the way in which events take place and can be used to provide description, test theory or generate theory.

A well known approach to case study research is the work on 'grounded theory building', in which data and theories are continually compared (e.g. Glaser 1968, Strauss and Corbin 1990). This approach begins with data collection and is inductive: the emergence of theory should stem solely from case evidence. The grounded theory approach does not depart from theory or hypothesis but ideally begins with the collection of case evidence from a 'clean slate'. However, Eisenhardt (1989) argues that departing from a 'clean slate' is impossible. Moreover, Eisenhardt finds that some degree of a priori specification enables more accurate measures of the phenomenon under study. Eisenhardt proposes a case study methodology that begins with specified research problems and research questions, identified constructs and a specified population of cases. Thereby, this approach to case study research includes both inductive and deductive features. In line with Eisenhardt's (1989) case study methodology, the previous chapters have specified: i) the research problem, technology application decisions in YTB firms; ii) the phenomenon under study, probing and learning, iii) aspects of probing and learning that require further study, probe decision making and patterns of probing and iv) several constructs from theory to study the relative influence of these constructs. The models, the constructs and the propositions described in this chapter will be used to guide the case study data collection, description and analysis in the following chapters.

Burawoy (1991) describes a similar approach of prior specification, the 'extended case methodology'. This approach builds on prior literature to extend and integrate existent theory. The approach is characterised by cycles of confrontation between data and theory, in an iterative process between existent theories and data, directing the analysis to additional data and drawing on additional concepts and theory. In the previous chapters, literature has provided constructs and conceptual frameworks to aid the interpretation of case study data. In addition, the case study research in the following chapters is expected to point to other relevant concepts and theories and enable the induction of new propositions and findings from the case study data. The case analysis involves looking for themes and patterns in the case study data, contrasting and comparing these to theory to extend and integrate existent theory. This approach is similar to the technique of 'pattern matching', described by Yin (1994), in which empirical patterns are compared with predicted construct relationships. The descriptive model of probing and the conceptual model of probe decision making will be used to guide the case study description and analysis.

6.8.3 Case Selection

This study has focused on FC technology as a case of radical technology application. As Eisenhardt (1989) suggests, the specification of a population for case study research is important to control extraneous variation. Moreover, a specified population helps to define the limits to generalising findings. In chapter 3 and 3, the industry and the technology have been characterised. For the case study research, a selection of cases within the FC industry needs to be specified. The selection of cases is an important aspect of case study research. Limiting the variation to cases within the FC industry minimises extraneous variables, facilitating a contribution to theory. Maximising variation between cases within the FC industry increases the possibility to identify the factors that influence the phenomenon under study. For the purpose of this study, variation between FC firms is desirable to observe the scope of constructs that may influence probe decision making. Given the limited number of cases that can be studied within the timeframe of this study, it makes sense to choose cases in extreme situations, referred to as 'polar types' (Pettigrew 1988).

A classic approach in innovation studies is to compare polar types in terms of successful and unsuccessful cases for building theories of success and failure. However, with radically new technologies such as FC technology, the numerous interrelated uncertainties make it difficult to link management practices to project outcomes. Besides, Van de Ven et al. (1999) argue that when an innovation process is not yet completed and implemented, it is not possible to determine whether an innovation will be successful. As the widespread adoption of markets is years away, the outcomes of FC firms cannot be classified as successful or unsuccessful as yet. Van de Ven et al. (1999) suggest that when the outcomes of an innovation process are unknown, a useful research methodology is to map the processes that underlie the innovation activities. Lynn et al. (1996) have mapped the process of probing and learning for singular cases. This study aims to derive a more in-depth understanding of probing processes and 'probe decision making'. The selection of cases will be based on a variation of probe decision making strategies.

For the purpose of this study, probe decision making has been selected as the dependent construct. Case variation over the dependent variable or construct is useful to describe the phenomenon under study and derive an understanding of the independent factors that influence this variable. By contrast, variation over the independent variables would be suitable to research the impact of these variables on the dependent variable. With the aim of better understanding probe decision making and the independent variables that influence this construct, the case firms are selected on the basis of variance over the construct 'probe decision making'. In this manner, the scope of factors influencing probe decision making can be identified. Furthermore, this study aims to gain insight into different probing strategies. According to the definition presented in section 6.2, the construct 'probe decision making' is variable in breadth of market segments and length of probe paths. The selection of cases will be based on a variable breadth of market segments. The length of probe paths will be described during the case study research. Firms can choose to engage in a narrow or a broad scope of market segments. The breadth of market segments is defined as the number of different market segments a firm is engaged in. The breadth of markets was measured in the year 2006. Probing strategies are also expected to vary for different types of innovations, therefore, in addition to variable breadth, the cases selection is also based on a variation of technologies applied.

To enable comparison, the differences between the cases must also be limited. The case firms are all selected on the basis of the following similarities: YTB firms within the FC industry focused on the application of PEM FC technology. In order to compare probe decisions between cases, the cases are selected from within the FC industry. The case firms target the development of the same technology, PEM fuel cell technology. Finally, with a focus on probe decision making in YTB firms, a selection is made of independent FC firms founded in the previous ten years.

Regarding the number of cases to select, there is a balance between the depth of the case study research and number of cases that can be studied in a given period of time. For the purpose of this study, the driving criterion is a sufficient number of cases to cover the range of explanatory constructs. Four case study firms in the FC industry are selected. The quantity of four cases enables comparison and variance as well as an in-depth understanding of the probing process. The four case firms are selected based on variance in the breadth of market probes and the technology applied. The selected case firms are: Plug Power, Hydrogenics, Intelligent Energy and Nedstack. Plug Power is a FC firm renowned for its focus on on-site energy applications and back-up power in particular. Probes are conducted with end-products developed at Plug Power. Hydrogenics has focused on two niche markets and applies FC modules with an integrated FC system to probe applications. Intelligent Energy collaborates with partners to develop FC systems for transport and niche market applications, targeting intellectual property (IP) licensing agreements. Nedstack is involved in a wide range of market segments, from stationary to transport and various niche market applications. Nedstack produces and applies both stacks and systems in these probes. On a practical note, these case firms each have their headquarters or a subsidiary office in the proximity of the Netherlands. Appendix A provides an overview of the selected case firm characteristics.

Variation in the breadth of market segments is expected to provide insight into the factors that drive a focused or broad probing strategy. A focused strategy is expected to result in an in-depth market understanding, yet a risky reliance on the success of these markets. By contrast, a broad strategy enables flexibility and access into numerous markets, but a firm may 'waste' resources on the various alternatives and develop a limited understanding of specific markets.

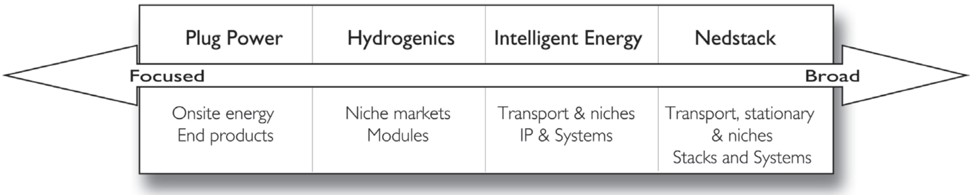

Figure 6.6 Case selection based on variable probing strategies in terms of market breadth and technology applied.

6.8.4 Data Sources

Case studies typically combine various data collection methods (Eisenhardt 1989). Combining multiple data collection methods and data sets, both qualitative and quantitative, is termed triangulation. The rationale is that triangulation provides evidence from various sources to validate constructs and propositions. According to Yin (1994), multiple data sources can enhance construct validity. From an inductive case study approach, researchers tend to work predominantly with qualitative data (Denzin and Lincoln 1994). Likewise, most of the data in this case study research is qualitative, derived from interviews and press releases. Some quantitative data is derived from financial data and patent databases. Appendix B provides an overview of the data sources.

Interviews Management Personnel

Qualitative data from interviews provides rich descriptions to better understand how a phenomenon occurs. In order to bring to light the drivers, motivations and experiences behind probe decision making, open interviews are considered to be a highly suitable research method. Therefore, interviews with management personnel of the FC case firms is the main data collection method applied in this case study research. Due to the explorative nature of this study and the complexity of the process at hand, open interviews were conducted in a semi-structured format. This format implies that although interview questions are used to guide the conversation, the interviewee was given the time to explain the decisions made and the experiences gained in his or her own words.

Interviewees were selected from management personnel because of their involvement in and experience with application decisions. The central criteria for the selection of interviewees include: i) their level of involvement in technology application decisions ii) the appropriateness of their position and level of experience to explain the rationale behind decisions and the lessons learnt from probe applications over time. The interviews lasted from one hour to two and a half hours. Two sets of interviews were conducted with each case firm. The first set of interviews carried out, focused on the motivations for engaging in probe applications. A second set of interviews was carried out half a year later, with different persons in each case firm. In this second set of interviews, the interviewees were asked to reflect on the main findings from the first interviews and subsequently the interviews focused on the learning and experiences gained in the main probe applications of the respective case firms.

Archives and Documents

To describe the probe applications in each case firm, archives and documents were researched to complement and validate findings from the interviews. Press release data in particular provided dates and descriptions of the decisions to probe, the development and the realisation of probe applications. The official press releases on the FC firm websites were used as a point of departure. In addition, databases with press release data have been used to countercheck and complement this information. The FC 2000 technology update provides detailed information on developments and demonstrations in PEMFC technology since 1996[1]. In each year and month the database was searched for the case firm names. In addition, 'Fuel Cell Today', 'Fuel Cell Markets' and 'Green Car Congress' provided complementary archives on activities and developments in the FC industry.

Furthermore, Plug Power and Hydrogenics are public firms and their annual reports provide a detailed overview of accomplishments and plans. The annual reports provide quantitative data in the form of financial data and sales. Additional information on Intelligent Energy is sourced from the Library House individual company profiles[2] and the London Hydrogen Partnership. Nedstack is involved in various projects supported by European and Dutch subsidies. Therefore, the Cordis database[3] and SenterNovem database [4] of subsidised FC projects provide an additional source of information on Nedstack's probe and R&D activities.

Other Data Sources

Other sources of information to describe and analyse probe applications in the FC case firms include presentations by the case firms at FC conferences and patent data. FC conference presentations provide up-to-date information on the case firms developments and plans. The European Patent Office[5] provides access to a database of worldwide patents. Patent data is a source of information to analyse the R&D a firm has conducted and its scope of proprietary technological competences. According to Archibugi and Pianta (1996) patent data provides some indication of a firm's strategies before they are implemented in the market. Considering the cost and time involved in pending patents, patent data are expected to provide an indication of a firm's commercial expectations and strategic intent with regard to particular technologies and applications.

6.8.5 Case Study Description and Analysis

The case study description, presented in chapter 7, brings together data from the above mentioned sources. Case study research is characterised by a large volume of data and different types of data. To describe and analyse this volume of data, a structure is necessary. Structuring case study data typically involves detailed and descriptive case study write-ups for each case (Eisenhardt 1989). There is no standard format to structure case study descriptions. In a case study research of three case firms, Van de Ven et al. (1999) describe a detailed sequence of events for each case firm. Geels (2002) described the historic development of several technological transitions. Case histories provide a descriptive account, tracing events over time. This form of case description appears suitable for analysing the probe applications a firm has pursued over time. This chapter has proposed a descriptive model to describe and analyse the probing processes of firms. Based on this model, an historic account of the probe applications in each case firm will be described. These historic accounts are described in chapter 7. The description of chronological events alone may provide insightful descriptions, but there is a risk of data becoming mere 'chronicles' (Yin 1994). In order to identify casual inferences and identify patterns within the chronological events, Yin recommends the description of constructs and the relationships between the constructs within a historic case description. Theoretical constructs and predicted patterns help to organize and focus the case study data.

[1] *Fuel Cell 2000, an online fuel cell information source: www.fuelcells.org*

[2] *Library House company profile: www.libraryhouse.net. An online service that provides information on innovative ventures in Europe.*

[3] *Cordis: Community Research & Development Information Service, http://cordis.europa.eu*

[4] *SenterNovem database, www.senternovem.nl/senternovem/projecten/*

[5] *European patent office: http://ep.espacenet.com*

Therefore, the predicted phases of probing and the theoretical constructs proposed in this chapter will be used to describe and structure the historic accounts of probing processes.

Case Study Analysis

The case studies presented in chapter 7 are concluded with an analysis of each case: a within case analysis. Chapter 8 discusses a cross case analysis of the case firms. As Coffey and Atkinson (1996) describe, the analysis of qualitative data begins with the identification of key themes and patterns. For case analyses, Yin (1994) recommends a technique of pattern-matching logic, in which empirically based patterns are compared to predicted patterns. Likewise, the cross-case analysis of this study will be based on the comparison of observations in the FC case firms and the descriptive model, theoretical constructs and propositions proposed in this chapter. In the cross case analysis, the cases are first compared and analysed along the explanatory constructs. Through this analysis, patterns of probing are expected to emerge. The emerging patterns are compared and contrasted to the phases and patterns conceptualised in this chapter. On the basis of the case study data, the theoretical propositions are tested: do the predictions hold true for the case study data? Finally, propositions are also induced from the case study data, guided by the new research questions proposed in section 6.7.2. Yin (1994) suggests that there are two criteria determinant for the quality of case study analysis. First, external validity, the domain to which a study's findings can be generalised and secondly, the reliability, the degree to which the operations of a study can be repeated. The scope of generalisation and the reliability of findings are discussed in the final chapter.

Chapter 7: Case Study Description

This chapter describes an historic account of the case firms' probing processes on the basis of data collected in the case study research. The models proposed in chapter 6 are used to structure the case study descriptions. The following structure is applied for the historic account of probing process: the firm's probe applications are described over three periods. For each period, the drivers or input for probe decision making are primarily described in terms of firm competences, resources, strategic motivations, resource availability and customer interest. The main probe applications are subsequently described in detail: the product-technology, the market segment, the time of announcement, the number of units demonstrated, the collaboration involved and their follow-through or abortion. The outcomes of these probing periods are described in terms of the experience gained and the consequences for subsequent probe decisions. The main sources of data for this historic account of the probing processes are interviews conducted with management personnel of the case firms (appendix A). Press release data and annual or strategic reports have been gathered to complement the interview data. In some cases, patent data is used to verify technological developments.

The case firms are described in the following order: the Plug Power case in section 7.1, the Nedstack case in section 7.2, the Hydrogenics case in section 7.3 and finally, the Intelligent Energy case in section 7.4. Each section describes the case firms in the following order: primarily, notable aspects of a firm's probing process are summarised. Subsequently, the case firm is introduced in terms of firm history, growth, supply chain position, business model and partnerships. The main part of the case study description follows: the historic account of the case firm's probing process, described in the above mentioned structure. Finally, a within-case analysis is discussed to explain the observed probing behaviour and probe decisions.

7.1 Case: Plug Power

The main interviews for the Plug Power case have been conducted with: i) Jos van der Hyden, General Manager of Plug Power's European, Middle Eastern and African operations in 2006 and ii) Ellart de Wit, senior project manager of the Plug Power office in the Netherlands in 2006. The interviews took place in January 2006 and April 2006 respectively. As a public company, the annual reports (AR) from the year 2000 up to and including 2006 provide complementary data in addition to press releases on the Plug Power website.[1.]

The Plug Power case has been selected for its focused market application strategy with primarily end-products. Plug Power's probing process, as described in the following paragraphs, shows an early focus on a select number of market segments in on-site energy (stationary) applications. In addition, the process shows early field trials with immature versions passing through multiple iterations in linear probe

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[1] *Plug Power: www.plugpower.com*

paths. Plug Power's probing process additionally reveals a number of notable instances regarding decisions to engage, pursue and abort probes. First, Plug Power pursued initial demonstrations in stationary and automotive markets and subsequently aborted the automotive segment. Secondly, Plug Power has targeted the CHP market for residential applications since founding, even though the expectations for market adoption have been postponed repetitively. Plug Power's probing process is subsequently characterised by a focused engagement and intensive pursuit of the back-up power market for telecom. Notable is the recent diversification to material handling markets.

7.1.1 Introduction to Plug Power

Plug Power is a PEM FC company with headquarters in Latham, New York. The company was founded in 1997 as a joint venture between Mechanical Technology Incorporated (MTI) and DTE Energy. MTI was an early developer of FCs and DTE Energy is the largest energy service and utility company in Michigan. Among the 22 employees at founding were people that had worked for American FC programmes such as NASA and the American Government. The company was founded to profit from the application of FC technology. According to Van der Hyden the founders believed that, *"FC technology is now so far that possibilities are emerging for companies to profitably apply their technology".*

Firm Growth

Between 1997 and1999, Plug Power focused its efforts on R&D and joint developments where conducted with Los Alamos research centre and General Electric. In November 1999, Plug Power completed an initial public offering. In February 2000 Plug Power acquired the Intellectual Property (IP) from the Dutch company Gastec NV to incorporate fuel processing expertise in the company. Subsequently, Plug Power Holland was established in February 2000 as Plug Power's European headquarters. In November 2002 Plug Power acquired competitor H Power, a FC systems manufacturer focused on back-up power applications. In April 2007, Plug Power announced the acquisition of Cellex Power Products Inc., a private developer of FC power systems for forklift trucks and other material handling equipment. In May 2007, Plug Power announced the acquisition of General Hydrogen Corporation, a developer of FC power units for electric lift trucks and other mobile industrial equipment.

The company grew from 22 persons at founding to approximately 500 in December 2000. In the following year, Plug Power dramatically decreased the number of personnel to 366, reported in December 2001. The following years the firm's size fluctuated around the 330 employees. In 2006 Plug Power reports 324 staff, of whom 211 are engineers, scientists and other employees with professional degrees.

Technological Competences

The technological core competence of Plug Power is PEM FC systems in the range of 5kWe for stationary power applications. Through the acquisition of Gastec and subsequent technological developments, Plug Power has developed proprietary reforming technology. In 2000, Plug Power filed a total of 123 patents and 18 patents were awarded, primarily in FC stack and system design. In 2002, Plug Power reports 23 new patents obtained, amounting to 41 patents. In 2003, Plug Power added and acquired 18 patents, several in the field of CHP system operation and reforming. The annual report of 2006 reports 148 U.S. patents, 10 foreign patents, and 173 patents pending worldwide.

Business Model & Supply Chain Position

Plug Power's business model with regard to the applications of its technology revolves around the manufacturing and sales of commercial products for large markets in the stationary energy sector. Plug Power is focused on the stationary energy sector, as De Wit describes, *"our vision statement is clean reliable energy, distributed energy, … so all our ideas fall within this vision. There are applications in which FCs are used for back-up power or prime power… and what we now fully continue with is back-up power and permanent power at remote locations"*

Plug Power supplies end-products, primarily to business customers, with the exception of the supply of FC subsystems to its partner Vaillant, an OEM manufacturer of heating appliances.

Strategic Alliances

Plug Power has partnered and formed strategic alliances for R&D, the development of applications and the formation of supply chains. In 1999 Plug Power and GE power systems formed a joint venture company, GE FC Systems. In this strategic partnership, the company GE FC Systems acts as the global distributor of Plug Power's FC products. Since 2000 Plug Power has a joint development agreement with Celanese GmbH of Frankfurt in Germany to develop a high-temperature membrane and electrode unit and a joint development agreement and a supply agreement with Engelhard Corporation to develop and supply advanced catalysts for reformers. In 2006 Plug Power formed a collaborative relationship with NexTech Materials, Ltd. to investigate the development of SOFC power systems.

Plug Power has maintained long term partnerships with Vaillant and Honda for the joint development of applications. Since 2000, Plug Power has partnered with Vallaint to co-develop FCs for combined heat and power in European multi-family homes. Vaillant is also a key distributor and customer. Since October 2002, Plug Power has been working with Honda R&D, under a joint development agreement to develop and test Home Energy Systems for FC automobiles. Plug Power and Ballard Power systems formed an alliance in 2006 to develop an advanced prototype FC back-up power system for the US Department of Defense. In October 2006, the Strategic Partner Agreement with the national innovation company New Energy Projects was formed to collaborate on technology and market development efforts in Russia.

Plug Power has formed supply agreements with, among others, 3M, Entegris and PEMEAS. The annual report of 2005 reports 17 distribution partners for its back-up power product world wide, including: the partnership with Tyco Electronics Power Systems and IST Holdings Ltd. (IST), based in Pretoria, South Africa.The Long Island Power Authority (LIPA) has been an early and long-term customer of Plug Power since 2000 for grid supplemental and back-up power.

Financial Resources

Prior to the initial public offering (IPO) in 1999, Plug Power primarily derived revenue from government research grants and development contracts. The annual report of 2000 (p.13) states, *"total revenues, primarily from the reimbursement of government contracts increased to $11.0 million for the year ended December 31, 1999 from $6.5 million for the year ended December 31, 1998".* Between the IPO in 1999 and through to December 2000, stakeholders had contributed $228 million in cash. During 2001, Plug Power raised $61 million of additional funding. The annual report of 2003 states that Plug Power gained $85 million in cash from the merger transaction of H Power.

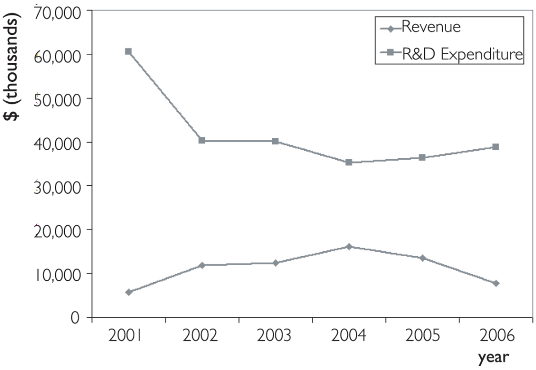

Figure 7.1 Financial data Plug Power. Source: Annual reports 2001-2006

Meanwhile, financial support from the government continues primarily from the Department of Energy (DOE), New York State Energy Research and Development Authority (NYSERDA) and the National Institute of Standards and Technology's Advanced Technology Program. The 2003 annual report describes further contracts in the order of $15.0 million in net cash from these government contracts. In 2006, press releases announce $8.6 million funding from the DOE. The 2006 annual report describes a $217 million investment by Smart Hydrogen, a joint venture of principal investors of Interros, a major Russian investment firm and Norilk, the world's largest producer of nickel and palladium. Nevertheless, R&D expenditure at Plug Power, to date, greatly exceeds total revenue (fig. 7.1).

Plug Power's Probing Process

The following paragraphs describe an historic account of Plug Power's probe applications over time. Figure 7.2 illustrates the probe applications Plug Power has engaged in since founding. The probing process has been categorised in three periods. Plug Power's probing process begins with a period of early demonstrations between 1997 and 1999. In a second phase, between 2000 and 2003, Plug Power developed and introduced its pre-commercial product line in parallel to probe applications with strategic partners. Plug Power's third period of probing is characterised by launching customers, field tests and customer orders. In addition to these probe applications, Plug Power has been involved in a number of public-private demonstration projects. Plug Power's current phase is characterised by initial sales and repeat orders.

The approximate numbers of installations and customer order throughout this probing process are described in Plug Power's annual reports. During 2000, Plug Power installed and tested 52 systems in the field. 2001 reports the installation of 75 systems installed at the LIPA. In 2002 Plug Power reports the delivery of 121 systems and in 2003 a delivery of 145 systems. In 2004, Plug Power sold 56 prime power systems and shipped around 100 GenCore systems. The annual reports of 2005 and 2006 announce 306 orders and 539 orders for GenCore systems respectively.

Each period is introduced with an overview of Plug Power's probe applications followed by a detailed description of the prominent probe paths in that period, determined by their i) centrality in interviews, ii) and announcements in annual reports and press releases. The prominent probe paths in this Plug Power case include the initial demonstrations in the first period, the partnerships with the LIPA, Vaillant and Honda in the second period and the probe with launching customer Orange in the third period.

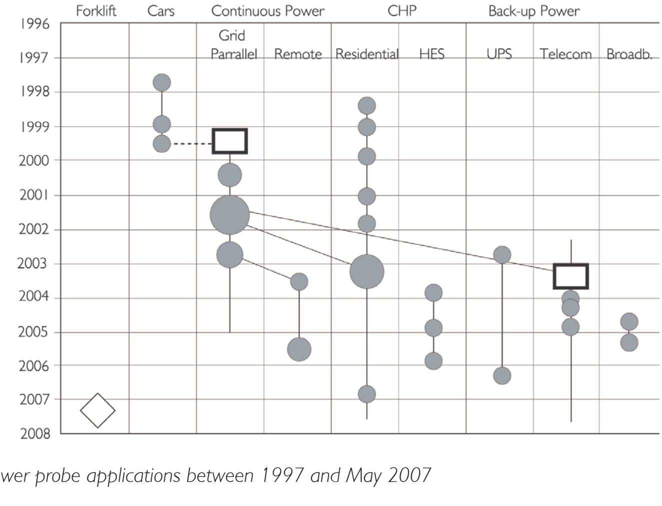

Figure 7.2 Plug Power probe applications between 1997 and May 2007

7.1.2 Period 1: Early Demonstrations

In the first period between 1997 and 1999 Plug Power primarily focused on R&D in FCs, building on the technological core competences in FC R&D inherited from MTI Energy. During this period, Plug Power primarily gained financial support from local and state institutions for R&D as price and performance of the technology were not competitive. In 1997 Plug Power received $15 million R&D funding from the US Department of Energy program. Additionally, Plug Power was funded by and involved in development programmes of the NYSERDA.

Plug Power's first probe is announced in press releases in October 1997: a technical demonstration of the first system to successfully convert gasoline to electricity. This first probe is a demonstration of Plug Power's FC stack technology and the demonstration of fuel reformer technology developed by Epyx. Subsequent technological demonstrations include the demonstration of a FC system on hydrogen and methanol in November 1998 and the demonstration a FC system fuelled by natural gas in December 1998. Van der Hyden describes this period of R&D as, *"understanding the do's and don'ts of FCs… is it applicable, what works in practice and what does not work in practice".*

The company conducted collaborative R&D with the Los Alamos National Laboratory aimed at the commercialisation of Plug Power's FC systems for stationary as well as automotive applications. Plug Power engaged in two different market segments during the first period: automotive and stationary power for the residential market. These initial probes for the stationary and automotive market were aimed at showcasing Plug Power's technology and demonstrating technological achievements.

Stationary Power Demonstrations

Plug Power's historic roots in the Detroit energy utility company led to the development of initial probes in the stationary power market. Moreover, large scale adoption of FC CHP units in the residential and small commercial market was expected within years. Plug Power's first demonstration in an application was announced as the world's first FC powered house and unveiled in June 1998[2]. Plug Power powered a residential house near the company's headquarters with a 7 kW FC system fuelled by hydrogen and methanol. In January 1999 the company announced that it had successfully completed the demonstration of a FC system fuelled by natural gas in a residential home. This probe additionally demonstrated Plug Power's natural gas reforming technology.

In February 1999 GE and Plug Power formed GE FC Systems as a joint venture to exclusively distribute, install and service Plug Power's residential and small commercial FC systems. GE was the inventor of the PEM FC in the 1960's and GE had the largest global sales and service network in the power systems industry. A Plug Power presentation in 1999 suggests that for Plug Power, *"the GE brand provides significant customer recognition"*[3]. With this joint venture for marketing and distribution support, Plug Power continued on the path of residential FC systems. Plug Power and GE developed the demonstration probe announced in press releases of December 1999: the 'house on wheels', a demonstration bus containing an operational residential FC for auxiliary power.

Outcome

The period is characterised by a high degree of R&D, technological development and testing. In a meeting with the LIPA in November 1998 the representative of Plug Power states, *"Plug Power conducted a significant amount of testing since General Electric has come on board" (LIPA 1999)*[4]. The demonstrations provided 'proof of concept' to potential early adopters and investors. Furthermore, Plug Power developed and acquired technological competences in reforming.

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[2] *New article on fuel cells 2000 of July 1998, www.fuelcells.org.*

[3] *From a Plug Power presentation September 1999. The Plug Power game plan, FCs for the residential market.*

[4] *Long Island Power authority, Minutes of the 118th meeting held on November 18, 1999.*

Automotive Demonstrations

Plug Power announced the demonstration of a FC automotive system in January 1999. The development of this system was part of a joint programme between Plug Power and Ford Motor Company funded by a US DOE programme, "Partnership for a New Generation of Vehicles". Plug Power demonstrated to Ford an automotive FC system responsive to actual vehicle power requirements. The subsequent automotive related probe was demonstrated in May 1999. Funded by a similar DOE program, Plug Power and the Epyx Corporation demonstrated an integrated system for conversion of gasoline to electricity with an overall system efficiency of 40% and near zero emissions. Further efforts were undertaken by the Plug Power and Epyx team to reformulate several other gases including methanol and natural gas. The probe demonstrated a promising solution for automotive power in onboard fuel processing and a FC system enabling the use of conventional fuels. Press releases show that at the time this achievement in efficiency improvement and emission reduction was considered to signal a major breakthrough for environmentally friendly automotive power generation. These automotive demonstrations appeared promising, as the following press releases indicate: *"these results prove that FC-powered automobiles are the best bet we have for meeting our global environmental initiatives," said Gary Mittleman, Plug Power's President and CEO"*[5].

Additionally Mittleman[6] stated, *"Although FCs for automotive applications are a number of years away from commercial reality, they will clearly constitute a huge market. Our recent demonstration to Ford with Plug Power's innovative technologies positions us as an industry leader in developing the automobile of the next millennium"* .

The early projects in automotive power did not lead to new automotive probes. After 1999, Plug Power did not conduct further probes in automotive power. However, as Brown (2007) comments, the automotive probes exposed Plug Power to the importance of fuel processing as part of the overall system, not to have to rely on pure hydrogen. Natural gas reforming was taken further as seen in subsequent Plug Power developments and probes largely based on natural gas fuelling. The acquisition of Gastec in 2000 additionally confirms Plug Power's subsequent reliance on reforming technology.

Outcome of First Period

Plug Power demonstrated its PEM FC technology in probe applications with mass market potential, to future customers and investors. Within this context the company generated sufficient interest to initiate IPOs at the end of 1999. At the end of December 1999 Plug Power had manufactured its first 52 FC systems. Through R&D and probe applications in the period 1997 to 1999, Plug Power further developed its technological competences. As De Wit explains, *"in the first years, 1997-1998, we had built up a lot of experience with stacks and hydrogen systems".* In addition, Plug Power developed and acquired reforming technology.

Moreover, feedback from the probe applications in this period revealed that mass markets where further away than initially expected. The early demonstrations gave a new perspective on the time horizon for technology adoption. De Wit describes the impact of the initial demonstrations: *"everyone thought within a few years, everyone was running to the market like crazy. They thought it was so close by, until the technology was put in the market. Plug Power was one of the first to put one in the market… then we saw, hey.. this doesn't make sense".*

In the fall of 1999, Plug Power was the first to present an adoption curve for its expected market adoption (fig. 7.3). This curve illustrated Plug Power's modified expectations and showed that the residential and automotive markets were further away than expected. The curve shows Plug Power's expectations for off-grid power generation, first to niche markets such as UPS and telecom and subsequently to residential stationary generation. In a meeting with the Long Island Power Authority, Plug Power stated that commercial rollout of its off grid stationary system was expected in 2001(LIPA 1999). The automotive market is still presented to have potential, with an expected mass market uptake in 6 to 10 years.

[5] *Press release May 19, 1999. 'DOE programme achieves important milestone'.*

[6] *Article in San Diego earth times, PRN News wire, March 1999. 'Plug Power breaks new ground in automotive FCs'.*

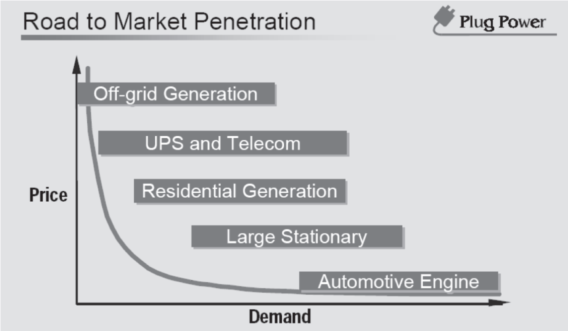

Figure 7.3 Adoption curve presented in 1999

7.1.3 Period 2: Technology Platform and Partnerships 2000-2003

By 2000, there were multiple changes in Plug Power compared to the initial years after founding. The initial probes had resulted in moderated and adjusted expectations with regard to the timing of market adoption, and Plug Power's modified expectations are key to understanding subsequent probe decisions. In the second period, between 2000 and 2003, Plug Power shifted from residential stationary and automotive markets to probes in niche markets within stationary segments.

By 2000 Plug Power had developed technological competences in FC, hydrogen and reforming technology. Additionally, Plug Power had become a public company. There were resources to build a manufacturing facility, but also the necessity to target a near term large market. The annual report of 2001 (p.1) states that *"the most dramatic change for us in 2001 was the adoption of a progressive market engagement plan"*. The value proposition for automotive and residential markets proved to be insufficient. Subsequent probe decisions appear to be explained by the necessity to identify and develop value propositions and strategically position the firm with respect to other firms in the industry. Plug Power began to seek near term applications that fit the firm's technological competences, as De Wit explains,
"the focus was necessary. At a certain point we saw: that mass market, we are not going to make it. What does that mean for the business? There are companies that have invested significantly in us. We have to have a large market. Then we looked at, what are we strong in? Ballard was in the automotive. Maybe portable, almost everybody was looking at DMFC. But that is a very different technology, that did not fit and it would not help us to reach that larger market. What are the possibilities to work with reformers and natural gas?"

Plug Power continued to receive financial support from government agencies, and in particular the NYSERDA and the United States Department of Defence (DOD). These agencies were also Plug Power's initial customers. The annual report of 2000 (p.6) states that *"The federal and New York State governments were instrumental in supporting our efforts to determine how our systems will work under real-world conditions"*.

In 2000 Plug Power built a series of pre-commercial products intended for field-trial probes. This application strategy of field trials with pre-commercial systems was aimed at gaining customer feedback. Between 2000 and 2003, Plug Power built a manufacturing facility with resources from the IPO. According to Van der Hyden, *"we did it the other way around. We have said, we assume that this is possible, we have the procedures in place and we are ready for delivery. We have invested our money in that…. From this perspective we are front runners in the industry because we are run as a company that is ready, or at any moment ready, to build 800 products when that client with an order of 800 comes"*. With this approach, Plug Power engaged in early field trials and continued to do so in subsequent years. Consequently, Plug Power's probe paths are long, showing numerous iterations and optimization cycles.

In June 2001 Plug Power demonstrated the Stationary Unit 1 (SU1), at a shareholders meeting. This FC generator powered a lamp, refrigerator and an air conditioning unit. The SU1 is a 5 kW integrated PEM FC system fuelled by natural gas. The system was sold and supplied to various demonstration and test sites such as universities and laboratories. The system was first tested in field trials with the NYSERDA. The Long Island Power Authority additionally provided an early test bed for Plug Power's first SU1. This probe path will be described in further detail as it provided a test bed for Plug Power's subsequent products. On the basis of the SU1, Plug Power developed technology platforms for various markets.

In the second period, between 2000 and 2003, Plug Power developed new market applications and made a transition to a focus on the back-up power, prime power and CHP market. Between 2002 and 2003, Plug Power developed and introduced the pre-commercial product platforms: the GenSys, GenCore and GenSite. The following paragraphs summarise the development of these product platforms. Subsequently, the main probe paths of these systems are described.

Technology Platforms

1. GenSys Path

Based on the SU1 FC system with a natural gas reformer, Plug Power launched the GenSys5C platform in July 2002, a Combined Heat and Power (CHP) FC system. The annual report of 2002 (p.3) states, *"GenSys™ 5C represents a major advancement into the market for combined heat and power".* The GenSys™5C unit provides supplemental heat and electricity to the facility and is capable of generating 5kW of electricity and 9kW of heat. The system was first demonstrated at the Town Hall in Babylon, N.Y under sponsorship of the LIPA. Subsequently, 10 Plug Power GenSys™5C FC systems were installed in support of residential and operational facilities at the Watervliet Arsenal complex in 2002 for the US DOD. The GenSys5P, a 5 kW grid parallel system fueled by liquid propane, was introduced in August 2003. Additionally, in 2004, fifteen GenSys systems were delivered to military and other federal facilities under the U.S. Department of Defense Residential FC Demonstration Program (AR 2003).

The GenSys was targeted at markets for grid parallel continuous power, as demonstrated in the LIPA partnership as well as markets for residential combined heat and power, as demonstrated in the Vaillant partnership. In the Honda partnership the GenSys was applied in the Home Energy System to generate heat and electricity in the FC and hydrogen from the reformer. Additionally, the joint development partnership with Vaillant applied GenSys technology.

2. GenCore Path

The 5kW Gencore Direct Hydrogen technology platform was developed on the basis of the SU1 and GenSys. Technological competences in FC and hydrogen technology where gained in the first years. De Wit explains that *"in the first years, 1997-1999 we already gained a lot of experience with stacks and hydrogen systems.* The Gencore is a spin off from that". Additionally experience from the SU1 and GenSys could be transferred as the FC system is virtually the same, excluding the reforming technology.

The opportunity for direct hydrogen back-up power for the telecom market and Uninterruptible Power Supply (UPS) was recognised in the years 2001, 2002. At the end of 2001, Plug Power reports: "A particularly exciting opportunity that we will address in the near future is the premium or back-up, power market". First applications of the back-up power system were with the LIPA for UPS and a NYSERDA- Version partnership for telecom customers. Following, the first GenCore was launched in July 2003. According to the annual report of 2003 (p.5), *"the need for such a product came from industry".* By the end of 2003, 19 back-up systems where shipped to early adopters and a year later, 100 GenCore systems had been shipped to early customers.

3. GenSite Path

In 2003 Plug Power additionally unveiled the GenSite product line, intended to provide reliable on-site generation of compressed hydrogen gas for industrial applications. This third platform is a hydrogen production unit. The Gensite is a spin–off from Plug Power's competences in fuel reforming, developed and applied in the SU1 and GenSys. The annual report of 2003 (p.3) announced: *"starting in the fall of 2004, we will begin field deployment of GenSite".* Among others, the system was applied in a Honda home energy system project and Plug Power installed a GenSite system for generator cooling at the Detroit Edison Company's Saint Clair power plant. Additionally, Plug Power sought early markets for this technology such as heat treating and electronics/glass-to-metal sealing.

Partnership Probe Paths

The main probe applications between 2000 and 2003 were realised through Plug Power's partnerships. Plug Power's second period shows multiple field trials and iterative development. The NYSERDA was a main government customer for Plug Power's early applications. The LIPA was a key early adopter of the application of Plug Power's technology. In addition, two main partnerships applied and further developed Plug Power's platform products this second period: Vaillant and Honda. These partnership probe paths run as a 'red thread' through this second period. These partnerships cover probe engagements in four different market segments: i) grid parallel power with NYSERDA and LIPA, large stationary installed systems; ii) CHP for residential and commercial heat and power with Vaillant as well as remote CHP with LIPA; iii) a Home Energy system with Honda; and iv) back-up power for UPS and telecom. Plug Power also explored several sub-segments in back-up power and the CHP power market.

NYSERDA

One of Plug Power's initial customers was the government agency NYSERDA. In 1999, NYSERDA and Plug Power initiated an evaluation and demonstration programme, in which Plug Power conducted its first field trials with a series of SU1 units. In total 20 Plug Power FC systems provided electricity to a variety of New York State facilities in a two-year demonstration programme that ran up to and including October 2001[7]. To date, Nyserda supports Plug Power in the realisation of field trials for its product platforms.

Nyserda additionally played a central role in the development of the GenCore product platform for telecom. In 2002 NYSERDA and Version Communications partnered with Plug Power in a 2 year programme to certify and test a direct Hydrogen FC system for back-up power. This represents the first probe to analyse and demonstrate the reliability and potential of the GenCore system for the telecom market segment. Following, the first GenCore was launched in July 2003. The first field trials were conducted in July 2003 under the NYSERDA and Version partnership, with the installation and testing of a GenCore prototype at Albany International airport. In February 2004 this prototype was replaced by the GenCore 5T designed specifically for telecom back-up power in outdoor applications. This system underwent NEBS certification testing by Verzion and in September 2004 was approved. After the programme, Verzion purchased a number of GenCore systems for further testing in its network. The development and application of the GenCore in the NYSERDA and Version programme, demonstrated the feasibility and potential of this application.

Long Island Power Authority

The LIPA provided Plug Power with a test bed for initial prototypes and was an early customer for Plug Power's prototypes. Consequently, Plug Power engaged in an early partnership with the Long Island Power Authority, Long Island's main electric service provider. Funding for the application projects was provided through the Clean Energy Initiative, a five-year, $170 million programme proposed by the governor of New York.

[7] Press release, 'NYSERDA/Plug Power Fuel Cell Demonstration Nears Completion', October 11, 2001

The partnership was aimed at testing and evaluating Plug Power's initial prototype FC systems in locations on Long Island. Following agreements in the fourth quarter of 1999, initial tests were conducted in June 2000. In the spring of 2000 Plug Power began with the installation of 6 integrated 'alpha' FC systems across the island (AR 2000). Based on the experience gained with these first systems, Plug Power introduced a next generation FC system: the 5 kW SU1 fuelled by natural gas. In October 2001 the LIPA announced that 75 Plug Power FC systems were connected to the grid at the demonstration site West Babylon. These FC systems fed directly into the Long Island electrical grid. At the time, the installation of 75, 5kW Plug Power systems at West Babylon New York was the largest grid connected installation of PEM FCs in the world.

In the summer of 2002 Plug Power installed 37 next generation GenSys systems of which 20 are placed at the prior site to continue technology evaluation. The additional 17 CHP systems were installed at Long Island's government, commercial and industrial customer locations, to demonstrate a 5kW CHP system. In the fall of 2002 Plug Power installed three prototypes of a FC back-up power system at U.S. Merchant Marine on Long Island. The 5 kW hydrogen fuelled systems were forerunners of the GenCore platform. These back-up power systems for Uninterrupted Power Supply (UPS) were planned to operate for one year. This installation provides the initial assessment of Plug Power's hydrogen FC power systems as a back-up generation source and the field data is used for the development of Plug Power's GenCore. In the winter of 2003 the LIPA purchased an additional 45 systems, of which twenty five 5 kW FC systems are installed at the West Babylon demonstration site. The other 20 CHP systems are installed to generate on-site heat and power for single or multi-family residential sites on Long Island.

Long Island has served as a **test bed** for Plug Power's novel generations and prototypes. Long Island Power Authority has provided Plug Power with a continuous test bed for the whole range of Plug Power's prototypes. Regarding the initial installations in 2000, the annual report states (2000: p.6), *"this testing has provided us with invaluable data that will assist us in advancing the design of the system"*. Plug Power installed and gained experience with the application of it UPS back-up power and CHP products for both residential and commercial applications. The probes were used for the development of the GenCore and GenSys. The installed systems provided Plug Power with data to model the development of next generation systems. As De Wit explains, *"this data came from America out of one of the test sites of the LIPA. 75 systems were installed and ran for a year. Those were significant data pools… With this data a model was made. You can only make a model once you have data from the field to make a model properly. Then you can run the model and use it to develop a new system"*.

The LIPA partnership enabled Plug Power to apply its product platforms on scale in long probe paths with feedback loops and optimization. The scaled field trials provided operational data used to improve the product platform and develop other systems.

Valliant, Commercial and Residential CHP.

Despite the postponed expectations for residential and light commercial CHP, Plug Power continued developments in this market segment. In March 2000, Plug Power engaged in the joint development of FC heating applications with Vaillant of Germany. Micheal Brosset, the director of Vaillant Gmbh at the time, states that *"Vaillant has a clear vision and strategy on how to develop the European markets for FC products"* (AR 2000: p.4). In this partnership Plug Power is the supplier of a FC subsystem, based on GenSys technology. Vaillant integrates this subsystem into its combined heat and power products and is the marketing partner. In March 2000, Plug Power and Vaillant signed a joint development agreement. During the fourth quarter of 2000, the partnership announced the successful operation of 3 beta combined heat and power systems in the laboratories.

The first demonstration resulting from the Plug Power–Vaillant partnership was unveiled in March 2001 at a large trade fair for heating appliances. An operational FC heating appliance was presented. In January

2002 Plug Power announced the installation of the first European certified FC combined heat and power unit in a multi-family home in Gelsenkirchen, Germany. The system operated on natural gas and produces 4kW of electricity and 9kW of heat. This first operation was a valuable experience, as De Wit explains, *"in that first operation, we learnt a lot about installation. What does a system like that do in a completely different environment? What do you need to fit such a system in existent buildings and heat loops? We have learnt a lot about installing and controlling that system. Additionally, we gained a lot of market information on customer specifications".*

The next generation prototype was a dedicated system design for Vaillant, integrating Vaillant system components. Data and experience gained from CHP installations on Long Island were of central importance to developing this dedicated system. May 2003 Plug Power and Vaillant started the installation of 54 of these systems in Europe. Half of the systems were installed at Vaillant customers. The other systems were installed for the European Union's Virtual Power Plant Programme. The 5kW FC heating appliances were installed in both multi-family homes and small businesses.

The probe path revealed a mismatch between the technology and the market / design requirements. De Wit describes the lessons from this multiple application as follows: *"we learnt, 1. How the system fits the heat loop of households. 2. That the costs have to be reduced and 3. The reliability has to be improved. A consequence of the latter is that we need to simplify the system".* Now, Plug Power considers high temperature membranes to be the solution.

In 2002 Plug Power expresses its doubts regarding the adoption time line for this market. Yet, the probe path continued. The EU demonstration project had created a protected niche to develop the probe applications for CHP, but in reality the market application was not cost competitive in the near term. As Roger Saillant, president and CEO in 2002 says, *"our company was originally premised on the idea that we would sell to the residential home owner and it is very clear to me that there is a number of other markets to enter before that"*[8].

The demonstration systems were functioning well and although clients were satisfied, the system was unable to compete with a classic heating appliance in terms of cost. The commercial application of CHP proved to be further away than other applications. As a consequence, between 2005 and 2006, the CHP development and marketing activity of the Vaillant- Plug Power partnership slowed down. In 2006 Van de Hyden explains Plug Power's variable engagement in CHP probes: *"at that moment it was the first segment in Europe in which FCs could be placed at clients... however in retrospect, the project with Vaillant primarily ran that well because it was partly funded by a governmental subsidies....but commercial application is further away, so for us that is currently a bit quiet."*

Once it became clear the heat output did not align with the current heat loops in households, Plug Power slowed down probe applications in CHP. Instead, Research and Development has continued on a path of high temperature membranes. At the Hannover fair of 2006 Plug Power presented a high temperature membrane system. A next step in the Vaillant and Plug Power partnership was announced in December 2006: Vaillant, Plug Power and a consortium of partners were selected to receive a European Commission grant for the development and demonstration of three high temperature CHP FC prototypes. The step back to R&D further postpones potential adoption in this market.

Honda Partnership, Home Energy System.

In October 2002 Plug Power and Honda agreed to co-develop a Home Energy Station (HES). The HES applies an integrated FC system, based on Plug Power's GenSys technology, comprising a reformer and FC system. The system supplies a house or business with electricity and heat as well as hydrogen to fuel a car

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[8] Quote from news article 'Plug chief seeks success by design' June 5, 2002 on www.Marketwatch.com

in a home refuelling system. This R&D partnership targets the development and assessment of the HES concept in a long term market adoption time frame. *"Our relationship with Honda is a long-term, growing collaboration that encompasses a broad spectrum of technologies with potential benefit to many of our products"* (AR 2005: p.7).

In a multi-phase development process the partnership has developed three generations of HES. The first system was demonstrated at Honda's R&D facilities in California in October 2003. The phase 1 system demonstrated the generation, storage and delivery of Hydrogen to the Honda FCX as well as export of electricity to the grid. The second generation, announced in November 2004 demonstrated a more compact and efficient design than the first generation. The system was installed at Plug Power headquarters in Latham, enabling the collection of operational data. The installation of the third generation HES was announced in November 2005. The system shows improved hydrogen storage and production capacity as well as the integration of back-up power ability. The GenSys, GenSite as well as GenCore technologies were applied. Plug Power and Honda have signed an agreement to develop a fourth generation HES.

The linear probe path of the Honda Plug Power partnership targets a long term application. Although the HES may facilitate the uptake of FC cars, automotive applications are considered to be further away. As Brown (2007) describes, the project *"completely redefines the relationship between the home and the car"*. In terms of probing, the partnership enables the application of Plug Power's products in an additional real life test setting. The annual report of 2003 (p.8) states, *"while Plug Power is not directly in the business of developing FCs for automotive applications, it is clearly beneficial that Honda has carefully and deliberately chosen Plug Power as its strategic partner in stationary FC development"*.

Outcome of the Second Period

In the period between 2000 and 2003, Plug Power developed field trials in various market segments. The partnerships enabled the iterative development of multiple probes in each market segment. A key outcome of the second period of probing is the apparent value proposition for back-up power, in particular for the telecom market segment addressed by Plug Power's GenCore product. In this second period, Plug Power 'found' its first commercial market: the GenCore became Plug Power's first commercial product and the telecom market proved to have a compelling value proposition. By the end of 2003, Plug Power further focused on the commercialisation of the GenCore systems. Consequently, by the end of 2003, Plug Power's original adoption curve was modified and centered on the adoption of the GenCore, followed by the GenSite and the GenSys (fig. 7.4).

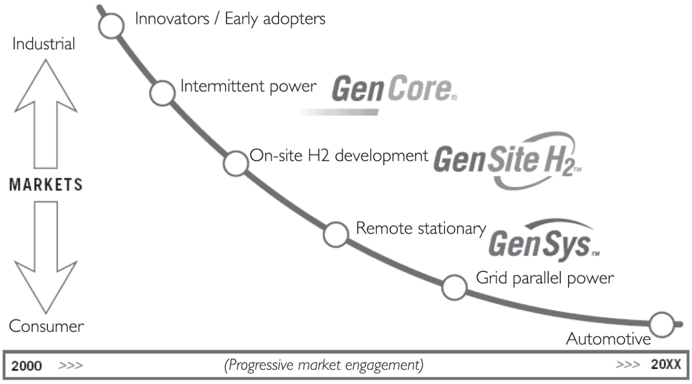

Figure 7.4 Adoption curve presented in the annual report of 2003

Plug Power has continuously developed the GenSys systems in multiple probes. Although, the GenSys probes preceded the development of the GenCore, their adoption expectations where reversed in subsequent years. *"We expect the GenCore to pave the way for market acceptance of GenSys"* (AR2005: p.10). Plug Power expects GenCore customers to be the first adopters of the GenSys systems. As the annual report of 2003 states (p.6), *"the next point on the curve should grow directly out of back-up power. As the telecom and broadband industries gain confidence in FCs for this application, they will consider FCs for primary power in remote locations".* The postponed adoption curve for the GenSys is expected to move from telecommunications, followed by industrial customers to commercial and residential customers in rural areas. Regarding the Gensite, Plug Power was still in the process of searching for markets.

The modified adoption curve illustrates Plug Power's shift from large mass markets to stationary markets with near term potential for revenue. The short and near term market segments for the product platforms were further specified. Grid parallel power has been postponed. The postponed development of systems for residential generation, with Vaillant, is reflected in the removal of this market segment. The annual report of 2003 states (p.2), *"we know that the most important goal for Plug Power at this time is to find the shortest path to profitability".* With a focus on the commercial roll out of the GenCore, Plug Power continues its probe strategy of field trials. Van der Hyden explains that 200 GenCore systems were manufactured after their introduction in 2003, intended for field trials with customers: *"we have done it the other way around…..we actually had the plan, we will build 200 in the manufacturing facility and then we will look how they do in the field. Do they comply with the requirements of clients? Do they keep on running in extremely cold or hot conditions?".*

The subsequent GenCore paths include numerous probes with launching customers as described in the following paragraph. By 2005, Plug Power began the commercial roll out of the GenCore. The market opportunity recognised in the years 2002, 2003 is proving to be larger than expected. As De Wit describes, *"this opportunity became more and more clear. We did not think it would be this big… the market is larger than we expected".*

7.1.4 Period 3: Launching Customers and Field Tests 2004-2006

The information available to Plug Power, on the basis of which probe decisions were made, notably changed at the start of 2004. The potential market for the back-up power in the telecom sector had become clearer. As a result, the third period is characterised by a strong focus on validating the GenCore systems to this market. In this process, developing legitimacy and credibility as a supplier to the telecom industry was a key challenge.

In a third period, between 2004 and 2006, Plug Power's probe process is characterised by GenCore probes with launching customers for telecom back-up power. A launching customer is defined as a customer making the first transaction, on the one hand, for a modified price, on the other hand, accepting the risk bound to a technology that has not been proven on scale. According to Plug Power, probes with launching customers are necessary to become a supplier in a market such as the telecom market. Engaging launching customers is part of a lengthy sales process, a period of building credibility as a supplier. The standard process is that first they try one. If satisfied they buy a few more and apply them in a controlled environment. Once they have worked well for about half a year, then larger follow on orders may follow. Customers ask for proven technology, with data on installed systems and performance. Up to 2004 Plug Power's experience and data with the new GenCore product was limited. As De Wit explains, *"collecting reliability data is essential. But around the time of the GenCore launch we did not have the funding for that. We chose not to invest in a reliability growth fleet ourselves, but to collaborate with a launching customer. That is more convincing. So first we did limited tests ourselves and then with a launching customer, because it gives more credibility".*

Plug Power sought a launching customer for a partnership in which the customer agreed to place a system on one of their locations. A launching customer runs a risk in applying a new product, but at the same time, the customer does not pay the full price for a first system and receives a large amount of publicity as a pioneer in applying FC technology. The first launching customer project was with telecom provider Orange and the second with launching customer Oneida County Rural Telecom Company in New York State. These probes are described as 'cases' central to the development of Plug Power as a telecom supplier.

The third period is also characterised by the search for back-up power sub-segments and the expansion of Plug Power's GenCore portfolio to meet specific customer needs. For example, industrial and wireline/wireless applications, wireless telecom providers, urban and remote locations. The annual report of 2004 reports the introduction of three new GenCore configurations designed to provide back-up power for electric utility substations. Furthermore, *"the GenCore systems may also play a role in another rapidly emerging industry: UPS"* (AR 2004: p.5).

In addition to key probes with launching customers, Plug Power sold GenCores to early adopters for field trials. For example, Loretel conducted field trials with the GenCore, supported by grants from the US government provided to stimulate market uptake. Field trials in 2006 with Plug Power's distribution partners include IST Holdings Ltd., Plug Power's South African distribution partner, who ran a six month field trial of Plug Power's GenCore. Following the successful trials, Magtholo Mello, Managing Director of the Telecom Division of IST Holdings says, *"we are seeing accelerating demand for the GenCore product from one of the nation's leading wireless providers"*[9]. Plug Power additionally participated in GenCore trials with Telefónica Móviles in other key markets including Mexico, Brazil and Spain. Product trials in Mexico and Brazil are being conducted with Plug Power's distribution partner Tyco Electronics Power Systems.

The main probes with launching customers for the GenCore, the further development of the GenSys and new developments are described in the following paragraphs.

Launching Customer Orange

Orange and FDT associates contracted Plug Power to install a Gencore 5T system for back-up power for a remote cellular communications tower at a remote site in Elgin, Scotland. The launching customer is Orange, a large mobile communications company. FDT associates provided design and construction services to telecommunications sites. This system was installed at the site on December 2003. The GenCore was marketed with hydrogen storage for 144 hours of back-up power, supplied by BOC. The location in Scotland was chosen because, as Van der Hyden explains: *"it is an extremely cold place, so in the winter is was quite difficult to get there. But, that was exactly the reason why Orange wanted to have a FC system there!".*

The 'Orange' probe provided operational data in extreme conditions. Additionally, installation experience was gained as well as experience in gaining permission and handling clients. This probe was the first operational installation of back-up power for telecom in Europe and provided good publicity for Orange as well as Plug Power. As Van der Hyden explains,*"at this moment it is still a lot of awareness creation and of course we do that by strong publicity on the basis of the projects that we do with clients. If you go to our website, then you see the Orange site…. We try to reference to companies that have already bought a system".* Similarly, the 2004 annual report (p.4) states, *"the positive Orange experience allowed GenCore to establish a foothold in Europe while validating its performance in extreme outdoor conditions".*

Launching Customer Oneida County Rural Telecom Company

In July 2004 Plug Power installed a GenCore5T48 with a second launching customer and the unit operated throughout 2004. This system, equipped with a remote monitoring package, was installed in a telecommunications hut in rural upstate New York. The Oneida County probe was additionally aimed at demonstrating the reliability of Plug Power's back-up power system for telecommunications applications. However, this probe addressed a different corner of the telecom market: Oneida is an independent local US exchange carrier and the Gencore was installed to support digital switching equipment in one of its remote huts.

[9] Press release, 'One of South Africa's leading wireless providers to deploy Plug Power Back-up Power FC systems', October 12, 2006. Plug Power website.

Consequently, *"Oneida experience is important for the future of GenCore because it opens the independent telecom carrier segment to further GenCore sales"* (AR 2004: p.4). Besides, the Oneida probe provided operational feedback for Plug Power and learning for the Oneida .

GenSys Field Tests

At the end of 2004, Plug Power reports the sales of 56 GenSys units, *"while continuing to probe markets and applications"* (AR 2004: p.7). Plug Power continued with the field trials for the GenSys systems, probing in various market segments. Through field trials with potential early adopters of continuous-run FCs, Plug Power continues to gather data on GenSys units in the field to improve and optimize the next generation GenSys. In the second quarter of 2004, Plug Power was contracted to install Gensys systems at naval bases in New York, California and Hawaii. Since 2005, 10 GenSys systems are operational at the Robins air force base in Atlanta, Georgia. Plug Power additionally announced a field test of the GenSys system for NASA in October 2006. In the press release[10] Mark Sperry, Plug Power's Chief Marketing Officer states, *"we continue to believe that field testing is the only way to truly understand customer requirements and characterise product performance".*

Throughout 2006, Plug Power continues field tests of the GenSys. As Van der Hyden explains, *"these systems are at the first field trials at clients. The tests will runs for another few months in which we will look at how often do the systems fail and if so, why do they fail and what happens. There are 10 systems there so that we can generate that information quickly".* The probe paths for Plug Power's GenSys technology are long. The product continues field trials as market adoption for prime power has repetitively been postponed and Plug Power continues to probe potential market applications for the GenSys.

An opportunity for continuous power generation arose when the American government awarded a contract to Plug Power and Ballard in 2005. In response to hazards such as hurricanes Katrina, the American Government has asked Plug Power and Ballard to look into the application of FC technology to power crisis centres or governmental offices. The application should ensure continuous power generation during natural calamities. Plug Power has put a number of employees on that project. According to Van der Hyden, *"that has potential. The client is already identified, that makes a difference. But I do not know, if you look back in four years, if there will be clients with large orders or if the project has gone in a different direction".*

Outcome period 3

In the third period, both the Oneida and Orange installations demonstrate the system's ability to serve back-up power in remote and rural environments. The probes provided positive experiences with customers, enabling Plug Power to focus on further commercial deployment of the Gencore. Plug Power refers to these probes as benchmark installations. Plug Power additionally further developed the Gencore for specific customers and identified specific markets for application. By talking to potential clients in various segments, a cost comparison between the GenCore and the current solution is made and specific applications for the GenCore are identified. As Van der Hyden explains,

"At each client with whom we talk about our telecom back-up power, we gain experience. With experience we can see that our GenCore is not the best solution at all the 6000 sites of a client. So we learn very quickly at which of these 6000 sites it is economically profitable to place a GenCore and at which sites it is not an option because it is a more expensive solution than the alternative. So slowly your sense of reality is sharpened by talking to clients… there are a few segments where we know that the GenCore cannot be sold and that we cannot earn back our cost price and other segments where that is possible…. So in sum, it is really a fundamental comparison of the alternatives in the market: what are the costs and profits for clients as well as for Plug Power".

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[10] *Press release, Plug Power continues runs GynSys systems, October 23, 2006. Plug Power website*

According to Plug Power, the value proposition for telecom back-up power has become calculable. *"This past year, GenCore, Plug Power's back-up power system for outdoor environments, emerged as a commercial product line with a viable economic value proposition for its target customers and applications"* (AR 2006: p.3). The annual report of 2006 explains that Plug Power is able to communicate the value proposition for back-up power: "taking what we have learned, we are refining our understanding of what is necessary to ensure client success. We have developed economic models of our products relative to the actionable alternatives. This helps our clients to quickly understand our value proposition" (AR 2006: p.2). Plug Power has developed a statistical database with data on operations. The company explains that subsequent projects with clients will follow a methodological approach from pilot testing to limited installation and standardisation. At the same time, Plug Power is optimizing towards greater efficiencies and cost reduction.The number of Gencore sales tripled between 2004 and 2005 and in 2005 Plug Power received its first repeat orders from IST Holding for the telecom back-up market for tens of systems. These figures support the further deployment of the Gencore. As Van der Hyden explains,

"Now we know, luckily, that the telecom back-up market really exists… in December we received an order from a client in South Africa for 80 systems. Well, that is a fact that cannot be denied anymore: we have a repeat order from a client. Apparently the clients would like more of our products. The series produced systems comply with market demand. That is a clear support in the back. If those orders had not been there we might have had to conclude that we would have to go to another segment or wait until our costs dropped further. But it strengthens us on the one hand, to commercially roll out… and on the other hand, to invest in R&D to make sure we have a better product next year".

Plug Power's focus on the GenCore is reflected in the centrality of the Gencore in Plug Power's modified adoption curve in the annual report of 2005 (fig. 7.5). The adoption curve has almost become 'bare', with the Gencore in the middel. The Gencore is expected to 'pave the way' for the GenSys. The grid parallel power with GenSys, is again, illustrated as further away than expected. There is no mention of residential power. A notable change is the removal of the Gensite from the adoption curve. Van der Hyden explains the reduction of Gensite developments, "*we are discovering that the energy we need to spend on marketing that product, weighted against the chance of significant turnover, is less favourable for the Gensite than for the GenCore".* On the other hand, Plug Power perceives an apparent value proposition for the GenCore. Nonetheless, Plug Power has modified its strategy in 2006. Plug Power reports that *"during 2006, the specifics of our markets and their power requirements crystallized"* (AR 2006: p.ii). Noteworthy is Plug Power's engagement in the material handling market: *"Plug Power considers telecommunications back-up and material handling applications to be attractive near-term markets for PEM FCs and has selected these as central components of the company's growth strategy"*[11].

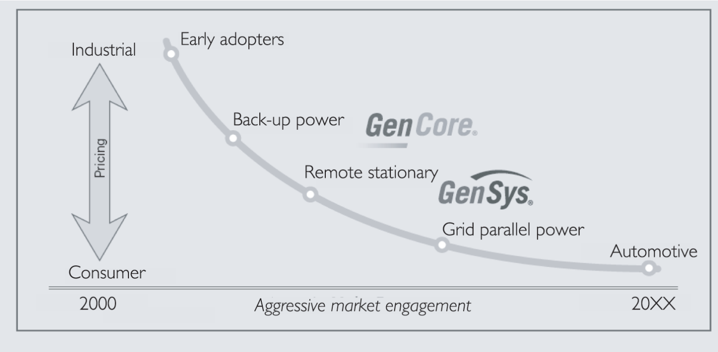

Figure 7.5 Adoption line presented in annual report 2005

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[11] *Press release, 'Plug Power announces completion of Cellex Power acquisition', April 4, 2007, Plug Power website.*

New Market Segment: Material Handling

In the annual report 2005 Plug Power describes the development of a GenDrive system, a hydrogen fuelled battery replacement module for material handling applications. The GenCore platform is expected to provide the basis for our development of the GenDrive platform. This platform targets a market segment that is new and different than Plug Power's prior engagements. Since the period of early demonstrations, Plug Power rarely conducted probes in markets and applications other than back-up power, prime power and combined heat and power. In response to the GenDrive for material handling, Van der Hyden comments, *"that is a sector with potential for FCs and we also work on that with a partner, but actually that is more the focus of Ballard. Ballard does more work on mobile applications, Hydrogenics too and there are a few others working on that. We have said, because others are working on that, we do not target that market specifically. But our stacks and our FCs are applicable there too. So we also have a project in that market".*

In 2006 Plug Power made a notable shift towards the material handling market: Plug Power acquired Cellex power in April 2007 and General Hydrogen in May 2007. Plug Power has entered into a two-year agreement with Ballard Power Systems Inc. to purchase FC stacks for the electric lift truck applications. The press release sates that "*with the combined FC expertise of the three companies, we expect to accelerate product development for all three classes of electric lift trucks*"[12]. The rationale for diversification to material handling is partly explained by the financial resources acquired through the Russian investment of $217 million in 2006 . With greater financial strength, the tactics of Plug Power were adjusted. *"It provides us with resources to enter new markets through potential acquisitions as well as continue to increase sales and marketing effort for our GenCore product"* (AR 2006: p.2).

The annual report of 2006 (p.3) also provides another explanation: *"the slow pace of GenCore installs also signals our need to accelerate the diversification of out product offerings and is the basis of our stated 2007 milestones to expand into new FC applications through strategic partnerships or acquisitions".*

7.1.5 Conclusions on the Plug Power Case

Plug Power's main probe applications have been described and are illustrated in figure 7.6. The process has been categorised into 3 periods. In the first period Plug Power's initial probes targeted two large markets: the automotive and CHP for residential power. After initial technological demonstrations, Plug Power aborted the automotive probe path and focused on searching for new applications within the stationary market with near term potential. This initial phase correlates to the characteristics of an explorative phase proposed in chapter 6. In search of niche market segments, the second period can be characterised as experimental. Although Plug Power focuses on niche markets in the stationary segment, the GenSys technology platform was developed for application in various stationary market segments. The GenCore was developed as a spin off and applied in various sub- segments including direct-current back-up power for telecom, broadband, utility and industrial UPS market applications. Plug Power's efforts began to converge towards the commercial deployment of the GenCore.The third period of probes with launching customers was central to this convergence as market demand began to emerge. Plug Power continues with iterative developments of the GenSys, apparently commercialisation is taking longer than expected. The initial market for the GenSys is now expected to be remote continuous power for light commercial and residential application, a market that may emerge from GenCore customers. The long term partnerships with LIPA, Vaillant and Honda characterise Plug Power's engagements' longer term development paths

Plug Power's focused development is noteworthy. There are other FC firms that focused on particular niche markets at an early stage. For example, Cellex Power and General Hydrogen, focused on the material handling market and forklift trucks in particular. Similar to Plug Power, both firms targeted near term niche markets and conducted assessments of market needs.

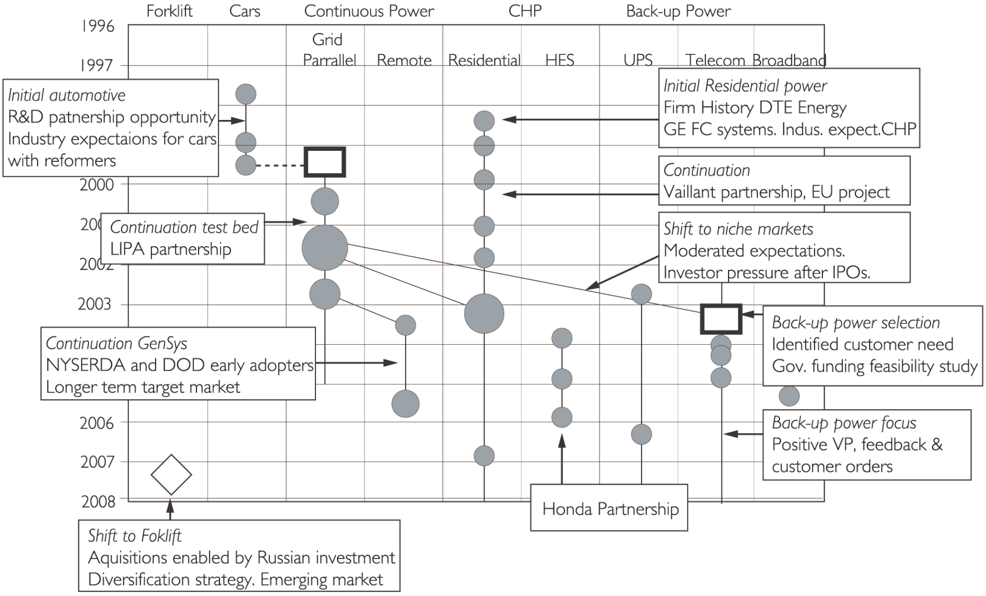

Figure 7.6 Plug Power probes over time and explanatory factors

Explaining INITIAL Probe Selection

Plug Power's pursuit of initial probes in the automotive market can be explained by industry expectations for mass market adoption. Between 1993 and 2000, the industry expected automotive adoption within years as automotive companies engaged in FC R&D and a multitude of FCV prototypes were presented. Among the technological options in development, integrated FC systems with reformers were expected to enable the near term adoption of FC vehicles and the US government funded R&D programmes to develop such integrated FC systems with gasoline reformers. The funded programmes enabled Plug Power to partner with Epyx and Ford. Plug Power's initial engagement in reforming technology for transportation can apparently be explained by the expectations for widespread adoption of this technology, the government funds and the possibility to partner with Epyx specialized in reformers for transportation. Subsequently, the possibility to participate in thepPartnership for a New Generation of Vehicles, among others with Ford, may have explained Plug Power's engagement in this automotive probe. Plug Power's behaviour appears to be opportunistic, taking the chances to partner and funds that came its way. However, quotes at the time suggest that Plug Power believed it could become an industry leader in integrated systems with reformers for the automotive market.

Plug Power's initial probes for residential stationary power can be explained by Plug Power's historic roots in the energy provider Detroit Energy. After founding, DTE Energy Technologies continued to be involved in Plug Power. Besides, there were industry expectations for the mass market adoption of residential and light commercial power, illustrated by the remark, *"everyone was running to the market like crazy"* (De Wit 2006).Regarding the timing of Plug Power's initial probes in stationary, initial probes were presented as proof of concept demonstrations. Considering the timing, it can be argued that Plug Power was creating value and legitimacy towards its IPO.

Explaining ABORTION of Automotive Path

The initial demonstrations provided Plug Power with a 'reality check' in terms of the market adoption time line for the automotive and stationary market. In particular, the automotive market was further away than anticipated. This 'reality check' was observed in the whole industry. Plug Power aborted automotive developments after this reality check, which can partly be explained by an insufficient value proposition for this market. On the other hand it can be argued that the market was too far away to satisfy Plug Power's investors, pressuring the firm to find near-term profitable markets. Moreover, industry expectations appear to have influenced Plug Power's decision. Plug Power's approach to FC systems for automotive applications was geared towards onboard systems with integrated fuel reforming. However, after 2000, the industry became more sceptical towards this technological option and it became less likely that this solution would become dominant. Apparently Plug Power's probe decisions were also influenced by industry level do's and don'ts and the sector level discussions on most likely technologies to dominate FC vehicles. Without the perceived opportunity for onboard reforming, Plug Power would have less chance for a competitive position the automotive market. This argumentation is supported by Plug Power's explanation for shifting away from the automotive market: there were already competitors targeting the automotive market. Apparently Plug Power's decision was based on strategic positioning with respect to industry expectations. Nevertheless, the automotive probes show cross-over learning. The reforming competences picked up in the automotive probes became central to Plug Power's subsequent strategy and were a necessary condition for developing Plug Power's subsequent probes and products, the SU1 and subsequently the GenSys platform.

Explaining CONTINUATION of the Stationary Paths

On the basis of its FC and reforming competences, Plug Power may have strategically positioned itself by continuing with stationary market applications. However, expectations for stationary power were also moderated. Plug Power, was one of the first to realise probes in the stationary market for residential applications, causing a reality check in this market as well. Nonetheless, Plug Power continued with stationary markets. The partnership with GE is likely to have influenced the continuation of stationary applications due to GE's historic interest in stationary power. The partnership was important for Plug Power to gain customer recognition. With the formation of GE FC systems in 1999, agreements regarding the marketing and distribution of Plug Power's stationary FC systems were already in place. Finally, the energy provider DTE technologies continued to be involved as a shareholder of Plug Power. Apparently Plug Power's partnerships and shareholders have had a strong influence on the formation of Plug Power's strategy and culture emphasising stationary power.

Moreover, Plug Power expected stationary markets, such as CHP for residential, to be nearer than the automotive market. Which factors determined that the CHP market appeared nearer than the automotive market? First, the cost benchmark for CHP in the residential market is around 10 times lower than for the automotive market. Second, industry expectations for residential CHP still lay within years. Finally, Vaillant had a clear vision of the European market for CHP FC products. Apparently, the opportunity to form a strategic partnership with Vaillant strongly influenced the continuation of probes in this market. Besides, the partnership with Vaillant is a key factor to explaining Plug Power's continuous engagement in CHP for residential applications.

Explaining Subsequent SHIFT to Niche Markets

The shift towards a search for niche markets can be explained by the moderated expectations for stationary market adoption. It is likely that the moderated expectations did not suit the time line of Plug Power's shareholders. As a publicly listed company, Plug Power was pressured to realise returns in a few years and become profitable as soon as possible. Subsequent probe decisions can be explained by the necessity to identify and develop near-term value propositions and strategically position the firm with respect to other firms in the industry. By focusing on its core competences, Plug Power strategically positioned itself in the stationary market. The development and acquisition of competences in reforming opened up opportunities for stationary applications and enabled the development of the SU1. Within the stationary segment, Plug Power began to look for markets that would fit the company's core competences in FC and reforming technology.

CONTINUATION and Postponement of CHP

The Vaillant partnership involved a series of probes in collaborative development. However, without government grants and programmes, the market is not cost effective. Regulatory support created a protected niche for a number of CHP applications but the intensity of probe engagements reduced after the funded project. Apparently, probe path continuation in this market not only depends on the Vaillant partnership, but also heavily depends on government funding. Furthermore, market adoption expectations were postponed on the basis of an observed mismatch between the low temperature PEM technology and market requirements, which brought this market application back to R&D. Thereby the probe developments revealed that the value proposition for this market was unsatisfactory in terms of time to large scale market adoption as well as alignment of customer requirements and system performance. R&D continue in partnership and with EU funding.

Explaining the PURSUIT of Early Field Tests

Plug Power was early to begin with field trials and manufacturing capacity with its 'progressive market engagement strategy'. Why did they do it the other way around? On the one hand, early field trials to receive customer feedback are part of Plug Power's probe strategy. On the other hand, the company was operated as a company ready to supply when large orders come. Financial resources from IPOs enabled the realisation of the manufacturing plant. It can be argued that as a publicly listed company, the company was under pressure to be 'ready' and to profit from this investment as soon as possible. This strategy suggests that Plug Power was expected to receive large orders within years. But, why was it so confident that large orders would come?

It was NYSERDA and the LIPA that enabled the early field trials. NYSERDA was an early customer and its funding was instrumental in realising the early field trials. The LIPA was Plug Powers largest customer at the time and the partnership with LIPA enabled test bed applications. The partnership was funded by the New York state government. This partnership explains why Plug Power was able to conduct long probe paths for markets, even for markets that turned out to be further away than expected.

Technology Platform

Plug Power was early to introduce a technology platform. It can be argued that to learn from field trials and incorporate feedback loops, a technology platform was necessary. The technology platform explains why Plug Power was able to 'cross-over' operational data between markets. The technology platform additionally explains the spin off to the GenCore and GenSys systems.

Explaining the Selection and Continuation of Back-up Power

Plug Power began to look for niche markets within the stationary market segment that would be profitable in the short term. A notable external factor is the hype around alternative forms of back-up power in the USA around 2001 and 2002. Apparently, Plug Power recognised a market need in this hype. The acquisition of H Power appears to be in line with this market interest, as H Power had developed back-up power applications. However, Plug Power has not further developed any of H Power's technology for back-up power in the low power range. It can be argued that instead, the acquisition provided Plug Power with financial resources to develop this application. The probe in public-private partnership with NYSERDA and Version was instrumental to evaluate the feasibility of the back-up power market for telecom. Again, the governmental grants enabled Plug Power to engage in a probe. The outcomes of these initial probes were positive with respect to feasibility and potential for short-term adoption. Apparently, the initial probe revealed a compelling value proposition. This value proposition explains Plug Power's subsequent focus and continuation of back-up power. Additionally, customer orders followed. The compelling value propositions as well as the emergence of market demand explain the subsequent focus on GenCore development. Technically, the engagement in a back-up power probe can be explained as a spin-off from GenSys technological competences. The initial GenCore units principally comprised GenSys technology without the reforming system.

Launching Customers

Plug Power explains probes with launching customers as a strategy to develop a reliability fleet with limited internal costs as well as a strategy to build credibility in specific markets. Once again the role of strategic partners appears to be instrumental in establishing credibility in a market sector.

Current Focus

Plug Power focused on the commercial roll out of the GenCore. Through conversations with potential customers in this market and the probes with launching customers, Plug Power was able to calculate the cost effectiveness of applications in this market. The launching customer probes continued to provide Plug Power with positive feedback. Furthermore, as this probe path proceeded, the market proved to be larger than initially anticipated. Thus, the positive market feedback is likely to have strengthened Plug Power's value proposition in this market. Moreover, Plug Power has received repeat orders in this market and Plug Power began to believe GenCore can pave the way for market adoption for the GenSys in subsequent larger markets.

In the meantime the FC industry expects back-up power to be the first commercial market. However, considering the timing of Plug Power's probes in back-up power and the length of its probe paths, it can be argued that Plug Power has developed and experienced its value proposition for this market internally. The fact that Plug Power was the first FC developer presenting at telecom trade shows, confirms this argument.

Explaining the SELECTION of GenSite Developments

Technically, the GenSite can also be explained as a spin-off from the GenSys competences. Plug Power had the competences for reforming fuels to hydrogen in-house. Apparently, Plug Power saw a market for on-site hydrogen production at industrial applications. It may have been an industry expectation because in the same period competitor Hydrogenics acquired Stuart Energy with similar hydrogen production competences. The Honda partnership enabled probes with the GenSite, although in a different market than initially intended. According to Plug Power the abortion of GenSite probes can be explained by a limited value proposition in comparison to the GenCore. The abortion of GenSite probes may be explained by the focus on the GenCore commercial roll out.

CONTINUATION of Long Term Developments

Plug Power's probe process is characterised by long probe paths. The long probe paths towards long term markets are characterised by joint development agreements, such as with Vaillant and Honda. With Honda, Plug Power is 'partnering for the future'. These probes suggest that probe continuation towards long term markets is largely dependent on partnership.

Explaining PURSUIT of the Forklift Market

Considering Plug Power's focus on stationary applications throughout its probe process, the recent engagement in the forklift market is surprising. In earlier years, Plug Power did not focus on material handling. This decision was explained by the firm's strategic positioning with respect to other FC firms. Nevertheless, Plug Power has become engaged in the material handling market in 2007. The industry expects this market to be one of the first commercial markets for FC technology, thus Plug Power appears to mimic industry expectations with this move. Internally, Plug Power's value proposition for the adoption of the GenCore appears to have been moderated as the commercial roll out is slower than expected. However, without external funding Plug Power would not have been able to acquire these competences. Apparently, Plug Power was able to mimic engagement in this emergent market through acquisition because they had the resources to do so. It can additionally be argued that investors have pressured Plug Power to diversify.

This case shows that Plug Power identifies and develops its value propositions through probing by developing proprietary technology, information to predict market adoption and a better understanding of customer requirements to align the technology to markets. Besides, government funding and strategic partnerships are instrumental to the realisation of Plug Power's probes. The early field trials in long linear probe paths have provided Plug Power with a large amount of experience to specify customers and understand their requirements. In terms of experience, Plug Power appears to be in a competitive position to validate its technology for the back-up power market. According to Plug Power, the emergence of competitive FC developers in this industry helps to gain legitimacy for the technology.

In conclusion, industry expectations have played a significant role in the selection of initial probes. Subsequently, Plug Power's development of an internal value proposition in an experimental phase appears to be more important. Strategic partnerships and external funding have played a central role in the duration of Plug Power's probe paths and acquisitions.

7.2 Case: Nedstack

The main interviews for the Nedstack case have been conducted with: i) Erik Middelman, the CEO and co-founder of Nedstack, in august 2006 and ii) Jan Van der Meer, director of marketing and sales in November 2005. Nedstack is not a public company and does not publish annual reports. Complementary information is derived from sources described in section 6.8: press and new releases and project databases.

The Nedstack case has been selected as a company in the FC industry focused on the development and manufacturing of FC stacks for a diversity of markets. Nedstack's probe process is characterised by applications in a broad scope of market segments. Notable aspects of Nedstack's probe process include a shift from an initial focus on the CHP market to a breadth of market segments with a FC stack platform. Subsequently, Nedstack focused its probe efforts on a high power stationary application: the PEM power plant project. However, this does not restrict the firm from engaging in new market probes and supplying to various OEM customers. Nedstack's probe process shows a high degree of cross-over learning, for example, from the large scale stationary power market to the bus market. The firm's probe process reflects how the company has been transforming itself to a FC stack production company.

7.2.1 Introduction to Nedstack

Nedstack is a FC stack developer based in Arnhem, the Netherlands. Nedstack was founded in the fourth quarter of 1998 as a spin-off from Akzo Nobel. Nedstack took over all Akzo Nobel's FC related IPR and the seven key people that worked on FCs. Akzo Nobel's FC activities started in 1989 and were primarily focused on the development of materials for FCs, such as catalysts, composites, carbon fiber and electrochemistry, including membrane chlorine electrolysis. When in 1998 AkzoNobel decided to stop its corporate FC R&D programme, the founders of Nedstack established the company. The company has grown from seven people in 1998 to around 18 employees at the end of 2002 and 43 employees in 2006.

Technological Core Competence

Nedstack's technological core competence at founding was derived from its Akzo Nobel history. As a consequence, Nedstack departed from material sciences. Van der Meer explains, *"we come from the materials side…. If we have those and those materials, what can we make with that? You can make a PV cell with that, you can make a FC with that. That is the approach from which we came forth…. Akzo had all the technologies in house, that is, in the field of membranes, cell plate materials, gas diffusion layers, catalysts.. ….. So we have been able to select the best materials and from that we started. That is a very different start than all the others".* Based on this material science expertise, Nedstack has developed core competences in FC stack development and manufacturing. Nedstack has over 20 patents and pending patent applications[1]. Technology development at Nedstack is focused on cost reduction, and the improvement of durability, efficiency and energy density of FC stacks. The company manufactures stacks for 2 kW to multi MW applications. Nedstack is making a transition from an R&D-based company to a manufacturing company, gradually building manufacturing capability. In 2006, the company claims to have a capacity of 2.5 MW/y with an expected increase in capacity to 20MW/y in 2007.

Business Model and Supply Chain Position

The business model of this case firm is centered around the manufacturing of FC stacks. From 2005 onwards, Nedstack began making a transition from a R&D company to a production company, targeting sales of large quantities of stacks to markets for FC applications. Thereby, the supply to the large scale automotive market is the prospective mass market for Nedstack's product. Few FC developers in the industry focus on the manufacturing of stacks, with exception of, for example, Ballard and UTC. Van der Meer explains the rationale for stack development, *"we are a new component for an existing market… and automotive people are pre-eminently system integrators. And so are the manufacturers of boilers. So we have said, we will focus on*

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[1] www.nedstack.com

the subsystem the stack, and that is what we are going to provide them with".

Thereby, Nedstack has positioned themselves as suppliers to OEM customers. However, in some markets, OEM customers are not system integrators. Besides, some OEM customers are not capable of designing FC systems. Therefore, Nedstack additionally develops and supplies FC systems. Finally, Nedstack is also licensing part of its PEM FC technology to a number of customers.

Financial Resources

Nedstack is owned for 65% by employees and ex employees and an external investor owns 35 % of the shares. Since 2003, Nedstack has acquired venture capital investment. As an indication of the financial size of the company, Nedstack made a net loss of approximately €500.000 with a commercial turnover of €500.000.. This commercial turnover is derived from stack sales and does not include government subsidies and grants. Nedstack has largely relied on governmental funding and subsidies for R&D and the realisation of demonstration projects, from the Dutch government and the European Union. Typically, such projects are conducted in consortia, over a contractual period and are partly funded. Demonstration projects in particular generally require 50% private funding.

Overview Nedstack Probing Process

An historic account of Nedstack's probe process is categorised in 3 periods: first, a period of early demonstrations between 1998 and 2001. Initial probes were conducted in the combined heat and power market. This probe path is described in further detail. Second, a period characterised by involvement of projects in a broad scope of markets and technologies 2002, 2004. The Akzo Power plant project dominates the period between 2005 and 2006.

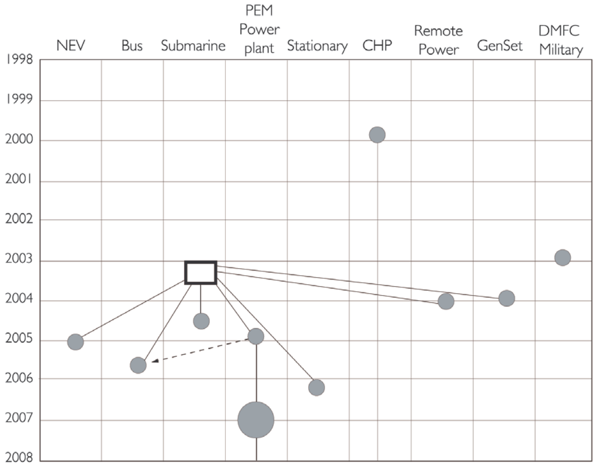

Figure 7.7 Overview of Nedstacks probe applications between 2001 and May 2007

7.2.2 Period 1: Early Demonstrations 1998- 2001

As a spin-off from Akzo Nobel, Nedstack's core competences in FC technology are based on the development of materials for FCs and electrochemical science. These competences are key to the development of FC stacks. Akzo Nobel had targeted the automotive market as a large scale market for FC stacks. Patent applications in 2001 on methods for the production of FC stacks show Nedstacks ambition to manufacture large quantities of stacks. In the first years after founding Nedstack decided to target the supply of FC stacks to an alternative large scale market: the CHP market for residential applications. As Van der Meer describes, *"when we belonged to Akzo, it was all about automotive, that was the main goal. Immediately after the Akzo period there was a clear decision for combined heat and power. That seemed then, in 98, 99 to be the first market that would come".*

In December 1999 Nedstack pursued its first probe: the realisation of a CHP system. The project was subsidised by the Economy, Ecology Technology programme (EET) of three Dutch ministries. In this project Nedstack developed and built a CHP system for residential buildings. The EET project, entitled Micro cogeneration plant based on solid polymer FC technology, targeted cost reduction of the system by a factor 100. Within the consortium Nedstack was responsible for the natural gas reformer, the FC stack and the FC system design. Nedstack's interest in reforming technology for the CHP market is also reflected in patents on a 'FC based heat and power generation unit', fuel processing and gas purification applied for in 2001 and 2002. Additionally, Nedstack supplied stacks to CHP system integrators. In particular the supply of stacks has provided Nedstack with insight into the dynamics of this market.

Nedstack was additionally involved in a path of R&D in Direct Methanol Fuel Cells (DMFC). The main target market for this technology was the military portable power market. In 2003 a joint venture was formed between Metal-tech and Nedstack, Bee power systems, to build DMFC power systems in the 50-200W range, including a DMFC power pack for soldiers. The joint venture was dissolved in 2004. Nedstack continues to supply components for Direct Methanol FC stacks, but has become less active in DMFC applications. Van der Meer explains, *"truthfully, we do not really believe in that, maybe for very small and* very *specific applications… we have developed DFMC for a military application together with an Israeli. So we have something, we have developed enough knowledge to build a good system, but..…we see it as an addition to our capabilities".*

Although research and development grants were in place, it was more problematic to find grants for the phases after that. There were limited grants for demonstration projects and regulatory support available for realising demonstration projects and to set up a product line whilst investments were significant. Besides the CHP project, Nedstack was primarily involved in feasibility studies and R&D projects financed by subsidies[2]. For example, Nedstack conducted a feasibility study for FCs in public transport between March 2001 and August 2002 and engaged in EU funded R&D projects in consortia targeting R&D, such as the Optimirecell project that ran from 2002-2005, for the development of a high-temp 10 kW FC stack for automotive applications. The Revcell project ran from 2002 to 2006 to develop an autonomous energy supply system with reversible FC as long-term storage for PV stand-alone systems and uninterruptible power supplies. Nedstack additionally supplied stacks to clients in combined heat and power and the automotive sector as well as to laboratories for testing purposes.

The period of 1998 to 2002 is characterised by a high degree of Research and Development. Although Nedstack was involved in a broad scope of applications, the company did not invest significantly in the development of proprietary probes. Van der Meer explains that Nedstack waited for applications to emerge: *"in contrast to Ballard, Plug Power and others, we have invested less and have started at a lower pace and we have waited, are there applications coming? And they will be coming gradually".* Nedstack waited some years to invest in probe markets. According to Middelman, the status of the technology would not enable competitive applications. Additionally, the company was not pressured to develop early demonstrations.

"We might be relatively late in all kinds of applications, but I think that much earlier particular applications did not make sense because the technology was not ready or the prices, on estimation, were not even close to what they should be. So I think that for a number of applications we are well on time. We were in a position that we did not have to do nice demonstrations for our shareholders to bring in money whilst other parties did have to do that and were dependent on much too early demonstrations for their financing" (Middelman 2006).

The first period at Nedstack is characterised by a high degree of R&D in a broad scope of technologies including PEM FC stacks, fuel processors for multiple fuels, FC components including membranes and electrodes, heat pumps, FC inverters and DMFC systems. Over the years, Nedstack restructured the com-

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2 Nedstack projects pending and concluded on: www.fuelcellmarkets.com/nedstack/news_and_information/

pany and focused its technological developments. For example, Nedstack has stopped making reformers, electro-catalysts and gas diffusion layers. As Middelman explains, *"when we started, when we stepped out of Akzo, we had our own electro-catalysts, membranes, gas diffusion layers, ideas to make stacks, reformers and ideas for systems... That has been reorganised partly because you learn which things you can do and which you cannot, which things you are relatively good at and which things you are less good at. So you use that knowledge to create some focus".*

An outcome of the first period is therefore a focus in Nedstack's scope of technological developments. From the main probe, the CHP project, Nedstack gained system integration experience. Besides, the initial probes in CHP and the supply to CHP system integrators gave Nedstack a better understanding of how fast this market was moving. However, Nedstack experienced that the market was not moving fast enough. Additionally, market requirements and in particular the required cost level, could not be met as yet. Therefore, although Nedstack had concentrated on micro CHP in the first years, the company shifted its attention to other areas besides CHP. Nedstack decided to develop a multi applicable technology platform to serve a broad scope of markets. As Middelman describes, *"in the beginning we thought we had to focus on micro CHP, so most of the work was spent on micro CHP applications. In the previous years we observed that* this market was not developing that prosperously and that probably other markets would come much earlier. Because of that insight, we shifted towards more universally applicable stacks with higher powers suitable for telecom and back-up. If we did not have that insight, then we would still be meddling with non saleable stacks".

7.2.3 Period 2: Stack Platform Applications

The development of a technology platform gave Nedstack a new point of departure for applications. Besides, Nedstack focused its R&D on PEM stack development and manufacturing. Through sister company 'Nedstack FC Components' Nedstack developed and patented conductive bi-polar plate materials and a mass production process to produce these plates. Thereby, Nedstack is targeting cost reduction of stacks through bi-polar plate cost reduction. This division also develops plates for DMFC, mid temperature PEM and high temperature PEM. Nedstack's probe process shows that the DMFC probe path was aborted and the CHP probes were slowed down.

At the start of 2003 Nedstack presented a technology platform: a multi applicable FC stack of 1kWe, 2.5kWe, 5kWe, 10kWe or 20 kWe (fig. 7.8). Van der Meer describes this platform as follows, *"we have a platform, chosen about three years ago. With that platform we can, in principle, serve the micro CHP market. ..we can serve the automotive market and the stationary market. Although, for large stationary it may be a bit small. In any case we have chosen somewhere in the middle… so that at least customers can buy a stack that is quite robust and flexible. We have built a platform that is multi applicable….and with it we can serve these markets quite well".*

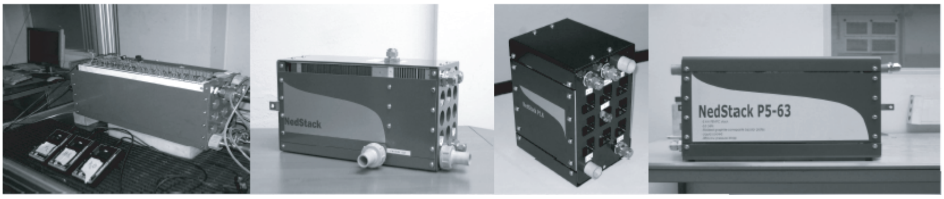

Figure 7.8 A selection of Nedstack's stack platforms

The platform stacks evolved and in 2005 Nedstack introduced a new generation of FC stacks. The Nedstack A 200 series is a liquid cooled PEM FC stack with a modular configuration from 5 kW, 10 to 20 kW. This PEM FC stack series showed improved power density and integrated balance of plant components such as a cathode humidifier and cell voltage monitoring. In 2006 Nedstack added a 70 kW module to the platform portfolio. Middelman explains the rationale of developing a multi applicable stack: *"most costs are* *in development, so you have to do that very efficiently. Quite soon we realised that developing two or three stacks in parallel was hardly feasible and that it would be better to develop one stack platform that is multi applicable. And that is what we did. That stack goes in buses, boats, telecom back-up, but also in micro CHP, generators, the PEM power plant, submarine".*

From this period onwards, the technology platform was applied in a broad scope of market applications. The application of the technology platform enabled Nedstack to address short term markets. *"For the short term, you first pick the low hanging fruit … and run from niche market to niche market"* Van der Meer explains. With the technology platform, Nedstack could serve a variety of markets as well as early adopters that approached Nedstack with ideas for applications. Van der Meer explains that apart from their own ideas for applications, ideas came from people that approached Nedstack For example, an entrepreneur that needs stacks or an OEM with a problem. The number of potential customers approaching Nedstack increases as Nedstack gains publicity. Nedstack engages in such applications when realisation appears feasible and make sense. Some of these projects are one-off and require customisation. The decision to take it on depends on the client, but requires resource allocation considerations says Van der Meer: *"if they pay for customisation, OK, but you can only use your man hours once.. If it only results in a few stacks, then the project may stand in your way".*

Nedstack became involved in applications in a broad scope of market segments. For example, in 2004 and 2005 Nedstack was involved in the development of a 300 kW submarine[3]. In a collaborative effort between NedStack and ESORO, a Swiss engineering firm, the HyCar was demonstrated in 2005. The HyCar is a neighbourhood vehicle that used the FC for motive power as well as an auxiliary power unit for powering equipment. In collaboration with Hygear and ECN, Nedstack realised a diesel Genset. At the Olympic Games in Torino 2006 Nedstack demonstrated a 50kW generator in a joint Italian-Dutch collaboration at the HyPark. Furthermore, Nedstack has supplied stacks in the material handling sector, telecom back-up. Nedstack additionally reports developments on an autonomous system for remote power and UPS. In addition, Nedstack has conducted numerous feasibility studies for various market applications including buses, ferries and trains and Nedstack supplies to OEM customers such as forklift, automotive and CHP. Thus, Nedstack has been involved in numerous developments and supplies that this study does not register as probes.

According to Nedstack, the technology platform is less suitable for portable power. No further probes are reported in this market. Between 2003 and 2006 the CHP path became a side track path as a result of moderated expectations and a better understanding of the speed of this market. Nedstack aborted the development of reformers. The CHP path has slowed down but Nedstack continues to be involved in developments. For example, Nedstack has developed cell plates to integrate high temperature membranes. Although the market is not considered to be commercially interesting in the short term, a technological breakthrough in high temperature membranes may open up mid-term opportunities. Therefore, Nedstack keeps options open to step back into the market in a number of years. As Van der Meer states, *"if I look at it commercially then I think, no it is not interesting at the moment…. But of course you have to keep everything open, so that if that membrane is there in two years, three or ten years that you can step in fluently. So what we can offer our clients is a high temperature cell plate, you can get that one. We make the design such that you can also use it in a low temperature cell plate and in a high temperature cell plate".*

Nedstack continues to supply to a number of CHP clients. In 2006 NedStack also reported the successful introduction of Micro Cogeneration stacks, ranging from 1.5 up to 5 kWe, in Japan[4]. Nedstack considers specific applications for CHP to be interesting and the company is involved in two application trajectories for micro CHP stacks: applications in hydrogen grids and grid independent houses. The application of micro CHP with hydrogen supplied from a pipeline or grid simplifies the technical challenges faced with

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[3] *Projects pending and concluded on www.fuelcellmarkets.com*

[4] *Announcement at the group exhibit Hydrogen and Fuel Cells Hannover Fair 2006*

micro CHP: a cheaper reformer, a relatively simple system with higher durability. The grid independent house does not require a reformer and is considered to have potential because it makes use of existent components. As Van der Meer describes, *"we are active in a project to build a house that will be totally grid independent. It is an entrepreneur that had approached us and said: I need a stack. We will start collaboration with him if the project continues. He has excellent solar cells, a good windmill and a nice system, well calculated. Again this is a matter of:, all the components exist and now we are going to tie it together".*

Outcome Period 2

The broad scope of applications enables Nedstack to generate volumes of stacks. Middelman explains that for Nedstack generating volume is more important than focus: *"the advantage to focus is not so big, that is why we do not do it. It is much more important to reach volumes".* This ambition to produce volumes of FC stacks illustrates that during this phase Nedstack was focused on shifting from a R&D company to a production company. At the same time the broad variation may help to focus in the future, as Middelman explains, *"of course everyone says that you have to focus, but nobody knows on what. And I do not think it is a good idea to guess on what to focus. So it gives us insight into which applications are most attractive on the short, mid and long term and helps us to focus on the things that contribute most to our goals and results…The broad variation helps us to, in a later phase, perhaps focus on the most attractive markets".*

7.2.4 Period 3: Pilot Plant 2005-2006

Although Nedstack continues to be involved in a wide range of applications, the development of Nedstack's first 'pilot plant' is central to the company's probe process. The rationale for selection was the need to develop a proprietary pilot and generate reliability data. Van der Meer explains, *"we have the vision and we have ideas about how it should be done, but we have little experience"..*

Akzo PEM Power Plant

In this third period, Nedstack targeted a shift from a R&D focused company to a stack production company. The stack platform developed around this time was applicable in stationary systems. This probe would enable the scaling of manufacturing capacity and the validation of the stacks. The target specifications are to install 50 MW nominal power with 2000 stacks of 100 kW peak power and 25 kW nominal power. Nedstack chose the 'PEM power plant' as a large scale demonstration/ pilot project for *"large- scale testing to show potential clients, look under these and these circumstances we have reached so many hours at these degradations" (Van der Meer 2005).* Middelman explains that durability tests on scale give a higher statistical reliability. This large-scale demonstration with a large number of stacks will provide reliability data, enable cost reduction and validate setting up Nedstack's production lines. *"We use these projects as durability tests. Also, we would like to enter the bus market on a large scale, but before we can enter the bus market, we need to have proven 20.000 hours…. Through a large scale demonstration and durability tests with a large number of stacks, you get a much better statistical reliability. And that again is necessary to enter the bus market"* (Middelman 2006).

There is dispute about the potential of PEM technology for large-scale stationary power generation in the PEMFC industry. Yet, Nedstack chose the PEM power plant application for its main pilot project. Nedstack believes that from a market demand perspective this is a potential market because clients can actually save money through efficiency gains. The value proposition is that chlorine electrolysis plants require large amounts of electricity, therefore, efficiency gains translate to significant cost savings. According to Nedstack this is an interesting niche market that can be cost effective and meet the durability requirements in the mid term, although additional subsidies may be required to make the application completely feasible. Additionally, Nedstack believes that there is significant market potential for PEM power plants. Worldwide, there are a large number of chlorine plants where 5 to 10 MW of Hydrogen is produced that could be used to produce electricity. Nedstack's interest in this market is reflected in the PEM power plant patent application in 2005: 'Power plant comprising FCs'. This patent is described as the generation of electricity in a power plant comprising of several hundreds of FC stacks, coupled to an electrochemical production process in which hydrogen is released.

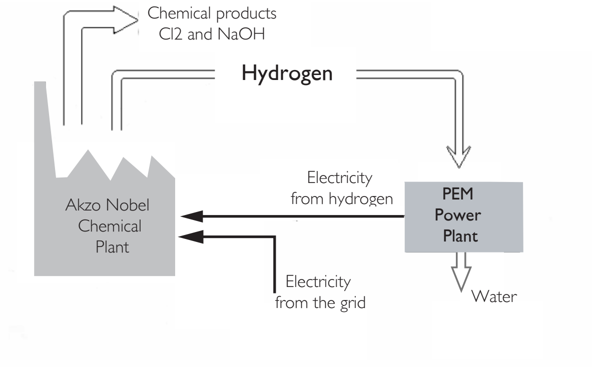

Figure 7.9 Diagram of the PEM Power Plant in Rotterdam. Based on Nedstack 2006[5]*.*

In January 2004 Nedstack commenced with the development of its first large-scale pilot project: the PEM Power Plant. In collaboration with Akzo Nobel, Nedstack developed and installed a FC system for an Akzo Nobel chlorine electrolysis plant. These plants comprise electrolysers that produce chlorine and hydrogen (fig. 7.9). The hydrogen is fed into the FC system and with the resulting electricity a number of electrolysers are powered. The first probe was the development of a FC module of 50 KW. Successful start-up was announced in January 2005 and the system ran for 6 months. This project was focused around material and stack development for application in a large system. This module was subsequently scaled to a 120 kW system and applied in the demonstration project 'Power plant demo Delfzijl'. The development, installation and operation of this system took place between April 2006 and September 2007. The demonstration status required full time supervision so it was operated for a limited period of 6 months, but the results where positive. The project is supported by the Dutch Ministry of Economic Affairs through its Energy Innovation Programme (EDI). Van der Meer describes the plans for future development: *"with the knowledge from that 200 kW system, we will build the first 5 MW… this zero series will then be rolled out to an eventual capacity of 50 MW nominal power".*

Nedstack supplies the whole FC system, instead of only the stacks, for the PEM power plant because in this market, customers are not system integrators. As Middelman explains, *"the clients are large chemical companies that do not regard the development of those types of systems as a core activity and therefore, they are not going to develop and build these types of systems. But they do want to buy them, and particularly exploit them, so there has to be a party that develops the systems. There was no system integrator for this market and it did not look like they would spontaneously emerge, so we fill that gap. So for the PEM power plant, large scale stationary applications, we offer complete systems up to 1 MW".*

The outcomes of the PEM power plant probes include technical lessons on durability and degradation. With feedback from the first pilot a number of improvements have been made on the stacks and materials resulting in durability improvements. Middelman explains, *"we have won a lot there in terms of durability. That is essential for our customers. The PEM power plant was an economical source of hydrogen for conducting durability tests".*

Nedstack has also gained a better understanding of the customers' technology in this market and the chlorine electrolysis technology specifically. For example, the problems customers have and their particular specifications and requirements. Regarding installation, Middelman explains, *"we have also learnt quite a bit particularly in the field of designing for the chemical industry. The chemical industry poses very different requirements on safety than for example a car or a bus. Now we know a lot more about all those safety procedures and*

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[5] Presentation Nedstack Fuel-Cell 2006, Raleigh Durnham. PEM power plant: stationary power generation with by-product hydrogen.

the safety systems that are maintained there. We gained that system experience". Nedstack has also gained an understanding of the chlorine electrolysis market and specific market information on, for example, where the factories are and how much they currently pay or earn from the hydrogen they produce. Furthermore, the project has received a large amount of publicity worldwide. As a result, Nedstack has gained contacts with potential customers in this market worldwide.

Bus Path

Nedstack has shown interest in the bus market since the feasibility study on FCs for public transport conducted between 2001 and 2002. Nedstack did not pursue probes in this sector in the years that followed. However, Van der Meer explains that numerous potential customers have shown interest and that there are locations with specific problems where customers are willing to pay more. Due to government support and regulation,s market opportunities in the bus market are emerging, for example, in Nedstack's home town of Arnhem. At the Hannover FC trade fair in 2006, Nedstack presented a 70kWe FC module for low floor city buses. The company is looking for partners to apply this module. Nedstack has expressed the intention to use the PEM power plant data to validate durability for the bus market.

Sales / Supply

In 2006 Nedstack's first significant repeat orders for FC stacks were reported. The company received a significant repeat order for FC stacks for a stationary application to deliver 40 of its 8 kWe PEM FC stacks to one of its most important customers[6]. Nedstack has been selling and supplying stacks to various customers for many years. These customers include universities and laboratories that purchase the stacks for testing as well as OEM customers. According to Middleman their customer base is steadily increasing. Although this study does not consider stack sales as Nedstack 'probes', Middelman explains that early involvement and the supply of stacks to OEM customers is crucial to becoming a supplier to established system integrators. To establish Nedstack's supply chain position, *"we have to participate in the early applications in order to be involved in the commercial applications. If we do not participate in the prototype and field test phase, then we will not be in as a supplier in the commercial phase. So for us it is a necessity that we participate"(*Middelman 2006).

Additionally, the sales and supply of stacks is a source of learning about applications of FC technology. Nedstack receives feedback from supplying stacks. Middelman describes what the company learns from supplying stacks to customers: *"we learn about durability, we learn a lot about how clients are able again and again and each time in different ways to break down stacks. And by supplying to all those markets we also have a much better insight into how fast those markets are moving…. We supply to all those system developers, so we know in an early stage what they are doing, which products they want to introduce, when and in which quantities".*

Among others, Nedstack has supplied to forklift OEMs, telecom back-up OEMs and the automotive industry. Nedstack is looking for OEM partners and customers in niche market segments such as forklifts and telecom back-up. Nedstack is supplying to a number of FC systems builders for telecom back-up power. In some cases Nedstack is involved for system integration, in others not. Several customers initially lack the capability to integrate the FC system. Nedstack has then helped to educate the customer on system integration. In the case of forklift trucks, Van der Meer explains, *"we are trying to find partners that know and understand everything about forklift trucks that can integrate our stack and possibly the system in the forklift truck. We could supply the BOP with it".* Furthermore, Nedstack has supplied FC stacks to a number of automotive firms for several years. *"We have a couple of automotive clients that buy stacks for benchmarking. They compare it with the status of their own technology. That is quite nice, because at least we receive the data. That is a group of clients"* (Middelman 2006). Regarding Nedstack's engagement in automotive development, Van der Meer explains, *"if you want to do something for the long term, then it really has to be interesting on the long term and otherwise you shouldn't even start and, they have to pay well for it".*

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[6] News release on Fuel Cell Markets, November 2006, www.fuelcellmarkets.

7.2.5 Conclusions Nedstack

Nedstack's probe applications have been described and are illustrated in figure 7.10. Nedstack focused its early developments around the CHP market. Although the company continued to engage in CHP, a shift in strategy took place towards the development of a technology platform for a diversity of applications. Finding that large markets where further away than expected, Nedstack turned to achieving quantities of stacks through a diversity of niche markets. The company supplied to and engaged in a broad scope of applications. Over time, Nedstack's probe process does not show significant convergence to a select number of market probes. However, the selection and investment in the PEM Power plant marks a third period of probing: Nedstack's proprietary pilot project to further develop and validate its FC stacks. In the third period Nedstack additionally presents a module for the bus market. To serve these two markets, Nedstack has developed FC systems. At the Hannover fair 2006, Nedstack suggests that it is now time for OEMs to integrate FC systems in prototypes and the demonstration of end products[7].

Many of Nedstack's developments are conducted internally with OEM customers. Additionally, the company has engaged in numerous subsidised projects for R&D, feasibility studies or demonstrations. Abiding by the definition of probes as publicly announced physical applications, the count of Nedstack's probes does not represent the scope of applications the company is actually involved in. An additional consequence of the subsidised projects is that Nedstack's probe paths appear short. Although the projects often last several years, typically, a single prototype is realised in these projects.

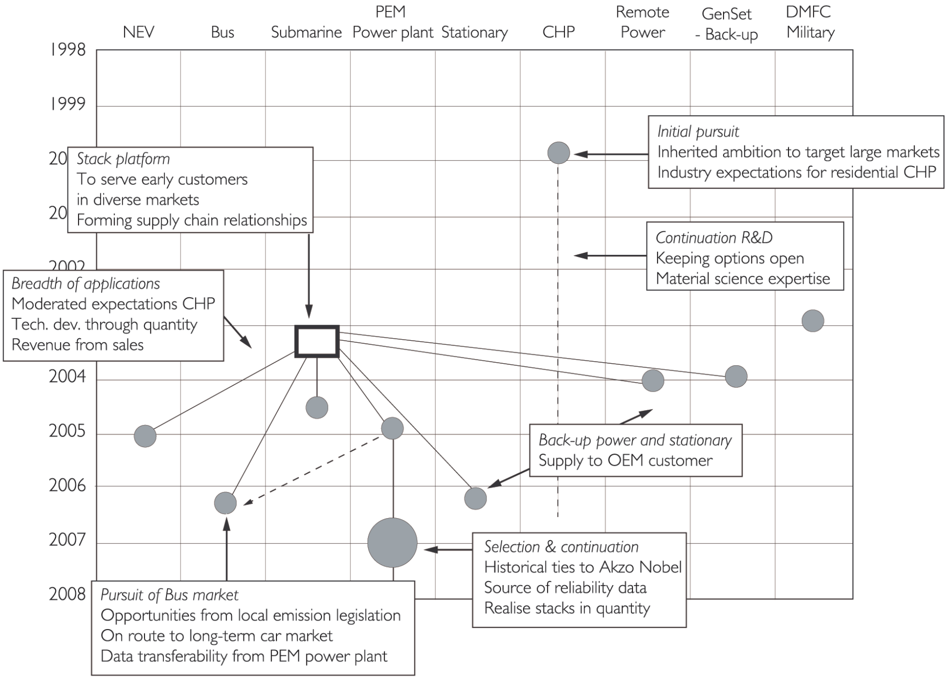

Figure 7.10 Overview Nedstack's probe applications and the factors that explain Nedstack's probing proces

In comparison to other firms in the FC industry, Nedstack and Ballard are FC stack manufacturers and both companies have positioned themselves as automotive suppliers. The choice of this position has consequences: *"concentrating on stacks automatically leasd to a concentration on fewer customers but it increased market flexibility"*[8].Both companies began to diversify when the automotive market was further away than

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[7] Forum discussion/ presentation at the Group Exhibit Hydrogen and Fuel Cells in Hannover 2006

[8] From questions answered over the email by Jochen Straub, Sales Account Manager Ballard Power systems in November 2006

expected. However, there are key differences: Ballard is almost 10 years older and 12 times larger and Ballard has been in large strategic alliances with automotive companies for many years. Similar to Nedstack, the company Nuvera has a history in the electrochemical industry. Nuvera suggests that in the case of automotive companies, "*these companies are so powerful, they just ask what they want and Nuvera tries to please. In this sense Nuvera is a technology provider*"[9].

Explaining INITIAL Probe Selection

Nedstack did not engage in early demonstrations for some years. The company explains that in terms of cost and performance comparison, probe applications did not make sense. In Nedstacks' perception there was no value proposition for probing, in terms of technology-market alignment and cost in particular. Additionally, the company explains that it was not pressured by its investors and shareholders to develop early demonstrations. Considering that Nedstack claims to have invested less than competitors and started at a slower pace, waiting for applications to emerge, it can be argued that Nedstack was run and financed as an R&D company. The focus on R&D may be explained by the company's material science background. However, the limited number of initial probes may additionally be explained by the lack of grants for realising demonstration probes in this period. Furthermore, Nedstack's initial developments are characterised by a diversity of technological developments. This approach to strategic positioning of technological competences may be explained by the company's material science background.

Nedstack's initial probe reflects the company's ambition to pursue large scale markets. This ambition can be explained by the company's stack manufacturing ambition. Apparently, this ambition is rooted in Nedstack's historic background; Akzo envisioned manufacturing stacks for large scale markets. However, Nedstack made the decision to shift away from the automotive industry. This may have been influenced by the lack of an automotive industry in the Netherlands. But this explanation is unlikely, because Nedstack continues to target this market on the long term. Besides, Canadian FC companies such as Ballard, target the automotive market in a country without a significant automotive industry. The shift away from automotive applications is more likely to be explained by moderated expectations of automotive adoption.

Nedstack thought they had to focus on CHP, because it was believed to be the first large scale market to emerge prior to the automotive industry. The expectations for CHP, were they insights within Nedstack, influenced by the industry or both? On the one hand, Nedstack formed internal expectations of the value proposition for this market, reasoning that this would be the first large scale cost-effective market. On the other hand, there were industry expectations at the time that the first large market for FCs would be CHP for residential. In any case, this market potential fit Nedstack's ambition to target large markets.

A European subsidised project enabled Nedstack to realise its initial CHP probe. Considering the financial support for demonstrations in these years, Nedstack appears to have grasped this opportunity to realise a probe and apply several of its technologies including its proprietary gas reforming competences.

Explaining SHIFT to Diverse Niche Markets

CHP may still become the first large scale market for FC technology, however, Nedstack realised that many smaller markets would emerge before this time. Feedback from initial probes and supply provided Nedstack with a sense of market dynamics. At the speed of this market Nedstack would not be able to supply quantities of stacks within a feasible time period. Apparently, Nedstack's shift away from its focus on CHP can be explained by the assessment that the value proposition for the CHP market was insufficient. Instead smaller markets would come first.

Nedstack proceeded to develop a stack platform. The development of a technology platform and the focus of Nedstack's technological competences can be interpreted as strategic positioning as a FC stack manufac-

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[9] *Telephone interview with Sales and Marketing Manager at Nuvera in February (2004)*

turer. It can be argued that the development of a platform was necessary, because with limited resources Nedstack was not able to develop different stacks in parallel to address different markets at the same time. The development of a multi-applicable stack platform enabled Nedstack to address a diversity of niche market and serve early customers in different markets. The rationale behind targeting diverse customers reflects Nedstack's supply chain positioning. According to Nedstack, early supply is central to the formation of long term supplier relationships. Apparently, Nedstack found that it would only be able to gain enough revenue and volume from multiple niche markets at the same time.

Nedstack's breadth of probes can therefore be explained by an approach to achieve volume through a multitude of niche markets. According to Nedstack, it has been a rational decision to probe in a breadth of markets because the perceived advantage of focus was not so big and volume was more important. Additionally, Nedstack mentions that the diverse applications help to learn to identify value propositions. Apparently, Nedstack had not identified a value proposition large enough to focus on. Nedstack's approach to niche markets can be characterised by "picking the low hanging fruit" and 'running from niche market to niche market'. This approach suggests a stronger focus on technology development and manufacturing than market development. Apparently, Nedstack considers market development to be the responsibility of OEM customers. Nedstack's approach to developing a value proposition for these markets is through cost reduction, which may be explained by the company's material science background.

However, the diversity of projects may also be explained by opportunistic behaviour from being resource dependet on subsidised projects and customer proposals. Nedstack engages or supplies to most projects proposed by early adopter customers that appear to 'make sense'. For example, CHP sub-segments are addressed because they see a value proposition in those markets and it appears to make sense. Feasible applications with minimal risk are existent components where Nedstack can focus on stack supply. Additionally, Nedstack has engaged in a diversity of subsidised projects. These projects provide revenue, however, typically, such projects are of limited duration. On the other hand it can be argued that these diverse projects also contribute to realising quantity and may contribute to the formation of supplier-customer relations.

Several of these projects have been of a limited duration. The duration and availability of subsidies may explain duration, explaining abortion as a lack of resources. On the other hand, probes are not continued because customers learn that costs and status of the technology are too far away. Apparently, Nedstack was unable to communicate the costs and risks involved. According to Nedstack it is learning focus on a select number of customers that are particularly worth while to build supplier relations with.

Keeping Options Open

Nedstack's probe process is additionally characterised by keeping technological options open. Although the company has focused its technological developments, the company tends to maintain these competences and continue with R&D in various areas. The option for CHP engagement is kept open through developments in high temperature plates. Nedstack appears to position itself as a technology flexible company, able to supply customers what they need if markets emerge. The firm's material science competences and background may explain this approach.

Explaining the PURSUIT of the PEM Power Plant

Nedstack selected the PEM power plant as a main pilot for testing and technology development. Several factors can explain this decision. First, the PEM power plant consists of many kilowatts, enabling Nedstack to scale production and generate volume. Additionally the company expresses the need to build experience to validate technology and convince customers. The number of stacks enables reliability testing on scale with a cheap source of hydrogen for reliability testing. Besides, Nedstack argues that the durability data and validations are applicable to the bus market. But why this specific niche market? Nedstack argues that it has identified an economic value proposition in this market; the application can save customers money through efficiency gains. According to Nedstack's observations in this sector, the market size is significant. It can be argued that this value proposition developed internally because Nedstack is one of the only companies in this market and the industry generally does not consider large scale PEM applications. Therefore, Nedstack's pursuit of this market cannot be explained by industry expectations.

However it is likely that Nedstack's probe decision for a power plant in the chlorine electrolysis sector is related to its historic roots in the electrochemical industry and Akzo Nobel in particular. On the one hand, Nedstack has an historic connection to companies in the chemical sector. On the other hand, Nedstack may rely on its historic relationship with Akzo Nobel to realise this probe in terms of costs and risks. This niche market is not cost-effective as yet and realisation requires funding and support from subsidies as well as the commitment from customers. Apparently, Nedstack relies on a partnership from its historic roots and government funding to realise this probe.

After the initial probes, Nedstack continues to scale the PEM power plant. Initial tests show that the system functions as desired. The operational data and the technological progress is positive. Besides, Nedstack has gained information on customer interest in this market and received extensive publicity. Apparently, Nedstack's unique value proposition continues to hold for the firm and may provide Nedstack with a strategic position in the chemical industry. However, full scale realisation of the PEM power plant is likely to require additional subsidies. Therefore future decisions to continue are likely to continue dependence on the availability of subsidies and customer commitment.

Explaining the Interest in Buses

Nedstack showed interest in the bus market in early years, but did not engage this market probe for several years. This interest can be explained by Nedstack's long-term automotive ambition; buses are on the path towards the automotive market. Besides, in line with Nedstack's probe strategy, buses require a lot of kWs, enabling stack volume. Considering Nedstack's technological competences, the company has developed system integration experience and is gaining reliability data to serve this market. Yet, Nedstack appears to have waited for the emergence of demand in this market. The lack of a value proposition and market demand explains this wait. As a small company, Nedstack cannot develop a bus probe without financial support and a customer.

The value proposition for this market depends on local regulatory measures and situations. Protected niches have generated demand for FC systems in the bus market. It can be argued that currently Nedstack perceives a value proposition for the bus market, because in the Netherlands as well as neighbouring countries such as the United Kingdom, such protected niches are emerging to solve local air quality problems. Moreover, there are several Dutch bus builders in the Netherlands enabling Nedstack to evaluate the interest of these potential customers.

Explaining Current Breadth

Nedstack has focused pilot plant activities on the PEM power plant and the company has become more selective in its customers. However, Nedstack continues to engage in a variety of markets. It can be argued that Nedstack has not found a niche market with sufficient sales potential. On the other hand, Nedstack's breadth suggests that it is in the process of forming supplier relations with customers for near and long term markets. The company argues that from supplying to a diversity of customers it gains valuable experience about the conditions in which stacks are applied by customers and a sense of market's dynamics. Besides, Nedstack argues that with a stack platform, a high degree of cross-over learning is possible and that there is a high degree of synergy between different market applications.

The formation of supplier-customer relationships is determinant for Nedstacks' probe process. Additionally, Nedstack's history with Akzo Nobel influences its approach to market applications, technology development and probe selection. The firm's material science background appears to have influenced the firm's strategic positioning as stack manufacturer and the firm's approach to developing its value propositions through cost reduction.

7.3 Case Hydrogenics

For the Hydrogenics case, the main interviews conducted include: i) Mark Kammerer, Head of Sales, Marketing and Business Development Power System, based in Gladbeck, Germany. This interview was conducted in January 2006 in Gladbeck. ii) Jon Dogterom, Director Business Development of the Business Unit Power Systems, based in Toronto, Canada. This interview was conducted in August 2006[9]. As a public company, the annual reports (AR) from the year 2000 up to and including 2006 provide complementary data in addition to press releases on the Hydrogenics' website[10].

The Hydrogenics case has been selected on the basis of its focus on two niche markets to which it applies proprietary module technology. Hydrogenics' probing process is characterised the pursuit of niche markets. The following paragraphs show how Hydrogenics initially engaged in probes with early adopters. Hydrogenics' probing process is subsequently characterised probes in a breadth of market segments. After these 'technology demonstrators', Hydrogenics focused on the development of two niche probes. Noteworthy aspects of Hydrogenics' probing process include the focus on early adopters markets for initial probes. Also the company applied a module in a breadth of market probe, in which Hydrogenics was one of the first FC firms to engage in light mobility applications. Hydrogenics' subsequent focus on back-up power and the forklift market is notable. Finally, although a key focus area, the back-up power probe path shows a long period of inactivity after initial demonstration.

7.3.1 Introduction to Hydrogenics

In 1995, three people with a vision of clean and sustainable energy founded Hydrogenics (AR 2005). The fully independent start-up company Hydrogenics was established in Toronto, Canada. *"Two of the founders were already working in hydrogen research and one of them had registered the name Hydrogenics as early as 1990, before the company even existed"* explains Kammerer. One of the founders, Pierre Rivard, had spent 25 years in the military and knew that there was some work being done on FCs and that there was potential. Kammerer describes the motivation for founding: *"the third founder decided on founding the company after being at a hydrogen company in Quebec, seeing the work that Ballard was doing with the first FC buses and they decided, this is where they were going to start a company".*

Firm Growth

The first three years after founding, Hydrogenics grew on the basis of its FC test and diagnostic business. Hydrogenics has also operated an Asian Pacific office in Tokyo, Japan for its FC test business since 2000. Hydrogenics completed an IPOs in 2000. In the following years, Hydrogenics expanded its business units through a number of acquisitions. In May 2002, Hydrogenics acquired EnKAT GmbH, a leading German-based manufacturer of FC test systems and established an office in Germany. In 2003, Hydrogenics extended its FC test and diagnostic business through the acquisition of Green Light Power and in January 2005, Hydrogenics acquired Stuart Energy Systems Corporation, a company with 57 years of experience in hydrogen production systems.

In 2005 Hydrogenics defined three autonomous business units: 1) On-site Generation, 2) Power Systems and 3) Test Systems. During 2000 the number of employees increased from 24 at the beginning of the year to 74 by year end. By 2002, the number of employees had increased to 235 employees and to 290 by 2004.

Technological Core Competences

Hydrogenics' initial years where focused on the FC test and diagnostic business and the company derived system integration skills from this business as the 2000 annual report states, *"the knowledge and expertise that we have acquired from the development and manufacture of our fully automated test and control systems*

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[9] *This interview was conducted over the telephone.*

[10] *Hydrogenics website: www.hydrogenics.com*

is being actively applied to the development of FC power generation products…We believe that we are one of a few PEMFC developers with these integration capabilities in addition to substantial FC expertise".

According to Kammerer, competences in PEMFC technology were developed after the founding of the company. *"They had alkaline FCs experience and they realised, from doing more investigations, that PEM was where there were most opportunities and the largest potential market. They started experimenting, doing tests and started right from scratch'.*

Business Model and Supply Chain Position

The mission of Hydrogenics, considering all three business units, is to be a leading global developer of clean energy solutions by advancing the Hydrogen Economy. Hydrogenics' business model for the FC power business unit is centred on the manufacturing of integrated FC systems, or FC modules, applicable to a broad range of markets and applications. Dogterom explains why Hydrogenics has focused manufacturing FC modules for OEM customers:

"Our modules, both for mobility and for back-up powe,r are typically purchased by OEMs and OEMs integrate them into their products for their customers. And there are a few reasons for that approach: in this manner you can reach numerous markets with minimal investments. …They understand their market a lot better than we ever would. …. If we were trying to do it on our own, we would have to focus on more of a single application. …..Thus, it allows us to streamline our manufacturing and ensures that we are working together with someone that understands the market a lot better than we ever would" (Dogterom 2006).

Hydrogenics provides system integration assistance where necessary and often supports the interfaces, to help make a FC product work. However, as Kammerer explains, Hydrogenics prefers to 'hand over' the modules, because *"a project is more appealing when we can just say, here is the unit".*

Strategic Alliances

In October 2001, Hydrogenics formed a strategic alliance with General Motors to 'accelerate FC developments into global commercial markets'[11]. According to the annual report of 2001, the strategic relationship provides Hydrogenics with *"a license to world-leading stack technology, access to global distribution channels, and numerous other benefits, not the least of which is co-branding opportunities with the world's largest manufacturer".* In 2001 Hydrogenics formed distribution partnerships in the Asian Pacific and the European market. Key strategic relationships in the Hydrogen systems business are ChevronTexaco, Shell Hydrogen, BP, Toyota and Ford. In the power generation business, Hydrogenics formed key strategic relationships, besides GM, with John Deere, and Hitachi Zosen in Japan.

Financial Resources

The financial data of Hydrogenics shows a higher gross revenue than R&D expenditure (fig. 7.11). This can be explained by Hydrogenics' business unit in the fuel cell test and diagnostic equipment. Revenue up to and including 2000 was primarily from test equipment and after 2001 this business unit constituted

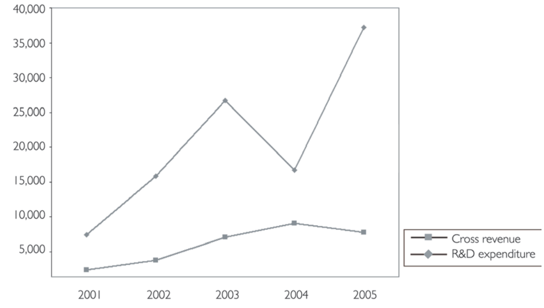

Figure.7.11 Financial data Hydrogenics. Source: annual reports 2001-1006

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[11] www.GM.com

50-60% of the revenue. After 2001 Hydrogenics began to generated revenue from its power modules, however, sales of the power systems remained limited. Hydrogenics has also generated revenue from providing engineering services to, for example, GM. Furthermore, the Canadian government provides Hydrogenics with R&D grants. For example, a press release in March 2001 reports that Hydrogenics received project funding of $2 million from the Canadian government. The financial data suggests that to date the company is in a developental stage with net loss of $37 million in 2005 and $130 million in 2006 (AR 2005, 2006).

Overview Hydrogenics Probing Process

The historic account of Hydrogenics' probing process is illustrated in figure 7.12. The probing process will be described over three periods. The first period between 2000 and 2002 is characterised by early demonstrations and R&D with early adopters. The second period between 2003 and 2005 is characterised by the introduction and application of the Hydrogenics FC module into a multitude of probe applications termed technology demonstrators. In the final period, between 2005 and 2006, Hydrogenics focuses on field trials for a select number of niche markets. The two most prominent probe paths in this period are described in further detail: the forklift path and the back-up power path.

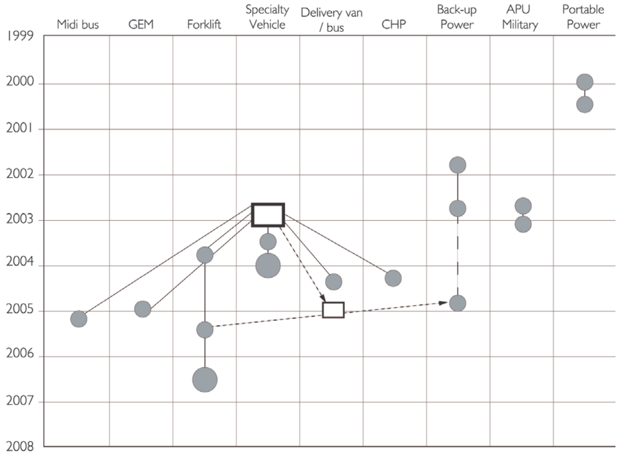

Figure7.12 Hydrogenics probe applications

7.3.1 Period 1: Early demonstrations 2000- 2002

Up until 2000 Hydrogenics' technological core competence and business were primarily focused on the development and sales of FC test and diagnostic equipment. With the FCATS system Hydrogenics was a first mover in this FC test station market. The annual report of 2000 (p.6) states, *"our today business is the development, manufacturing and service of control and test products for FC research and market development"*. However, before and during this period Hydrogenics conducted R&D on PEM FCs and electrolysers for broader commercial application. Hydrogenics' strategy, as stated in the annual report of 2000 (p.3), was: *"from FCATS to commercial power products"*. The FC test and diagnostic business provided some initial revenue. More over, Hydrogenics argued that the system integration expertise gained in FC test and diagnostic equipment business was directly applicable to the development of FC power systems. Furthermore, customers in the FC test and diagnostic business provided a starting point for the development of FC power systems. The annual report of 2000 (p.3) states, *"by working closely with our FCATS customers we have discovered different ways of thinking about FCs, their potential applications and the systems that control and surround them"*. Kammerer explains that at founding, *"we had the plans to develop FCs but also find customers, find where we could make money early on. And we interviewed different potential clients and were given opportunities to provide test equipment and we found that was something there was a demand for and after a few projects it really gave the company a good start"*.

According to the annual report of 2000, Hydrogenics aimed to exploit markets across the stationary, transportation and portable power spectrum. Additionally, the report indicates that Hydrogenics aimed to start with premium niche markets, *"the route to commercial products for broad markets is through premium power applications"* (AR 2000: p.4). In line with this rationale Hydogenics' first FC probe was the demonstration of the HyTEF power generator for remote power markets. This premium power product incorporated Hydrogenic's FC stack experience from the FCATS systems. The product could generate between 10 W and 1 kW portable power. Field trials of the HTEF alpha version were held at the start of 2000 followed by durability tests at the end of 2000. The challenges for 2001, Hydrogenics states, are to move towards commercial FC products because *"we believe that the investment markets and stakeholders are growing impatient for FC technology to move from the laboratory to working commercial products that are utilized in everyday life"* (AR 2000: p.2).

Besides customers from the FCATS business, initial customers for Hydrogenics first FC systems were the military and aerospace industries, primarily funded by the governments of Canada and the United States. Between 2000 and 2002 Hydrogenics pursued two main probe paths for premium markets: 1. portable power for the military and 2. critical back-up power with GM. Hydrogenics had supplied both GM and the Canadian military with test stations. *"Hydrogenics' strategy has always been to pursue early markets via reference customers. Collaborations with these reference customers provide us with a solid platform from which to take products to broader markets. We are confident that the development of products for niche markets today will lead to the mass market opportunities of tomorrow"*[12].

Military Niche Market

Hydrogenics has a historic connection to the military through Pierre Rivard's background in the military. In 2000, Hydrogenics announced the development of the HyPort for the early adopter military market. The development was funded by the Canadian Ministry of Defence and the Ninistry of Natural Resources, but potential for broader commercial application was expected. Hydrogenics demonstrated an alpha version of the HyPort multi kW generator in 2000. The 'HyPort' was a technology platform for applications in portable and back-up power, incorporating a Hydrogenic's PEM FC stack and a fully integrated rechargeable metal hydride fuel source. In February 2002 Hydrogenics demonstrated the HyPort Chemical Hydrid power generator to Canadian and US Tank-automotive and Armaments Command (TACOM). The 500W system was developed under contract of the Canadian Department of National Defense. In November 2002 Hydrogenics delivered a regenerative FC auxiliary power unit (APU) to the US TACOM. The 5kW peak power system was developed for the US TACOM for deployment and testing on army vehicle platforms. Subsequently in January 2003 Hydrogenics, General Motors Corp. and the U.S. Army revealed a diesel hybrid military pickup truck equipped with a FC APU.

By the end of 2002 Hydrogenics had developed prototype modules of HyPort for sub kW and 1to 5 kW, primarily for military applications. The chemical hydrid technology integrated in the HyPort prototypes was not followed on by Hydrogenics. As Kammerer explains, *"the Sodium boroxide hydrid, a regenerative system for the DND, was a niche product interesting for the military. But they were faster with the patents. Anyway, it will still take a while before it is commercial".*

Telecom Niche Market

Hydrogenics' system integration competences were applied to the development of the integrated FC systems, the HyPort and HyTeF power modules. Hydrogenics continued with the development of power modules. At the end of 2000 Hydrogenics started with the development of a 25 kW plug and play power module. The 2001 annual report also reports the introduction of HyPM power modules for stationary markets in the range of 5, 25 and 40 kW. In 2001 this module was deployed in GM automotive trials in which

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[12] *Pierre Rivard in press release December 2000*

Hydrogenics provided system engineering services and following the supply of FC test systems, Hydrogenics signed a key alliance with General Motors in 2001, a joint effort to accelerate the development of FC technology. General Motors has been involved in FC development since 1964, a key player in the development of FC cars (Van den Hoed 2004). Since 2000 GM has also developed stationary FC applications.
In 2001 Hydrogenics and GM collaboratively developed and unveiled the HyUPS system, a 25 kW back-up power generator, about the size of a refrigerator. The press release explains that the system is *"designed to meet critical back-up power needs across multiple markets. The initial target market for this product is the demanding telecommunications industry"*[13]. In the fall of 2001 Hydrogenics presented a regenerative back-up power system at several telecom sites and trade shows. First, Hydogenics and GM unveiled the alpha prototype at a telecommunications conference in Las Vegas in October 2001. This HyUPS Regerative FC / electrolyser system contained a GM FC stack, the Hydrogenics' 25 kW FC engine, electrolysers and fuel storage. This probe, *"very clearly demonstrates the strength of our jointly applied expertise involving GM's superior stack technology and Hydrogenics' system integration capabilities" says Pierre Rivard*[14]. In the same month, Hydrogenics and Nextel Communications agreed to demonstrate the HyUPS. The successful installation of the HyUPS regenerative back-up generator at a Nextel trial site was announced in September 2002. In the following two months field test trials we run on the prototype. Kammerer describes, *"in that demo we simulated power outage, applied the mult- functionality of the Electrolyser and the FC system"*.

7.3.3 Period 2 HyPM Module and Technology Demonstrators 2003-2005

By 2003 Hydrogenics had transferred its system integration competences in the FC test and diagnostic equipment to the development and demonstration of FC powered probes, as demonstrated in the HyTEF, HyPort and HyUPS probes. Hydrogenics continued with the strategy of developing an integrated FC power system, a plug and play HyPM module. An important change in Hydrogenics' position was the alliance with General Motors (GM) who had a 28% stake in Hydrogenics' outstanding equity. As part of the agreement, Hydrogenics would not pursue automotive probes with competitors. Hydrogenics did not pursue proprietary automotive probes in the years that followed. *"The automotive side was basically closed to us for two reasons. One is that a lot of the companies are quite advanced, the other reason is that GM does not allow Hydrogenics to work with competitors. We did talk to some motorcycle or bus people, that would have been ok, but that just didn't quite work out"*[15].

In December 2002 Hydrogenics announced the supply of a HyPM LP2 to Deere and company. This third generation HyPM module of 20 kW was integrated into a Deere commercial work vehicle. Thus, although Hydrogenics could not develop automotive probes, the company became involved in light mobility applications. In June 2003 Hydrogenics supplied 6 new HyPM modules of 10 kW to Deere. This module was a direct adaptation of the 20 kW HyPM module and was launched as a commercially available module a few months later. The HyPM 10 module was integrated and demonstrated in Deere's next generation FC commercial work vehicles. The first deployment of a small fleet of FC powered Deere Gators for end user validation was at the Toronto Exhibition in July 2005. After the integration and evaluation of the HyPM modules in Deere's off road vehicles, including grounds equipment and utility vehicles, Hydrogenics applied the HyPM module in numerous mobility applications in the off-highway light vehicle mobility segment. The relationship with Deere sparked the further development of the HyPM modules and Hydrogenics' involvement in light mobility applications.

In June 2003 Hydrogenics additionally announced the sales of 6, 10 kW HyPM modules to General Hydrogen, in addition to the Deere supplies. The supplies of these modules provided Hydrogenics with positive feedback for FC developments, as Kammerer explains, *"then we thought, hey we got something here. The focus shifted to about 40% FCs"*. Additionally, in July 2003 National Resources Canada announced that it would provide Hydrogenics with $500.000 funding for reliability testing and further development of the

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[13] *Press release on HyUPS*

[14] *Pierre Rivard, President and Chief Executive Office*

[15] *Interview with Business Development Manager for Asia-Pacific and General Manager for Japan between 2000 and December 2005.*

HyPM-LP2 module. Subsequently, in November 2003 Hydrogenics announced the standardised and commercially available 10kW HyPM. According to the Hydrogenic press release, the focus of the standardised HyPM 10 module design was to drive pilot production of Hydrogenics HyPM product line. Similarly Kammerer explains,
"the first 10 kW module was a good way to focus developments. Hydrogenics could focus on developing, testing and learning from one module. Also Hydrogenics could give one module to OEMS and learn from the tests and applications of one module. It was a way to minimize the complexity of factors… We tried to make something that was self contained…. The 10 kW was an area that other firms did not cover. It was a green field. Additionally, there appeared to be many markets for this power range".

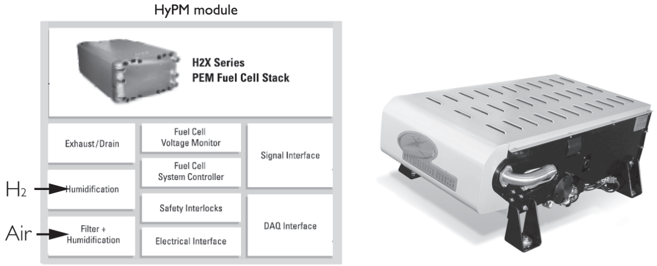

Figure 7.13 Configuration of a HyPM module (left) and the HYPM10 module (right). Source: Hydrogenics HyPM product specifications

After 2003 Hydrogenics focused its probe process on development and application of a standardised technology platform: the HyPM modules. The 10 kW HyPM module comprises a Hydrogenics FC stack with the FC system components built around the stack. The system components include filters, humidification, drains, voltage monitors, system controllers, safety interlocks and interface components (fig. 7.13). The HyPM module range was extended in November 2004 to include a module of 7 kW and 65 kW. Hydrogenics probe process in this phase is characterised by the application of these modules in a broad scope of market probes. Hydrogenics was one of the first firms in the FC industry to develop a standardised FC module, commercially available to customers. The HyPM module was an integrated FC system with associated components, subsystems and control software. In several cases Hydrogenics did not only supply the modules but also system integration services. Dogterom explains that,
"for a lot of the demonstrations we have done complete integration. … That was in order to really stimulate end user interest. Because I think for a lot of the OEMs that we work with, the thing that drives them is their customers wanting to try out FC technology and they were not necessarily well equipped to do the first demonstrations. It was in many ways easier for us to step in and help them with the first one and kind of build up their expertise a little bit on FCs and integration'.

The various applications of the HyPM10 module, and later the HyPM 7 and HyPM65 are considered to be a test group for Hydrogenics. Most of the applications are 'technology demonstrators', enabling Hydrogenics to validate its technology and enabling customers to learn about FC technology. As Kammerer explains,
"from our various projects, it looks like we are going at all different vehicle markets at once. We are actually not, those are what we are calling a demonstration market, which is validating the technology, it is gaining some early revenue for us, sure, and it is proving to us and different potential OEM clients that the technology can work in many different applications. With the experience we have now, we can go into these markets now and say, yes we have done this we have done that, it works".

The technology demonstrators were a marketing tool, they helped to communicate and sell systems. As Dogterom explains, *"from a demonstration point of view the importance is market development, like, showing people that the technology actually works, what it can do and how it can be applied".*

Hydrogenics aimed to pursue premium niche markets. Perceived markets for the application of the HyPM 10 module were back-up or standby power, auxiliary power units, propulsion for light mobility electric motorised vehicles. However, *"at first it really wasn't that clear where we were heading. We were just trying to understand these applications"*[16]. Hydrogenics applied the HyPM in a broad scope of market probes, termed technology demonstrators, to determine the value propositions of various markets and their expected timing of adoption. As Dogterom states,

"we did field trials with really a lot of different markets, we did a lot of the very early demonstrations. …. And then we were able to look at actual data and figure out, how much did we improve productivity by? Getting feedback directly from customers,when you do those early demonstrations, is extremely valuable. …So we looked at all the different applications and discovered that there were definitely some niche areas where we could deliver products earlier than we could into others".

Technology Demonstrators

Between 2003 and 2006 the HyPM modules were applied in a broad scope of probes. The majority of the HyPM probes were in light mobility applications. In October 2003 Hydrogenics received approval to lead a consortium to develop and demonstrate FC powered forklifts. Two forklifts were outfitted with the HyPM10 in a hybrid configuration and presented at several conferences and tradeshows. The alpha prototype forklift trucks were subsequently operated in field trials for four months up to October 2005 at the GM and FedEx logistic centres at Toronto City Airport.

Other technology demonstrator projects include the GEM and the midi bus. In 2004 Hydrogenics integrated the HyPM10 module with a hybrid system in a GEM car, a neighbourhood vehicle. The probe was for internal research to test a hybrid system. As Kammerer explains, "we do not believe in a near term commercial market for this product, but it is something we wanted to test, a hybrid system. The GEM helped us do the forklift project". In August 2004 the GEM vehicle was presented at the opening of Toronto's first hydrogen fueling station as part of the Toronto's Hydrogen Village. According to Hydrogenics, to supply such a demonstration project can be seen as a market, a small market, but it is a market. In a similar application Hydrogenics engaged with Th!ink Nordic to integrate HyPM10 modules into the electric vehicle prototypes. The vehicles are being developed for various demonstration projects and hydrogen communities. These projects need FC vehicles, forming a small market. Additionally, Kammerer adds, *"the Th!nk project provides more validation, gains exposure, provides experience with an OEM, and the project could turn into multiples".*

In November 2004 Hydrogenics announced a contract to develop a fully operational electric hybrid midi bus for the state of North Rhine Westphalia in Germany. Hydrogenics integrated a hybrid HyPM10 system in the midi bus and completed and demonstrated the midi bus in July 2005. In December 2005, the midi bus was granted certification as a public transit vehicle in Germany. Regarding the HyPM 65 kW module, in February 2004 Hydrogenics was contracted by Purolater to develop a FC hybrid delivery van. Hydrogenics integrated a 65kW module in the Purolater Courier Van in May 2005, the vehicle is running to date.

Furthermore, Hydrogenics has supplied the HyPM 10 module to various other OEM customers involving a varying degree of system integration support. In July 2003 Hydrogenics was selected for the integration of two HyPM 10 power modules into a low speed 30 foot battery-hybrid bus Hawaii's Hickam Air Force Base. The FC system extends the driving range of the battery dominant hybrid system, designed by Enova systems. In 2004 Hickam put the bus in service on the air base, collecting data to assess the status of FC technology for heavy vehicle applications. In April 2004 Hydrogenics supplied a 10 kilowatt HyPM™ to HaveBlue, a California-based company that has integrated the system in a sailing yacht and demonstrated it in operation. In 2004 Hydrogenics supplied 2 HyPM 10 kW modules to the SunLine Transit Agency for integration into an APU in a modified standard Class-8 truck. In 2005 the Sunline truck made a trip

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[16] *Interview with Business Development Manager for Asia-Pacific and General Manager for Japan between 2000 and December 2005*

across the US to demonstrate the technology and a significant overall reduction of fossil fuel consumption. In 2005 Hydrogenics supplied a HyPM power system with electrolyser to Raytheon Integrated Defense Systems under a product development contract for the U.S. military. The system is deployed on board Light Armored Vehicle (LAV) as an APU. The HyPM 10 was also supplied to a stationary application in the Mie Prefecture, Japan in May 2004. The HyPM 10 was integrated into a back-up power system as part of a demonstration programme led by ITOCHU Corporation[17].

Outcome of Second Period

Hydrogenics gained system integration experience in the technology demonstrator projects. For example, by developing the hybrid system of FCs with ultra capacitors and/or batteries. Dogterom explains, *"because, we have done a lot of these early demonstrations, where we have been the system integrator, we have developed some good and unique competencies around that. I think, as far as unique competences go on the technology side, these early applications have really done a lot for us".*

Additionally, the technology demonstrator projects enabled the development of relationships with a wide range of OEM customers. *"Actually margins are not, usually, that good. But you just have to do it because all of the big relationships started small, I mean with one unit. Through that one unit you build a relationship with your industrial partner and possibly with other partners, maybe government, and also you gain exposure in the market"*[18].

Apart from the stimulation of market development and the development of system integration experience, the technology demonstrators enabled the identification of specific niche markets. According to Hydrogenics, demonstrations are necessary in order to specify exactly which operations to target and to determine the value proposition of a market. Demonstrations reveal the real costs of operation such that the costs of an application can be evaluated and compared. Kammerer explains, *"not everything is clear until you are actually involved…. you have to do a demo first… It is hard to know who actually wants it, so we step in and test the waters".* Hydrogenics learned on which markets to focus from the technology demonstrator projects. Subsequently, the company chose to continue with the development of material handling applications.

7.3.4 Period 3 Focused Field Tests 2005- 2006

The outcomes from probes in the second period changed the input for subsequent probe decisions. The HyPM modules provided feedback from a broad scope of customers, operational data and system integration experience. After the breadth of technology demonstrator projects, Hydrogenics continued with the material handling market. Dogterom explains, *"as far as early applications go, the primary ones that we are focused on are back-up power, both AC and DC back-up power and material handling, replacement packs for forklifts. The importance of these early applications for us is that they have the most economic value proposition. We can actually go in and save people money with our systems….These early applications that we have identified now are the first commercial ones. They are critical just because they allow us to increase our volume and drive down our cost even further so that other applications open up, some of the ones with more pricing sensitivity".*

Through the technology demonstrations, Hydrogenics found a compelling value proposition in material handling. It took several years of probing to identify the potential of this market. *"I think that what really changed, at one point, was when we really started to identify these early markets….It took us a long time to really focus on these markets and once we decided that back-up power and forklift material handling were the main markets, then we had to try and find technology demonstrations, but within that field"*[19].

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[17] *ITOCHU is a sogo shosha, i.e. a large Japanese trading company*

[18] *Interview with Business Development Manager for Asia-Pacific and General Manager for Japan between 2000 and December 2005*

[19] *Ibid.*

In this third period, Hydrogenics focused on three niche markets, as the annual report of 2005 (p.3) states, *"our Power Systems unit identified three key markets that offer the best opportunities for near-term returns".* In addition to material handling, Hydrogenics focused on back-up power for critical data centres and back-up power for telecommunications infrastructure such as cell towers.

Forklift Path

Following the technology demonstrator projects, Hydrogenics expected that the material handling market would have potential as one of the first niche markets. Beforehand there were expectations about this market, spurred on by market research conducted at GM. The forklift project with GM and Fedex validated this opportunity and enabled Hydrogenics to analyse the value proposition for the material handling market. As Kammerer explains, *"the fork- lift projects have been important to gain data, to look at all the costs and to demonstrate to OEMs. Now we know when it makes sense. For example, FC forklifts do not yet make sense when it only operates for one shift during the day…. Besides, without the operational data, the OEMs have too many questions".*

Material handling proved to make financial sense. The big driver for switching to FCs in material handing is increased productivity. Being able to refuel with hydrogen quickly, instead of changing different sets of batteries every 8 hours and requiring battery charging stations provides an economic drive to switch to FCs. Hundreds of vehicles can be fuelled with one refueler. Moreover, Kammerer explains, *"the feedback from clients, forklifts and end users, showed that they really like it. They are comfortable with it".*

In July 2006 Hydrogenics announced the plans for a follow-on demonstration project. As the initial project, the consortium partners Hydrogenics, GM and the NACCO Materials Handling Group, received funding from the organisation Sustainable Development Technology Canada. The demonstration project will apply Hydrogenics' next generation HyPM FC Power Packs in up to 19 fork-lift trucks and tugs. The beta version demonstration project plans to operate the industrial vehicles for a two-year period at GM's Oshawa car plant. This larger demonstration project will enable Hydogenics to further technology development and showcase their technology. As Dogterom states, *"we will continue to do field trials and in material handling we recently announced the plan to do 19 or 20 units at an automotive assembly plant. That is big, that is a great demonstration. That many vehicles out there will really help to prove the potential I think".*

The HypM power pack is a hybrid module comprising 12 kW FC power packs to handle base load requirements and ultracapacitors to handle peak loads and capture energy from regenerative braking. The module is designed to fit into the existing battery compartment of material handling vehicles. Initial orders from material handling manufactures emerged. On July 18, 2006 Hydrogenics Corporation announced orders for four HyPM FC Power Packs for STILL International. STILL is a large European electric forklift manufacturer, a wholly-owned company of Linde AG. Two FC Power Packs will be integrated into STILL Class 1 forklifts. The remaining modules will be integrated into two airport tow tractor vehicles to be deployed at the Hamburg Airport in Germany. Pierre Rivard explains that *"the local service and technical support that we have based in Germany is an important consideration for all of our European customers, both OEMs and end-users"*[20]. Similarly Hydrogenics can provide technical support from the office in Japan. In the same month, an order was also announced for a HyPM FC Power Pack for a Japanese OEM's Class 1 forklift.

Back-up Power

In the back-up power market, Hydrogenics focuses on two segments: AC power for critical data centres and DC power for telecom customers. The company developed a dedicated module for back-up power: the HyPM XR. Hydrogenics main probe in back-up power were the field tests in telecom with Nextel in 2002. The probe demonstrated operation in the field to potential customers. The back-up power market was recognised in the early years.

20 Press release: 'Hydrogenics Receives Order for HyPM'R' Fuel Cell Power Pack from Japan'. July 24 2006

"I think for back-up power it was quite clear from the beginning that it would be a market, because there was a little bit of a hype around that. Around 2000, at the peak of the FC stock boom, there had been a lot of power failures, and people were saying, every time a power failure occurs it will cost the US economy billions of dollars. People were talking a lot about back-up power and getting their own back-up power. So any technology was seen as real promising"[21].

In the technology demonstrator period Hydrogenics was primarily active in mobility applications. In November 2004 Hydrogenics announced that it had received a follow-on order for 25 FC power modules to be incorporated into back-up power products from one single OEM customer, the American Power conversions Corporation (APC). The order follows field trials with the customer on singular units. Dogterom argues that Hydrogenics was capable of supplying back-up power because of their prior experience in mobility applications. *"Unlike a lot of other FC PEM companies, we started of with mobility applications and back-up power, sort of. We got certain ways with mobility and then we said, you know, back-up power is really easy for us to do at this point in time. Because we had been working on mobility, the size of our power module was extremely compact because we had to fit within a vehicle, so we quickly had a really good option for back-up power " (Dogterom 2006).*

Apparently, Hydrogenics was able to transfer experience in mobility probes, and their technological competences in particular, to other market segments. *"At the end of the day, the reason why APC would want to work with Hydrogenics is not because we want to do back-up power but it is because we have got good PEM technology that has been used in many different applications. In all those bus projects and one-off projects that we have done all over the world, each one contributed to that, to the technology and to the understanding of a FC system and stack"*[22].

At the time, the APC order was Hydrogenics' largest repeat order for HyPM modules. APC integrated the power modules in AC back-up power for data centres on a commercial basis. In November 2005 Hydrogenics introduces the HyPM XR series, 500W modules designed as a rack mountable unit for back-up power applications. In the fall of 2006 Hydrogenics received a follow-on order of 500 HyPM XR units. With APC, Hydrogenics went through several field test trial stages and went into a commercialisation stage with them. The follow-on orders give Hydrogenics verification of real demand for this market. As Dogterom says,
"things have really changed recently in that we have made an agreement with APC for up to 500 units. That really changes things within the industry. Now we can go back to our suppliers and say, OK I am not buying in the 10s and 20s anymore, I am buying in significantly larger quantities and it just helps us to lower costs a lot by being able to make such types of purchases. The other thing that we find is that it validates the technology for a lot of other OEMs that may be questioning it right now. To see someone taking a step forward like that, with the technology, is really the best validation you could have".

Regarding the DC market for back-up power, targeting the telecom market, Hydrogenics conducted further field trials with customers in 2006. As Dogterom explains, *"all the large customers in the telecom market they always want to try out one or two at one of their sites before they make a larger volume decision."*

Demonstration Market, the Midi Bus

Although not a prime focus, Hydrogenics continued with the development of midi buses for the European demonstration market after the first demonstration in July 2005, Germany. Kammerer argues, *"I recognise a compelling value in FC buses for early demonstration: it can be experienced by the public, there is a lot of space for advertising. Also, there is a lot of space, making integration easier and it provides good validation. For example, it has to stop and start a lot and it runs 12 to 16 hours on end. Additionally, it is a fleet application, facilitating fueling and maintenance".*

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[21] *Interview with the Business Development Manager for Asia-Pacific and General Manager for Japan between 2000 and December 2005*

[22] *Ibid.*

For the development of the first midi bus Hydrogenics paid 57%, the state 43% through subsidies. In this first probe, Hydrogenics gained valuable experience in automotive related applications. As Kammerer explains, *"this was good to develop competences, to learn something new and to prove the technology to this market….. It is easier to do smaller systems first and then larger, scale it up. That is the case for the midi bus too. We are learning for bigger buses. …We have an agreement with GM not to be active in competitive markets. Therefore, we are approaching the automotive market with the buses; GM is not in that market at the moment". Additionally, "the midi bus approval process was a good experience. Now we know how to do that"*
The midi bus is deployed in governmental funded demonstration projects. Hydrogenics' European strategy for demonstration applications is slightly different than in America. In Europe, Hydrogenics is actively involved in the HyChain project, a large European Commission project to deploy 158 low power vehicles. Like the CUTE project[23], Kammerer explains, *"too bad it is not as big as the Cute, but there are more vehicles in total".*

Certification of the midi bus in December 2005 enabled further application of the midi bus. In July 2006 Hydrogenics announced an order for a FC hybrid midi bus from the public transit authority of Dusseldorf, Germany, to install a hybrid HyPM power module in an electric midi bus platform. This order represents the first commercial contract for a FC hybrid midi bus. Although Hydrogenics recognises the potential of this market and has gained expertise in a number of projects, Hydrogenics considers the potential for commercial sales in this market to be more uncertain than the niche markets for back-up power and material handling. As Dogterom say, *"I mean there are some other really interesting applications; the small electric bus market is definitely of interest and I can see that one maybe coming along next, but it is a little hard to say".* For Hydrogenics, the midi bus market is primarily a demonstration market, cost-effective applications in niche market are expected to be further away. *"There must be 4, 5, 6, major midi bus projects now, so we have quite a bit of expertise at the system integration group. Those projects are not too distracting. But to be honest, we do not really see it as a commercial market, we see it as a demonstration market. It is going to be like that for a while"*[24].

One-off Projects
Hydrogenics has also conducted a number of probes without follow up. A custom/one-off project is carried out if there is enough potential for revenue and the margins are rich enough. An example of one-off projects is the stationary probe in Japan. Although stationary power is a big field in Japan, there are numerous projects around 1 kW combined heat and power systems, Hydrogenics did not continue this path. The project was well paid, but the stationary applications are not Hydogenics' focus.

"We did get a lot of people asking if we could do 1 kW systems or 5 kW systems…..but it is not really where our heart was and the Hydrogenics PEM FC is not really designed for that. I think people make a big mistake in a lot of energy literature, to assume that these are kind of the same technologies, that there is going to be a lot of scale economies. But it is not that simple because they are really designed very differently. Stationary is a completely different ball game because you are running it continuously. We never really were in the stationary field…. But for this project in Japan they had given us a lot of money. …So that was good for the company, to get some revenue, but at the same time it was a distraction. Wel,l perhaps they kept that experience to learn about it, and it was actually tougher than they expected too, but it is basically a distraction"[25].

The selection criteria for one-off projects are not only on revenue. The main criterion for selection is that developments on a one-off project should help in other markets, as a stepping stone. Also the potential for follow-on units is highly desirable, if the project has a life afterwards. Ideas are filtered on the basis of such criteria. Although most projects could be realised, they form a distraction because the engineers are allocated to a one-off project instead of the Hydrogenics' strategic focus. As Kammerer explains, *"we get*

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[23] Clean Urban Transport for Europe. A European project in which 27 buses where operated in 9 European cities.

[24] Interview with the Business Development Manager for Asia-Pacific and General Manager for Japan between 2000 and December 2005

[25] Ibid.

a lot of crazy application ideas, to the majority we have to say no…We often have to say that it doesn't make sense for you or for us. But, we are trying to avoid the science projects".

7.3.5 Conclusions Hydrogenics

Hydrogenics probe applications have been described and are illustrated in figure 7.14. The company engaged in its first FC probes several years after founding. On the basis of the FC system integration experience, gained in the company's FC test and diagnostic equipment business, Hydrogenics developed portable power units. These first probes were conducted with early customers, targeting niche markets in military and back-up power for Telecom. In line with the first power units, Hydrogenics continued the development of integrated FC modules for different power levels. However, Hydrogenics subsequently focused on the development of a 10 kW module, targeting probes in a broad range of applications. The HyPM module powered several light mobility applications as well as APUs and a CHP project in Japan. These 'technology demonstrators' contributed to learning and market development. With experience in these technology demonstrators, Hydrogenics chose to focus on the fork-lift truck market for subsequent development. In addition, Hydrogenics picked up an early market path: the company continued with the development and application of FC modules for the back-up power market as a key focus area.

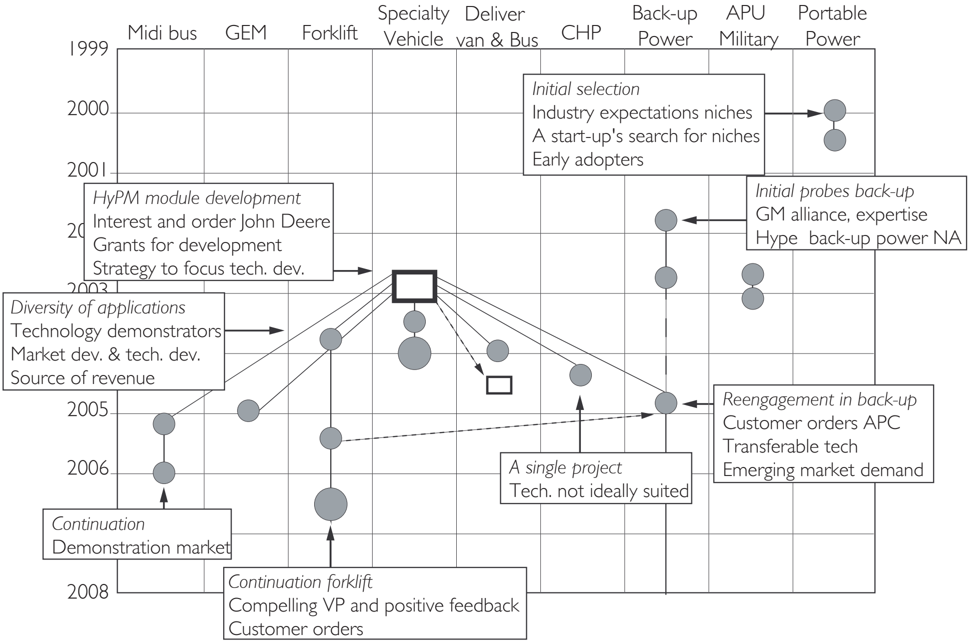

Figure7.14 Hydrogenics' probe applications and an overview of factors explaining the firm's probing process

Explaining the INITIAL focus on FC Test Business

After founding, Hydrogenics began to develop a FC test and diagnostic business. According to Hydrogenics, they had identified market demand for the test and diagnostic market in the FC industry. But why did Hydrogenics first develop this business instead of PEM FCs? Hydrogenics was founded as a start up with no prior employment or financial ties to the industry. The founders had some hydrogen experience an entrepreneurial vision and a network, however, with regard to PEM FCs, the company started from scratch. Hydrogenics' limited PEM FC competences at founding explain why the company did not conduct probes with PEM FC in the first years. Moreover, as a new start-up in the FC industry, it can be expected that Hydogenics used the FC test and diagnostic business to strategically position itself in the FC industry. The

FC test and diagnostic business enabled Hydrogenics to build relationships and a reputation as a newcomer in the FC industry and in the meantime conduct R&D to develop PEM FC competences. The decision to pursue PEM FC was made in these initial years of FC R&D, in which the potential for broad application was identified. It can be argued that this realisation came at a time when the FC industry began to explore non-automotive applications such as portable and stationary markets, suggesting a degree of mimicking in technology choice.

Explaining the Timing of INITIAL Probes

What explains the timing of initial probes (RQ 3a)? Hydrogenics waited for customer interest in FC applications to emerge. In the meantime, Hydrogenics learnt from and gained initial revenue through the FC test and diagnostic business. With initial revenue from the FCATS business, Hydrogenics managed to 'survive' the first years after founding. However, Hydrogenics' IPO in 2000 appear to have put external pressure on the firm to demonstrate its FC technology, as the report at the end of this year illustrates, *"investors and stakeholders were growing impatient, they wanted to see our FC technology move from lab to market"* (AR 2000: p.2).

Moreover, the company explains that it did not engage in a FC probe until initial customer interest emerged, primarily from their FCATS business. Apparently, Hydrogenics was strongly focused on the formation of strategic partnerships, as a start-up company in the FC industry. Additionally, their strategy of engaging in probes with reference customer suggests emphasis on reputation building. Furthermore, it can be argued that Hydrogenics had to wait because it was still in the process of developing PEMFC competences. The FCATS business shaped the firm's technological core competence towards FC system integration and the development of Hydrogenic's integrated FC modules.

Explaining Selection of INITIAL Probes in Niche Markets

Hydrogenics' first probes where conducted in niche markets, following a strategy to primarily target premium markets. The niche market strategy is in line with the entrepreneurial spirit of this start-up company. Hydrogenics explains that it did not engage in markets where other FC developers had advanced in. FC firms prior to 2000 had been targeting large markets for automotive and stationary applications. For example, there were players in the automotive market, including Ballard, with years of probing experience in this market. It can therefore be argued that the company was looking for niche markets to strategically position itself in the industry with respect to other FC developers. Soon after, Hydrogenics could no longer engage in the automotive market due to its strategic partnership with GM.

The telecom back-up probe was conducted at the start of Hydrogenics' alliance with General Motors. However, why telecom back-up with GM? The GM alliance can be seen as an opportunity for Hydrogenics to develop its PEM FC competences and bind the company to an established name. Through this alliance, Hydrogenics could access GM PEM stack technology. The first probe illustrates Hydogenics' competence position: Hydrogenics supplied the system expertise and GM the Stack. Moreover, as Hydrogenics agreed not to engage in automotive markets, apparently the alliance agreed they would target niche markets. With years of experience and research into PEMFC applications, GM had knowledge of niche market applications. It is likely that GM's expertise influenced the pursuit of the back-up power market for telecom. Hydrogenics claims they had identified a 'market pull'. This observation coincides with a market hype for back-up power in North America around this time. On the other hand, the decision to engage in the back-up power market may be explained by industry expectations. Considering that the GM-Hydrogenics alliance was one of the first to probe in this market, it is expected that the GM alliance expertise to recognise a value proposition in this market outweighed expectations of the FC industry. By presenting a FC solution, the probe may have contributed to the back-up power hype.

Regarding the initial probe for the military, Hydrogenics was awarded a project to develop a military portable power unit. On the one hand, the military is a renowned early adopter of new technologies. On the other hand, this niche market can be explained by Hydrogenics' historic ties with the military.

Explaining the Development of the HyPM Technology Platform

Hdyrogenics chose to develop integrated FC modules. This strategy can be explained by the technological core competences the company had developed in the FCATS business. Moreover, Hydrogenics appears to have strategically targeted this supply chain position to reach multiple niche markets. With positive customer feedback from the sales of initial modules, Hydrogenics continued to develop the HyPM modules. These module became the centre piece for Hydrogenics' subsequent probes. The development of this module can be explained by Hydrogenics' strategy to address a breadth of markets, yet focus on technological development. The rationale for a single platform in a breadth of markets was to apply a quantity of modules whilst controlling validation and technology learning. Moreover the development of this module was probably motivated by the emergence of customer interest in this module, after the supply of initial modules and the grants received by government to further develop this module.

Explaining the Breadth of Probes

What explains the breadth of market segments (RQ 3b)? Hydrogenics focused on the development of one module (HyPM) and applied it to a broad range of applications. The multiple applications in light mobility is notable. The Deere orders for FC modules appear to have influenced this development, providing Hydrogenics with positive feedback on the market potential for FC modules in light mobility. Moreover, the HyPM module proved to be applicable to a diversity of light mobility applications. The diversity of applications suggests that Hydrogenics was not highly selective in these probes in terms of economic value proposition. The majority of these applications had no economic value proposition in the short term, but appear to be selected on the basis of the future potential and technical feasibility. Hydrogenics explains that the technology demonstrators provided data to identify the most compelling value propositions. Additionally, the company explains that the technology demonstrators were intended for market development, to support OEMs in stimulating end-user interest as well as to educate OEM customers and attract their interest. It can be argued that the technology demonstrators were of central importance in developing the firm's legitimacy and customer relationships, by validating their technology and making themselves known to customers in a broad scope of markets.

Apparently, the need for market development and demonstration to customers outweighed the low economic value proposition of these market applications. On the other hand, supply to the technology demonstrators also provided Hydrogenics with some early revenue. Hydrogenics was one of the only firms in the industry supplying integrated modules to early adopters. Some of these projects may have been a distraction to future developments. Therefore, opportunistic behaviour in pursuit of short term revenue may have influenced the breadth of Hydrogenics' probes.

Explaining Limited Probes in CHP

Hydrogenics' supply to a CHP probe in Japan appears to be a probe primarily for short term revenue because Hydrogenics has not engaged in other CHP probes. Besides revenue, the probe may have contributed to developing relationships in Japan. Regarding the lack of probes in CHP, Hydrogenics explains that their HyPM technology is not ideally suited and designed for this application as the application requires a stationary mode of FC operation. On the other hand, this decision may be explained by factors related to the firm's culture, 'that is not where our heart is'. Apparently, both firm culture and technological core competence are determinant for Hydrogenics' decision not to engage in CHP probes.

Explaining the CONTINUATION of the Midi bus

Hydrogenics developed and continues to engage in the midi bus probe, primarily for Europe. The continuation is not based on an economic value proposition: a commercial market is not expected to emerge in the short term. Rather, this probe decision can be explained as a probe with a demonstration value proposition. Hydrogenics experienced a demand for the HyPM in demonstration projects. The focus on Europe can therefore be explained by EU funding for light mobility demonstration projects. Within this market there is customer demand for the midi bus. On the other hand, Hydrogenics explains that the midi bus contributes to learning for bigger buses, as the company intends to approach the automotive market through buses. However, Hydrogenics developed a strategic position as one of the only suppliers of integrated modules for early markets and the midi bus appears to be a significantly different market than the bus market. Apparently, Hydrogenics' continued engagement in the demonstration market can primarily be explained as a market for early revenue because, without the market demand it is unlikely that Hydrgenics would continue to pursue this market.

Explaining Subsequent FOCUS on Material Handling

Hydrogenics' focus on the forklift market can be explained by the information and positive feedback gained in the technology demonstrator probes. The operational experience enabled a realistic evaluation of the value proposition for this market. With data from the technology demonstrators, Hydrogenics was able to evaluate and specify an economic value proposition for this market. Therefore, although industry expectations of the forklift market emerged in this period, Hydrogenics' conclusions appear to be made on the basis of information and experience gained within the company. The firm's value proposition for this market was further confirmed by customer orders. In addition to this positive value proposition, the decision to continue with the forklift market is likely to be influenced by the Forklift partnership: this partnership was in place for further development.. Moreover, the partnership includes GM, who is also a major shareholder in Hydrogenics.

Explaining the PURSUIT of the Back-up Power Market

Hydrogenics has also focused on back-up power. However, the company had not developed probes in this market for some years, since the initial telecom back-up probe. What explains Hydrogenics' focus on back-up power? Technically, the firm explains, the technology is similar. Apparently, the experience gained with the HyPM modules in light mobility were transferable to modules for back-up power. Hydrogenics re-engaged in the back-up power market once it received orders for AC back-up power modules from a large client. This customer has now placed repeat orders. This decision appears to follow the 'change' of customer orders instead of a value proposition identified by Hydrogenics. At the same time, industry expectations emphasise back-up power as the first commercial market, with emphasis on DC back-up power for telecom providers. Considering Hydrogenics' lack of probes in this market and no report of significant customer orders prior to engagement, the company's emphasis on back-up power for telecom may have been inspired by industry expectations of an emergent market.

In conclusion, Hydrogenics positioned itself on the basis of core competences in system integration. Throughout the firm's probe process, emphasis on the formation of partnerships has had a strong influence on probe selection. The technology demonstrator probes appear to be driven by market development ambitions. This strategy enabled the identification of a niche market with a compelling economic value proposition. By contrast, the back-up power markets appear to be influenced by 'chance' industry expectations. The decision to focus on this market and the back-up power markets is explained by the need to focus technological developments using these niche markets to increase volume and validate production.

7.4 Case Intelligent Energy

For the case Intelligent Energy the main interviews were conducted with: i) Andy Eggleston, Project Director of Intelligent Energy's ENV motorbike in February 2006 and ii) Dennis Hayter, Director of Business Development at Intelligent Energy in September 2006. Both directors are based in the London office.

This case firm was selected on the basis on Intelligent Energy's probe applications in a breadth of markets with a business strategy towards Intellectual Property Licensing. The firm's probe process shows a high degree of collaboration with customers in various market segments. Through the application of multiple technology platforms, Intelligent Energy customises solutions for customers and strategic partners. Noteworthy aspects of Intelligent Energy's probe process are the early probes in portable and remote power and a diversity of probes. Intelligent Energy's probing process subsequently shows a surprising shift to the internally funded ENV bike becomes a key area of focus and development.

7.4.1 Introduction to Intelligent Energy

Intelligent Energy Ltd. is a UK based FC company founded in 2001 by Dr Harry Bradbury, following a successful private placement fundraising in London. The funds enabled the acquisition of AdVanced Power Sources (APS), a UK based R&D company that was a spin-off from research at the Loughbourough University in 1995. The FC research at Loughborough University started in 1988, formed by a collaboration between the departments of chemistry, aeronautical and automotive engineering. APS was funded by the UK's Department of Trade and Industry and through joint development programmes with other commercial entities. Hayter describes the history of IE as follows: *"at Loughborough University they had been conducting FC research since the 1980s. Around 2000 the people at Advanced Power Systems believed that the technology was ready to commercialise. After a process of raising funds and finding investors, Intelligent Energy was founded in August 2001".*

Firm Growth

At founding, Intelligent Energy comprised the entire team of experts who had worked together at Loughborough University as well as all directors and 10 employees of APS. Intelligent Energy secured all intellectual property rights held by APS in PEMFC and related technologies. In 2001 Intelligent Energy began a collaboration with the South African company Sasol to develop a hydrogen generation system. In May 2003, IE acquired the US-based Element One Enterprises, a company specialised in fuel processing, hydrogen generation and hydrogen refuelling technology. In 2006, Intelligent Energy counted approximately 75 employees based in the UK, in the United States (Long Beach and Albuquerque), and in South Africa.

Technological Core Competences

IE promotes itself as an energy solutions and FC development company. The company is developing a range of technologies based around hydrogen FCs. Intelligent Energy's technological competences comprise PEMFC expertise, fuel processing expertise and fuel-flexible distributed hydrogen generation methods. According to Eggleston, Intelligent Energy's core competences are at least partly derived from FC testing: *"we have done an awful lot of testing ourselves. ….. So I think that is at the heart of our core competence, for many years we have been designing our own test rigs and test machines. We have been able to sell them on the market to other companies that want to test FCs".* According to Intelligent Energy, its competitive strength stems from three main factors: i) a business model that involves forming partnerships with third party OEMs and customers, ii) the company's modular technology and iii) Intelligent Energy claims that its technology is designed from the start to be highly power-dense and with low cost volume manufacturing in mind[1].

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[1] Intelligent Energy company profile from Library House, downloaded from www.libraryhouse.net/profile, May 2007

Business Model and Supply Chain

Intelligent Energy's business model differentiates itself from other young FC developers. Intelligent Energy does not aim to be a manufacturing company, instead, its business model is based on Intellectual Property rights. "*We are always looking for joint development agreements leading to licensing*" (Hayter 2006). The process towards revenue from IP involves partnering with potential customers. Intelligent Energy aims to build strategic partnerships with major corporations for joint development or licence of proprietary FC technology. With this model, the company aims to address mass markets in distributed electricity generation, motive and portable power. Intelligent Energy works with manufacturing partners, offers design and customisation and builds services to OEM partners. Within this business model, demonstration projects are part of joint developments towards licensing agreements. "*We have always said that we want to work with major companies*"[2]. Joint development relationships publicised in press releases include partnerships with Boeing and PSA Peugeot Citroen. The company aims to approach market and volume manufacturing through these partnerships in order to accelerate, and reduce the risk of, market entry[3].

Financial Resources

The founding of IE was based on private placement fundraising. In a second round of fundraising in February 2003, the company expanded further through the acquisition of Element One Enterprises. In October 2005, Intelligent Energy announced it had raised up to £11.3 million in working capital. The company's most significant investor is Yukos Oil Company, a large oil & gas group in Russia. In April 2007, a press release reports that Intelligent Energy had raised over $17 million in a round of fundraising, involving new shareholders including expertise in Clean Energy technologies[4].

Overview Intelligent Energy Probing Process

Figure 7.15 illustrates Intelligent Energy's probing process. The probing process is categorised in three phases. In the first period between 2001 and 2002 Intelligent Energy presented portable power demonstrations. This period is followed by a second period of probes for a diversity of customers and consortia. Additionally, the ENV bike was developed and introduced in this period. This motorbike had a significant impact on the company and characterises the third period: Intelligent Energy's probes and partnerships after launch of the ENV bike.

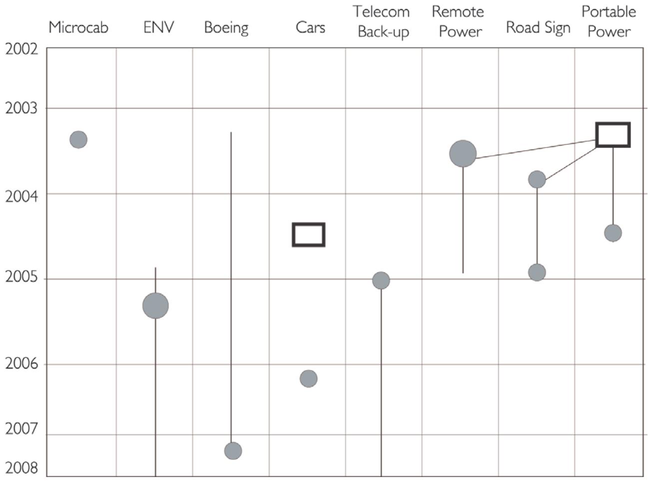

Figure 7.15 Intelligent Energy probe applications between 2003 and May 2007

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[2] *Intelligent Energy website viewed on April 2007: www.intelligent-energy.com*

[3] *Intelligent Energy company profile from Library House, downloaded from www.libraryhouse.net/profile, May 2007*

[4] *Press release Intelligent Energy raises over $17 million, 17th of April 2007*

7.4.2 Period 1: Early Demonstrations 2001-2002

Intelligent Energy's core competence at founding was derived from the FC know-how and intellectual property of Loughbourough University and its spin-off Advanced Power Sources (APS). These competences included PEMFC technology with an historic bias towards vehicle applications. Regarding applications of the technology, APS had been working on FC prototypes. In September 2001 Intelligent Energy established a pilot production plant. In this plant the first prototypes where built with Intelligent Energy's proprietary PEMFC stack design, which is based on the use of thin stainless steel bipolar plates. Intelligent Energy's first probes were demonstrations of low power portable power products. Thereby, Intelligent Energy focused on niche markets for distributed power solutions and military power. Intelligent Energy's first major showing at a large trade exhibition was at the Hanover Fair FC tradeshow in 2003. Hayter describes the rationale behind Intelligent Energy's demonstrations and presence and trade shows in this period: *"in the beginning we needed to start and show ourselves in the market place… To gain recognition and to find out who is asking for what in the market".*

At the tradeshows, Intelligent Energy presented a portfolio of technology platforms of both open and closed cathode stack technology, primarily for small scale distributed and portable generation. The first demonstrations of Intelligent Energy's technology were a series of portable power units[5]. A low power package of 100W was presented for remote power, residential use and industrial applications such as telemetry. The second low power unit presented was the personal power unit, a back-up system of 50 to 200 W to power desktop applications such as computers. The third low power system was a 200 W portable power unit for remote power applications. Intelligent Energy also displayed a larger portable power unit at the Hannover Fair in 2003. This 4 kW system, hybridized with a battery pack, was designed as a stand alone generator for the military. Under an agreement with the US Department of Defence, Intelligent Energy supplied the US army with a 3 kW FC generator to be tested and evaluated as a portable power source for soldiers. This system, designed in a rugged version, was presented during the Hannover Fair in April 2004. At tradeshows and conferences in 2003 and 2004 Intelligent Energy also presented itself with one of its partners, Microcab, who developed a lightweight vehicle using Intelligent Energy's 1.3 kW stack technology, another stack in Intelligent Energy's technology platform portfolio. In addition, Intelligent Energy worked on the development of a 2-5 kWe system for residential and commercial CHP applications in this period.

Outcome First Period

In the first period, IE developed and patented different types of FCs stacks, including an ambient series and a pressurised series. The ambient series with open cathode stacks, in the range of 50W to 1000W, and a pressurised series for 1.5 kW, 3 kW, 12 kW and 75 kW. The stacks were presented at tradeshows and developed for early adopter customers such as the military. However, these customers were not Intelligent Energy's target customer for licensing agreements. From the initial probes Intelligent Energy learned that the technology involved more learning for customers than expected. As the pace of technology adoption became clear, Intelligent Energy started to doubt their licensing strategy.

7.4.2 Period 2: Various Probes 2004-2005

Intelligent Energy became more aware that given the time to commercialisation for FC technology and considering Intelligent Energy's business model, significant revenue from IP would be years away. Eggleston says, *"I think the timing was all wrong…….. So where we went license model, they went production with the timing a long way out. So everybody got it wrong because the market did not turn up when they said it would. I'm not saying they got it wrong, but the investors have to be patient because the market is coming later".*

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[5] *Article on Intelligent Energy in Fuel Cells Bulletin August 2003, Energy solutions-fuel cell developments and beyond.*

The subsequent probe period is characterised by a divergence of technological options and probe applications in a diversity of markets. Intelligent Energy elaborated its platform portfolio for partnerships with automotive customers. In 2004 Intelligent Energy commenced a programme to develop advanced automotive FC systems, partly funded by the department of trade and industry of the UK government. In April 2004 Intelligent Energy first displayed a new 50 kW stack design. In 2005 presented a 10 kW system applicable to the automotive market and a 75-100 kW automotive stack. The portfolio additionally included the 200W platform for remote power and a 350-500 W hybrid system for portable power.

In line with Intelligent Energy's business model, most of the probes in this period involved joint developments with partners to tailor the technology to the partner's specific requirements. The main probes in this period are: the application of a low power portable unit in a consortium and the development and application of a 20kWe system for a large customer, Boeing. Two other main probes were developed in this period, remote power in South Africa and the development of the ENV motorbike.

Fuel Cell Variable Message Sign

Intelligent Energy applied its 100 W packaged system in a road sign that has been in continuous field operation since august 2003. A second road sign probe was in place by October 2004, applying Intelligent Energy's 200 W FC system. The package was redesigned for a vertical arrangement and protection from outdoor weather conditions. This road sign probe was conducted in a consortium led by the Tees hydrogen partnership. Hayter explains,
"we worked with Tees Valley Hydrogen, centre for process innovation, where they believed there was a very significant market in providing power to portable and fixed road signs. …There is a market that was identified, being anything from a couple of hundreds of units a year, and we were asked to participate in validating a sign that could be used for this sort of purpose. In this particular case we thought, yes, we can see that…….....At the moment there are a lot of councils that would like to be seen having carbon free, or at least carbon neutral, variable message signs around schools, on the roadsides, in traffic works and so on and they are prepared to pay to install a mix of these…the market and the economics, looked fine".

However, the project faced problems in the approval process. The authorities were not able to certify the road sign for operation on public roads. The consortium was told to self certify the road sign. However, within the consortium, Hayter explains, nobody was in a position to self certify the road sign:*"we looked at it and said, well, in this consortium there is somebody who makes the bits you put it into, somebody who makes the sign and electronics, a hydrogen company that comes a long with the cylinders and replaces the cylinders and so on. Who is going to self certify? Well, in the end nobody was in a position to be able to do that…. Nobody knew enough about the issues or wanted to take responsibility over the issues or had a process in place by which they could deal with the issues and therefore, their way of dealing with it was to say, well you self certify. But because we are a small FC company we can't self certify".*
Subsequently, the road sign was placed and operated on a private estate, limiting the demonstration value. Nonetheless, the probe proved that this FC application worked and experience was gained in dealing with the certification process, as Hayter explains, *"we did all of those things as far as we could, but we hadn't thought to make sure that you get an initial test of validation with whoever was going to be responsible for it. So I think the lesson would be, if you are going to do it again, make sure you have at least talked to these people before you go ahead and build the demonstrator and then test is".*

Boeing, FCs for Aviation

In December 2002 Intelligent Energy was selected to supply Boeing with a FC system for the 'The FC airplane demonstrator project'. The collaboration represents the type of customers and joint development IE sought. As Eggleston explains, *"if a company comes and they want to pay us money to do that, then, like any good business, we will say, fine, we could do it".*

In collaboration with the Boeing Research and Technology Centre, Intelligent Energy provided a 20 kW FC system package, that was integrated into a hybrid system with 30 kW Li-ion batteries. The design of this package was challenging due to the weight and volume restrictions of a small aircraft, packaging the components had to be consistent with aircraft practice. A press release of March 2007 announces that the first flight is planned later in 2007.

Boeing's objective was to evaluate and prove the potential of FC technology in order to optimise fuel usage for and reduce noise and emissions of a commercial aircraft. As Miguel A. Heman, R&T Center's General Director explains in the Boeing press release, *"the idea is to develop the expertise and understanding of how to use FCs in aerospace application"*.[6] The demonstrator was tested to meet the unique and stringent aerospace performance and safety requirements. In this prototype, the FC system provided prime power to the aircraft. For commercial applications, Boeing was primarily interested in the application of FCs for auxiliary power on board of commercial passenger and freight air fleets. Eggleston acknowledges the logic of applying FC technology for APUs on aircrafts: *"the rational engineering logic is that in an aircraft you have a huge wiring loom and the wire has to go to the four engines and the auxiliary power unit which is a small turbine in the tail. So the wires have to go all the way around and this wiring weighs a lot. But if you could have a galley running on a FC, then all of the sudden you don't have to go there with the wires".*

Intelligent Energy's press release of May 2003 describes the project as a graphical demonstration of the potential of FC technology to power many applications. *"None more graphically demonstrates this potential than a manned flight in its centenary year"* said Dr. Harry Bradbury, CEO of Intelligent Energy at that time. Similarly Eggleston says, *"the fact is an aircraft is a graphic illustration of FCs in aviation".* In addition, Intelligent Energy expected to learn from this project. *"Everything we do on this project,"* said Dennis Hayter in the Boeing press release, "will develop further knowledge for us, which will be of value to our other projects". Intelligent Energy continues to show interest in this market for aeronautical applications although continuation depends on the formation of partnerships and customer commitment.

Remote Power in South Africa

In 2003 Intelligent Energy responded to the UK Government's request for South African initiatives to benefit rural poor and was awarded a £4.3 million contract. With funding from UK overseas development funds and Intelligent Energy's local partner Afrox, African Oxygen Limited a subsidiary of BOC, Intelligent Energy installed FC systems in three different rural applications. Intelligent Energy installed the systems in 2004 and in March 2006 completion of the demonstrations was announced.[7]

The rationale for engaging in the probe was external pressure to demonstrate the technology. As Hayter explains, *"we also have this pressure too, not necessarily just from us but from others: come on intelligent energy show us what you have got. We needed to have something out there. And this is where sometimes you can be pulled into demonstrations before you really should. And then in that case the timing was right to show that we had the technology".*

Three types of systems were installed. Intelligent Energy installed a FC system in a frontline medical clinic to provide back-up power to a special vaccine fridge in a region susceptible to frequent electrical grid failure. The second installation was for Durban Metro Water, providing telemetry remote monitoring in a water station near Durban. In response to grid and solar intermittency, Intelligent Energy installed and demonstrated a FC-based generator that powered the equipment for a period of four months, then as a UPS mode to back-up the mains grid in case of failure. The third showcase was with partner Nuon RAPS a provider of energy to remote rural areas. Nuon Raps was interested to explore the potential of FC technology for application in rural areas. Two 100 W FC systems were used in a UPS configuration for a critical energy supply application, to power a computer and security lighting.

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[6] Press release Boeing August 2003: www.boeing.com/news/frontiers/archive/2003/august/

[7] ESI Africa reports on developments in the power sector in Africa. ESI issue 2, 2006.

According to Hayter the projects showed mixed successes. The projects provided Intelligent Energy with valuable information on running FCs and field operation revealed the required ruggedness for systems applied in the field. Additionally Hayter explains, Intelligent Energy learned that the successful operation of a FC demonstration project does not only depend on the FC, it is part of a larger system.
"The programme was one of very mixed success. We had some FCs that worked wonderfully throughout…but we realised they were not rugged enough on the wiring and the electronics side. There were other instances where the filters would be disconnecting and the batteries weren't working. A lot of things on our side, yes, but equally, a lot of things where it didn't matter how good the FCs were, for example, if somebody disconnects the hydrogen and then reconnects but doesn't connect it properly, …So what we were finding was that we are just a part of a larger chain, and we had a lot of issues with local maintenance and that is not necessarily maintenance on the FC" (Hayter 2006).

The South African probes provided validation and proof of concept of Intelligent Energy's technology in remote locations. However, Intelligent Energy continued internal developments in rapid iterations as the prototypes in this probe were being applied and tested. Subsequently, the speed at which the company's technology was developing internally, did not match the timing of the South African probes, as Hayter explains, *"in that particular instance, we haven't even gone back to that same architecture, because if we were going to do it again, we just wouldn't do it in that way at all. And the realisation came when we were already part the way through the project that, this is really nice stuff but really, lets put that to one side and lets have a look at all of the other things that we should be doing".*
Learning was gained in the South African probe, however, the outcome of the South African probes was not incorporated into further technological development. As Hayter explains, *"in a way the advantage and* the benefit was that we did learn a couple of very valuable lessons: don't do the electronics like that, shrink it down etc. So it alowed us to leapfrog a little bit, but frankly there are other ways. There were other things that we could have been doing".

ENV Bike Development
During the South African probes, Intelligent Energy began the development of a proprietary showcase: the ENV motorbike. The initial design brief of the project was not to design a motor bike, but to showcase Intelligent Energy's technology. The UK based industrial design company Seymour Powel was commissioned to begin the project in the autumn of 2003 under the name 'Project Velocity'. A series of workshops were held to generate and evaluate a number of product concepts. The dedicated design of a FC motor bike was chosen. The team has faced design challenges to incorporate the FC system and hydrogen storage in a compact and light solution. The design also included an innovative 'detachable core'. The Emissions-Neutral Vehicle (ENV) was Intelligent Energy's initiative to demonstrate and explain its technology. Hayter describes Intelligent Energy's rationale for developing a proprietary demonstration product: *"we genuinely were looking for a way in which you actually get an interaction. In the case of portable power, people can appreciate that the technology achieves the functionality, but it doesn't in a way that interacts with the user. Now, for that reason we were quite convinced that just having another portable power source was not going to do it".*

Intelligent Energy followed a demonstration strategy: demonstration of an exciting product to catch people's attention and stimulate interaction, subsequently enabling Intelligent Energy to explain their technology. As Eggleston explains, *"I think that it was done because we needed a way of demonstrating to a wider public that this technology was ready to rumble. The motor cycle was chosen because it is an exciting emotional market, you know, it is full of dynamics and youthfulness, beauty and the machines are exciting So what they wanted to do was make an application that was so beautiful. Even people that don't like motorcycles are going to see it is beautiful. So they go, wow that is really beautiful. And of course the next thing you want to do with something beautiful is you want to have it, you want to own it. So they say, I'd really love to have that and then you ask a lot of questions. But one of the main questions you are going to ask is, well, how does it work? And then you get to talk about the technology. So the beauty was a way of opening the doors so that people could understand the technology".*

Intelligent Energy additionally sensed a market opportunity for an exciting FC product in the gap between consumers 'waiting' for environmental solutions and automotive firms not in a hurry to commercialise FC cars. Eggleston explains that Intelligent Energy placed the ENV right in the middle: *"you can drive ENV straight in there (middle) it is not going to satisfy everybodys needs, but it is going to establish a brand in the consumers mind which was a brave brand swimming against the tide, where the guys said, well OK we are just going to do this and they did it. Now, where it is going to lead, I do not know, but there is defi'nitely a gap there, that is our experience".*

Intelligent Energy invested internal resource on the development of this proprietary ENV demonstration product. As Eggleston comments, *"it was expensive in the beginning…because we couldn't produce a motor cycle, so yes, it was expensive and to get a product to market is a very costly process. So this is bigger, magnitudes bigger than anything IE has invested in before".*

Intelligent Energy launched two prototypes of an ENV bike in March 2005 (fig. 7.16). The ENV is a motorbike designed to incorporate Intelligent Energy's 1 kW ambient FC system with an open cathode stack[8]. The objective of this probe is to demonstrate and explain IE's FC technology. The ENV has been demonstrated at numerous events, conferences and tradeshows including a media launch in Los Angeles, and a public demonstration in Trafalgar Square in October 2005.

Figure 7.16 The ENV motorbike. Source: www.envbike.com

Impact of the ENV Bike

The scale of publicity and positive response was larger than expected. The ENV probe launch generated large amounts of publicity worldwide. Eggleston says, *"it worked. It was brilliant. The public reaction to it was completely beyond anything, beyond what these guys have dreamed of. I mean we have a media tracking service, a quarter of a billion people, through one medium or the other have seen this bike, they read about it, they have heard about it on the radio they have seen it on the TV, worldwide".* The publicity and interest in the ENV has also resulted in a database of consumer information, providing a pool of test users. Eggleston explains, *"we can get information from the consumer quite readily. All we have to do is wead out the mad man from the sane ones….We've got a community now of several thousand ENV supporters all around the world.*

Thus the ENV is effective in generating consumer awareness. Additionally, IE argues that it has gained considerable credibility. Consequently, the ENV has helped Intelligent Energy to find partners and clients. As Eggleston describes, *"there is an increasing number of people now that get it, that didn't get it 5 years ago…. We are using the beauty of the bike to attract the consumer attention and explain the technology. That was a very good strategy. It has given us a huge credibility boost and a huge profile in the market. I mea,n no one else is being talked about like IE, are they? I mean, you know that they have been watching it".*

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[8] Press release on launch of the ENV motorbike April 2005

7.4.4 Period 3: After the ENV Bike

The overwhelming outcomes of the ENV probe had a strong impact on Intelligent Energy and subsequent probe decisions. The third period of probing is largely determined by the ENV outcomes in terms of confidence in the potential of the ENV and the credibility gained in the ENV demonstration. As a consequence, Intelligent Energy focused developments and engaged in a select number of niche markets and new partnerships and developments. The outcome of the ENV influenced the company's engagement in other market segments. Intelligent Energy found that it had to focus developments to make the ENV work and Intelligent Energy began to converge to a select number of developments. Hayter explains,
"to some extent it has actually stopped developments in other areas. Where we had previously been working on 100W system, 200W system, and up to 500 and then 1kW and so on, we have now got to sustain and support the next iteration around that same sort of ENV platform. Whether it will be 1 kW or 1.5 kW, whatever it needs to be, we have to make sure that it achieves performance, longevity, it needs to get survivability in cold weather, hot weather and all of the features that ultimately are going to go from where it is now into the product. That has dominated all of the activities of those that have been involved in the open cathode FC technology. And there are plenty of other markets there that will equally have the same economic benefits in the long term as it would do for the ENV motorbike but we are not able to continue to address them because we have got to make this one work".

After the launch and positive reception of the ENV bike, one of the directors remarked that they 'a tiger by its tail' (Eggleston 2006). The ENV outcome additionally fired a strategic debate at Intelligent Energy. The outcome has had a big impact on Intelligent Energy's internal strategy debate. As Eggleston explains,
"Intelligent Energy hasn't done anything like find a new strategy…. they did something and then they found themselves in a different place. And they are going hmmm, what shall we do with this? ….you have to do al the normal business things, but the idea is so good, the concept is so good. And gradually, the kind of, lets say license based mentality of this company is changing to think that this application maybe is a good thing to do. And we want to do it by sharing risk with other shareholders, so we are not going to bet the farm on it".

Due to the immense positive feedback and publicity resulting from the ENV, Intelligent Energy continued the development of this application. Also, the strategy of the company has been questioned and modified. In April 2007 the chief executive of Intelligent Energy, Dr Winand, states that the company intends to concentrate its efforts decisively on the niche markets it has identified.[9] Despite this focus, the company will also go on building relationships with large OEMs. Intelligent Energy also plans to continue the strategy of customised products. In the following paragraphs, the ENV probe path is further described in addition to two main joint development partnerships in this period.

ENV Continuation

The ENV path will be continued as a result of the positive feedback. Due to this positive response, IE is confident about the continuation of the ENV as a product for a premium market. Eggleston describes,
"the reason why we are going ahead with this is because the consumers said we should… people went nuts, they literally went nuts. Our confidence comes from the technology and for me the confidence also comes from the fact that I have seen and tasted and smelt and felt the reaction of consumers to this particular product. So I know if we make it good, there are enough people out there who will buy it for it to be successful at low volume. So I am quite confident about that. I don't know what it is, it just seems to have captured something".

The next probe step is evaluation and testing. Eggleston summarises the key challenges ahead: *"we will have to know whether we can make this bike at a cost which means we can sell it for profit. If we can't, then we won't go ahead, so costing is the main thing. But the other thing is, you know, there are technical issues as well. No not on performance, but this FC will have to be protected from aggressive chemicals for example, and other things….. the next 18 months is going to be all about operational demands. So we will break them, we will make them*

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[9] *Intelligent Energy company profile from Library House, 2007.*

and we'll break them. The big issue I think is regulatory. There are no regulations for FC motorcycles, so I think the critical path is, those technical problems are solvable, but will people be happy to sit on a gas bottle that is 350 bar… I do not think that these problems will be unsolvable, and actually the technology is largely de-risked, and the bike design is very easy to finalise, because we built a prototype so we know what is wrong with it. So we have already changed things that were wrong with it. And it is not a lot that we changed. So I think it will be the middle of 200 when, we could have the first bikes being offered on the production line".

In line with the company's business model, Intelligent Energy began to look for partners and licensing agreements. In January 2007 Intelligent Energy announced a partnership with Suzuki to develop a new prototype of a fuel cell powered motorcycle, applying the FC engine of the ENV bike[10]. Within the company, Intelligent Energy is further developing the ENV bike towards a certified product to maximize the potential value of the ENV bike in future licensing agreements.

Telecom UPS Back-up Power

For telecommunications applications, Intelligent Energy became involved with small scale back-up power and UPS systems in 2005. Therein, Intelligent Energy is focused on what goes into a cabinet rather than what powers an entire base station for a mobile network. The power range for this application is anywhere between 700 Watts and 2 kWs. The targeted customers are the suppliers to the telecom industry. Intelligent Energy did not recognise this opportunity for FC application at first instance. Hayter explains, *"we have previously looked at the Telecom market, had met with a number of companies in the UK and had been given a fairly clear message that these companies were looking for powering the base stations. So they wanted 5 to 7 kW and they typically wanted it with a liquid fuel and they wanted to be able to do it in remote areas because otherwise they are just going to connect it to the grid. The economic justification only really applies in this particular set of circumstances. So in a sense we had walked away, thinking, well that is going to be a problem because that is tough…the last thing we want is putting 5 kW FCs on mountains in Scotland and seeing how they run with a liquid fuel. So we put it to one side thinking, oh forget that one then".*

IE found a sub-market segment in this market that did fit the company's strategy and technology. This sub segment in telecom was identified after talking to OEM companies supplying telecom systems and installation services to the telecom providers. Hayter says, *"it was when we moved away from the Telcom operators and started talking to some of the companies that are the OEM suppliers to the Telcoms,…They have got the market feel. We hadn't appreciated that and nor had we appreciated that there was such a significant opportunity for battery replacement in the cabinets that make up the base stations. …There is a sub-market there that we just had never appreciated. That is the value of talking to a mix of those companies".*

Intelligent Energy started the process of talking to some of the companies that were OEM suppliers for telecom. Additionally, IE has spoken to OEM telecom companies in countries with extreme conditions including India and countries in Africa. *"So on the one hand, talking to different stakeholders along the supply chain gives you a sense of opportunities for that particular market, and on the other hand talking to different telecom markets al over the world gives you a sense of possible operating locations"* Hayter explains.

PSA Peugeot Citroën

In February 2006 Intelligent Energy and PSA Peugeot Citroen announced a joint development programme in which IE's automotive FC systems will be tested and integrated in the PSA Peugeot Citroën's electric cars. For this programme, IE delivers a series of 10 kW systems. The systems will be configured to fit in the PSA Peugeot Citroën electric vehicle configuration[11]. Regarding the developments in this partnership, Hayter explains, *"the customer specifications evolve in dialogue. You don't just exchange the combustion engine with a FC system. A lot has to be changed and the car has to be taken from the production line. So it is a costly matter. In dialogue we had to define what exactly should the stack be able to do and what should it look like".*

[10] *Press release, Intelligent Energy and Suzuki announce new partnership, 6th of February 2007*

[11] *Press release, Intelligent Energy and PSA Peugeot Citroën announce fuel cell development programme, 12th of January 2006*

Hayter explains that this partnership in automotive applications involves a lot of learning, *"which is why the uptake is slow, because it is not their core business. Even if we have done a deal with an amazing car manufacturer, it is not their core business.* The automotive partnership is a longer term development. *"There is a team of specialists working on it but it is a seed project for the future".*

Outcomes Intelligent Energy strategy

The company has thousands of hours of operational experience.. Yet, Intelligent Energy has not followed a strategy of multiple units in the field. Instead, Intelligent Energy's probe applications have been customised for clients. Hayter argues that this has resulted in unique competences: *"the intensive dialogues with customers have proven to be very comprehensive. You may have a very complex and sophisticated technology, but unless you get intimately involved with applications, you do not know how it will really be used. Now we have to be as creative and effective as possible".*

Intelligent Energy is now focusing on a select number of customers. This focus is in line with the company's partnership strategy. Hayter explains, *"the thing is I do not want more than about 10 customers. If we have more, then we will not be able to have the degree of intimate knowledge and collaboration. More customers would cost too much time and resources. Because in every project we do, we have to invest. So by now we are pretty stringent of what we want to do and with whom".*

7.4.5 Conclusions Intelligent Energy Probing Process

Intelligent Energy's probe applications have been described and are illustrated in figure 7.17. The company's first probes were functional demonstrations of the company's technology targeting niche markets for (military) portable power and remote back-up power. The Intelligent Energy case represents the probe process for a company targeting IP agreements. The probe process is characterised by a partnered probe approach with 'major corporation', as the demonstration and development of probes with potential customers is part of the process of joint development or securing IP agreements. With this strategy Intelligent Energy serves a diversity of customers with a broad range of technology platforms and customised systems. However, from experience in early probes the company found that the uptake of their technology was slower than expected. For many customers, Intelligent Energy explains, the technology is not their core business and involves a great deal of learning. IP agreements with large customers was perceived to be years away and the company realised it could not wait for that long. The company subsequently invested in an internal initiative and proprietary development, the ENV motorbike. The dedicated design of a FC motorbike was developed to showcase their technology. The success of the ENV motorbike has influenced the subsequent probe paths of the company. Although the company has developed several technology platforms, it has focused on making the ENV platform work first. Also the company has focued on developments for a select number of customers. As Hayter described, *"we thought we could do everything, but we couldn't".*

Explaining the Selection of INITIAL Probes

Intelligent Energy's initial probes were demonstrations of the firm's technology in portable power. As a new spin-off company in the FC industry, these demonstrations can be explained as an introduction of the company to the industry and markets. Considering the company's partnership model, it is likely that Intelligent Energy needed these probes to stimulate customer interest and form partnerships. On the other hand, the decision to present prototypes two years after founding is likely to be influenced by pressure from shareholders and investors. From either perspective, the showcase probes appear to have been a necessary condition to form partnerships.

Why portable power units? Intelligent Energy's initial probes in portable power coincides with a shift in industry expectations from large markets to niche markets for short term adoption including back-up power and portable power. The company's decision to develop portable power probes may have been influenced by these industry expectations. However, industry expectations do not explain Intelligent Energy's selection of portable power. Intelligent Energy positioned itself as a company with proprietary stack design technology with relatively high energy densities compared to the technology of other firms. The company's selection of portable power modules may be explained as a suitable application to showcase the compact design of Intelligent Energy's FC technology. In line with the company's model of strategic partnering, the firm formed partnerships as demand from early adopters emerged in this period. Intelligent Energy's portable power probes for the US Department of Defence can be explained as an early partner with funding from a government body.

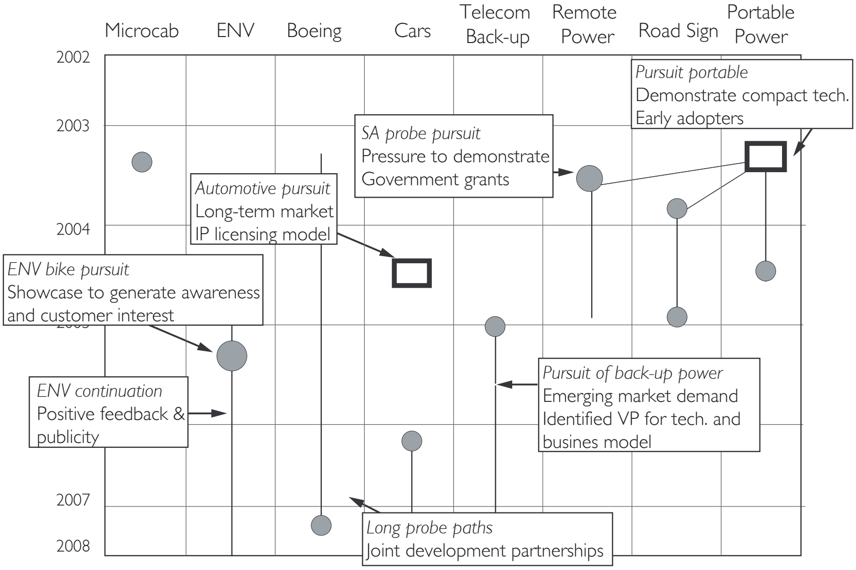

Figure 7.17 Overview Intelligent Energy probe applications and factors that explain the firm's probing process

Explaining BREADTH of Probes

The breadth market probes in this case firm are also related to Intelligent Energy's partnership model. The company engaged in probes with a diversity of partners, explaining the company's breadth of market probes. The focus on joint developments with partners explains the breadth of Intelligent Energy's technology platforms and customised systems. Apparently, targeting joint developments with strategic partners results in customised systems for a diversity of markets, if engaged in any partnership that makes sense and has potential for future collaboration.

In line with Intelligent Energy's business model the company engaged in probes with major corporations. The company was approached for the Boeing probe. With few other FC developers in this market, Intelligent Energy's decision to engage in this probe is not based on industry expectations or a value proposition for short term markets, but on partnership opportunity. In addition, the partnership enabled learning and an illustrative demonstration of Intelligent Energy's technology. On the other hand, the road sign probe did not involve a major partner. The probe was selected because Intelligent Energy perceived a value proposition and there was funding for the project. This type of probe decision appears to show opportunistic behaviour.

Similarly in the South African probes, partnership formation appears to play a less central role in probe decision making. Additionally, an economic value proposition was not expected. Intelligent Energy explains that it felt pressure to demonstrate its technology in applications. Apparently, this pressure strongly influenced the decision to engage in the South African demonstrations. On the other hand, the company would probably not have considered the probe without the availability of government funding and a local partner in South Africa. Besides portable power, Intelligent Energy has been involved in the CHP market. The distributed power theme of these applications may have been influenced by major energy companies investing in the company.

Explaining the PURSUIT of the ENV bike

The development and pursuit of the ENV motorbike is a notable probe decision. According to Intelligent Energy, the company needed a better way to explain the technology and attract attention of potential partners. Apparently the initial probes were not effective in explaining the technology to customers and attracting partners. Rather, in response to initial probes and feedback, Intelligent Energy appears to have modified expectations of adoption. The large markets where further away than expected and the process of customer learning was taking more time than expected. The selection of the ENV probe is unique to the industry and cannot be explained by industry expectations. Additionally, partners or customers did not propose the development. Instead, the idea was initiated and developed within the company. The main rationale appears to be market development, as a way to explain the technology and enthuse potential partners, above a cost effective value proposition. On the other hand, Intelligent Energy had sensed that consumers were becoming impatient for an exciting FC product.

Explaining the PURSUIT of Telecom

Intelligent Energy has become engaged in probes for back-up power in the telecom market. Considering the company's timing, industry expectations for back-up power are likely to have influenced the explorations in this market. However, at first Intelligent Energy decided it would not engage in this market because market specifications did not fit the firm's technology. Besides, the application did not fit Intelligent Energy's business model with regard to the supply and maintenance requirements of end-user customers in this market. When Intelligent Energy eventually decided to engage in back-up power for telecom, it had found a value proposition for its technology in this market and OEM customers to partner with. The decision to engage in telecom applications is influenced by industry expectations but determined by the firm's strategic positioning within this niche market.

Explaining FOCUS

In the third period IE focused on the development of the ENV platform and a select number of customers. The ENV outcomes have been determinant for this focus. First, Intelligent Energy decided to continue with the ENV and focus developments. This decision can be explained by the positive feedback and publicity from the ENV launch. The value proposition for the ENV proved to be stronger than expected. Intelligent Energy explains that it could not commercialise all its technology platforms at once and had to focus on developing the ENV platform. This necessity is illustrated by the limited cross-over learning from the South African probes due to differences in speed of development. On the other hand, resource limitations may explain the company's need to focus developments. After the ENV, this case firm additionally focused on a select number of customers. This decision is in line with Intelligent Energy's business model. It can be argued prior to the ENV, Intelligent Energy grasped the opportunities for projects and partnerships that came along. Now that the ENV has attracted attention of customers and provided Intelligent Energy with credibility, the company can be more selective of probes with partners.

Chapter 8: Cross-Case Analysis

Chapter 8 presents a cross-case analysis of the case study data described and analysed in chapter 7. According to Eisenhardt (1989) a cross-case analysis involves a cross-case pattern search, by looking at the data through diverse structured lenses. Using this approach, the constructs, models and patterns predicted from theory in chapter 6 will be compared to the empirically observed events and patterns in the case study data. The cross-case analysis will primarily compare similarities and differences between the case firms. The cross-case analysis will address the following revised research questions (section 6.8):

- What explains probe decision making in fuel cell firms? (RQ 3)
- What characterises a fuel cell firm's probing process? (RQ 4)

The within case analyses in chapter 7, discussed possible explanations for the probe decisions of the case firms. In this cross-case analysis, first, the cases are analysed and compared along the explanatory constructs (8.1). The role of these constructs in explaining probe decision making is discussed to validate the conceptual model presented in chapter 6. Section 8.2 compares the probing histories of the case firms in terms of market segment involvement. Subsequently, the probing processes are compared along the descriptive model to characterise the process and derive patterns of probing (8.3). The differences in probing processes are described in further detail to analyse what drives the different patterns (8.4). Finally, on the basis of the cross-case analyses and case study data, the propositions presented in chapter 6 are tested and new propositions are inducted from the case study data (8.5).

Comparing the case firms, it is important to note that the case firms are different in terms of ambitions, core competences and strategies. The variation of probe strategies was chosen to compile a more general understanding of probing processes and probe decision making from different perspectives. For the cross-case comparison this implies that it is not possible to claim a better or worse strategy.

8.1 Comparison of Explanatory Constructs

A conceptual model of probe decision making was proposed in chapter 6 to address the research question, "What explains probe decision making in FC firms"? In this section, the case firms are analysed and compared along each of the explanatory constructs of the conceptual model. The constructs, specified in section 6.5, include firm internal and external constructs. The firm internal constructs include: firm history and financial resources, technological competences and a firm's value propositions. The external constructs that are expected to influence probe decision making are: strategic partners, industry expectations and customer familiarity. To validate the conceptual model, the role of these constructs in explaining probe decisions is discussed in the following paragraphs.

8.1.1 Firm History

On the basis of theoretical constructs, firm history is expected to influence probe decision making in YTB firms and primarily the selection of initial probes. Firm history includes inherited technological competences, a firm's historic ties to a market sector and the ambitions of its founders. The case firm histories differ considerably. As a spin-off from Akzo Nobel, Nedstack inherited the FC R&D, the FC stack focus and the material science approach. The material science approach is reflected in the company's wide range of R&D activities in the first years after founding. It can also be argued that the material science background explains Nedstack's technology push approach to market applications. The company did not hasten to shift from R&D to applications. By contrast, Plug Power's history appears to have influenced the opposite approach to technology application. Plug Power inherited fuel cell R&D from MTI and was founded to bring the technology to commercial markets as soon as possible. The joint venture between MTI and the utility company Detroit Energy appears to have influenced Plug Power's focus on the development of products for the stationary market. The selection of Hydrogenics' initial probes for military portable power, similarly appears to be influenced by the founders' military background and connections. However, this military connection primarily gave access to an early adopter of FC technology and in comparison to Plug Power this part of Hydrogenics' history does not appear to influence longer-term probe applications and ambitions.

Despite the difference in 'haste to market', both Nedstack and Plug Power appear to have inherited the ambition to target large markets. This ambition is reflected in their initial probes for the residential CHP market. Nedstack's inherited ambition to target large markets additionally explains the company's ambition to manufacture large quantities of stacks. Intelligent Energy's business model, targeting licence agreements, suggests that Intelligent Energy was also founded with expectations for large-scale automotive adoption. Similar to Plug Power and Nedstack, Intelligent Energy inherited R&D experience and patents at founding. In contrast to these case firms, Hydrogenics was not founded on the basis of prior R&D experience. This may explain why, in the first 5 years after founding, the company did not engage in probes but R&D on FCs. The limited history as a new start-up may additionally explain Hydrogenics' 'entrepreneurial spirit' at founding, reflected in the search for opportunities and niches in the FC industry. To differentiate itself from more experienced firms in the industry, Hydrogenics initially identified and focused on the FC test and diagnostic market. The firm's entrepreneurial history appears to have driven Hydrogenics' pursuit of niche market applications whilst Plug Power and Nedstack were focused on larger markets at the time.

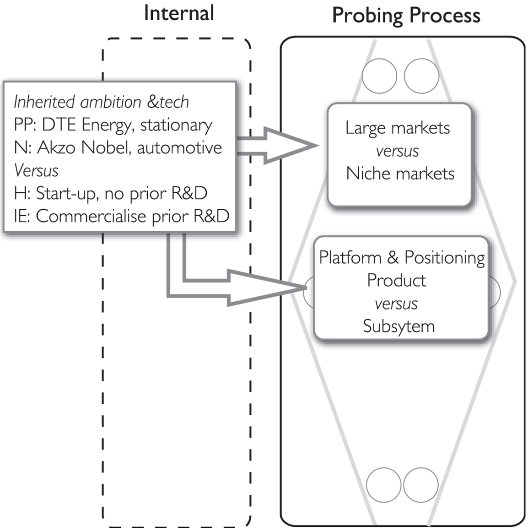

Figure 8.1 The influence of firm history on the case firms' probing processes

In conclusion, the case comparison suggests that firm history influences the firm's probing processes (fig. 8.1). Firm history appears to have some influence on the selection of initial probes. However, the influence of firm history is more apparent in the strategic positioning in supply chains and long-term market ambitions of the case firms. Moreover, the 'maturity' of a firm's technology and ambitions at founding appears to influence a firm's haste to pursue applications. In conclusion, the case data suggests that the differences in firm history may at least partly explain difference in probing strategy and approach.

8.1.2 Financial Resources

The conceptual model suggests that the availability of resources to pursue probe applications is likely to influence probe decision making, primarily in the early phases of probing. The financial resources available to the case firms vary considerably: first in the difference between public versus private funding structures and second, the difference in availability of government grants. The case firms also gained initial revenue from various sources such as partnerships and early customers, initial sales and engineering services. The financial resources of the case firms are compared and their influence on probe decisions discussed.

In the first years after founding, the federal and New York State Government provided Plug Power with significant financial support for R&D as well as early demonstrations. The government support was of central importance to realising Plug Power's initial field trials. Similarly, the Canadian Government provided Hydrogenics with R&D grants. Hydrogenics additionally gained initial revenue from engineering services and the FC test and diagnostic business. By contrast, in the same period, Nedstack had difficulty to fund or acquire resources for demonstrations. European funding for PEM FC developments was several years behind North America. Differences in the availability of government funding are likely to have driven differences in the pursuit of initial probes.

Furthermore, the financial structures of the case firms differ. Plug Power and Hydrogenics became publicly listed around 2000. Plug Power's resources from its IPO partly explain why the company was able to invest in a manufacturing facility and subsequently field trials on scale. After its IPO, Hydrogenics did not build such a manufacturing facility. Instead, the company continued to develop its FC test and diagnostic business and began to develop FC modules for early customers. In comparison to Plug Power, Hydrogenics appears to have put more emphasise on the formation of partnerships, probably as a means to fund initial probes. The publicly listed case firms, Hydrogenics and Plug Power, are larger than Intelligent Energy and Nedstack in terms of number of employees and assets under management (appendix B). It can additionally be argued that this larger size may have influenced the number of total probes realised. A larger firm is likely to have more resources to allocate to probing. Additionally, Hydrogenics and Plug Power appear to move from R&D to market applications at a faster pace to meet milestones and satisfy investors. This does not imply that private equity investors put less pressure on performance and targets. The Intelligent Energy case suggests that after the rounds of fundraising, initial probes were necessary to demonstrate and prove its technology to investors. By contrast, Nedstack was financed to focus on R&D in the first years after founding. The firm's variable necessity to convince external investors appears to influence their probing behaviour.

The Nedstack case suggests that its initial focus on R&D and relatively late initial probes can be explained by the lack of investor pressure to realise early demonstrations. The company's venture capital funding, since 2003, coincides with its change of strategy to a diversity of niche markets. Nedstack additionally pursued a diversity of subsidised projects. These decisions may be based on external resource dependence. Furthermore, Nedstack has generated initial revenue from FC stack sales. Similarly, Hydogenics has gained revenue from the sales of modules, projects and engineering services. Early sales, supply and engineering services provided these case firms with initial revenue. It can be argued that these probe decisions are based on opportunities for short-term revenue instead of a strategic probing plan. Such opportunistic behaviour may explain the diverse and large number of short probe paths in these case firms. On the contrary, long probe paths appear to be related to partnerships. Thereby, partnerships provide an external source of revenue. Both Plug Power and Intelligent Energy conducted probes in long-term partnerships. In line with Intelligent

Energy's business model, the company relies on contracts with major customers to generate revenue. The opportunity to receive contracts from diverse customers explains Intelligent Energy's diversity of projects and the length of the probe paths. Similarly, Plug Power's long probe paths are related to its partnerships. For example, Plug Power continues to develop the Home Energy System in the strategic partnerships with Honda and residential CHP systems with Vaillant. These case firms suggest that the continuity of long probe paths is related to the availability of funding from partnerships.

Furthermore, the Russian investment in Plug Power, enabling the acquisition two FC developers specialised in material handling. This case suggests that large external investments influence the strategic options open to a firm. Thereby, the availability of external resources explains the firm's ability to acquire competences and shift to a new market segment. It can also be expected that such external investors will influence future decision making. The case study suggests that financial resources influence the pursuit of initial probes in two ways: i) the availability of government support appears to influence a firm's ability to realise initial probes and ii) the necessity to convince investors appears to influence a firm's haste to realise initial probes. Finally, the financial resource construct appears to cause different patterns of probing. On the one hand, resource dependency on external resources appears to at least partly explain short probes in diverse markets. On the other hand, access to financial resources through partnerships appears to explain continuity in probe paths.

8.1.3 Development of Technological Competences

The case firms were selected on the basis of different technologies applied for probing. The case firms show that their scope of technological competences changed and developed throughout the process of probing. Thereby, this construct addresses how firms learn from probing in terms of their technological competences. This paragraph describes the interaction between changes in the firms' technological competences and their probe decisions over time.

The R&D experience gained in early probes further specified Plug Power's proprietary competences. In particular, the experience gained in the automotive probes was determinant for Plug Power's subsequent emphasise on developing and acquiring reforming technology. Reforming technology became instrumental in the development of Plug Power's integrated FC systems and GenSys product. Plug Power has sought applications in line with its reforming technology and this competence partly explains the company's focus on stationary FC systems. Within this focus, Plug Power specialised on the 5 kW power range for stationary applications. By contrast, Nedstack stopped R&D on reforming technology and focused on stack development and manufacturing for a broad power range. This technological focus on FC stack platforms enabled the company's pursuit of diverse applications.

After a wide range of R&D activities, Nedstack decided to focus on the development of its FC stack technology, targeting increased performance, cost reduction and manufacturing. Nedstack's material science competences explain its decision to focus on the chemical heart of a FC system. This change in competence focus explains the divergence from residential CHP to various market segments. Likewise, the development of Hydrogenics' proprietary FC modules is central to explaining its pursuit of diverse market segments. The company's system integration skills were derived from its test and diagnostic business. The diverse technology demonstrator probes became instrumental to Hydrogenics' further development. Through these probes Hydrogenics further developed its system integration competences and became specialised in the development of FC modules. Besides, the modules became a marketing approach to facilitate and stimulate OEM customers to integrate FC systems in their products. Nedstack also 'helped' out OEM customers with system integration and through these probe applications Nedstack further developed its system integration skills. The development of these competences may explain Nedstack's subsequent pursuit of new market segments where customers acquire systems instead of stacks, such as the PEM power plant and bus market. With these system integration competences, Nedstack presented a 70 kW bus module. In contrast to Plug Power, Nedstack and Hydrogenics, Intelligent Energy has developed proprietary competences in customising FC stacks and systems for customers.

The case comparison suggests that the development of technological competences in the case firms, at least partly, explains differences in their probing approach. The experience gained in initial probes influenced the firms' technological focus and the development of the firms' technology platforms. These platforms appear to have influenced their probing behaviour in subsequent probe applications. Finally, the technological competences developed through probing appear to determine the scope of market segments a firm is able to pursue without prior experience.

8.1.4 A Firm's Value Propositions

The conceptual model proposed in chapter 6 suggests that probe decision making can also be explained by the level of a firm's value propositions. What is the role of a firm's value propositions in explaining probe decisions? A firm's value proposition is shaped by its technological and market competences and determines a firm's ability to identify market opportunities for its technology and align its technology to customer requirements. Thereby this construct addresses how firms learn throughout the probing process.

The conceptual model suggests that initially a firm's value propositions are low and have limited influence on the selection of initial probe applications. In line with these expectations the case data suggests that a firm's value propositions are unsuitable to explain the selection of initial probes. The majority of initial probes were either aborted or postponed and subsequently, expectations and probe strategies were modified. The feedback from initial probes triggered a search for and engagement in new niche market probes. This behaviour appears to be driven by the necessity to develop the firms' value propositions. What differences and similarities between the firm's value propositions can be observed and how has this influenced their probing process?

Ability to Identify of Niche Markets

Compared to the other case firms, Plug Power was relatively early to recognise the niche market for telecom back-up power and focus on its development. Plug Power did not probe in a wide range of market segments prior to this focus. Relative to the other case firms, the company appears to have spent more time talking to potential customers than probing in diverse markets. Plug Power claims to have identified the 'need' for alternatives in this market and the firm's value proposition was assessed in a feasibility study. By contrast, Hydrogenics argues that probing in a diversity of markets was necessary to identify the most compelling value propositions. Hydrogenics argues that although cost comparisons with the current solution could be made beforehand, operational data from the technology demonstrators was necessary for a realistic evaluation of operational costs, performance in practice and specific customer requirements. For example, Hydrogenics learnt that forklift operations with its FC modules were only cost-effective, in the short term, in continuous shifts. It can be argued that Plug Power had a higher value proposition than Hydrogenics at the time: the company had identified a market opportunity that fit its technology whilst Hydrogenics sought for compelling value propositions. This difference may explain why Plug Power focused and Hydrogenics pursued a diversity of technology demonstrators. This argument implies that a breadth of market segments may be explained by a firm's low value proposition. According to Nedstack at the time, *"nobody knows what to focus on"* (Middelman 2006).

In the case of Nedstack it can be argued that the company prioritized initial revenue and the production of stack quantity from various probes above the selection of specific niche markets. From this perspective, the firm's behaviour is not explained by a lack of technical and market competences to identify compelling value propositions, but a strategy to produce quantities. Nedstack's pursuit of power generation in chlorine electrolysis plants appears to be driven by this quantity strategy, although the firm has also developed a specific value proposition in this market. The company has become familiar with this highly specific market and Nedstack's technology is applicable to the requirements. Similarly, Intelligent Energy appears to have prioritised strategic partnerships in various segments above the selection of specific niche markets. Nevertheless, once Intelligent Energy identified a compelling value proposition through the ENV bike, the company focused developments. Therefore, the level of a firm's value propositions, in terms of the ability to identify a market opportunity for their technology, appears to influence the breadth of probing (fig. 8.2). However, the breadth of probes may also be explained by revenue and partnership opportunities.

Although the breadth and duration of probing alternatives varies, the case firms suggest that some form of probing alternatives was necessary to identify niche markets with compelling value propositions. Field tests and demonstrations provide operational data for further technology development. The case firms suggest that probing is instrumental in learning about customer requirements and preferences as well as the speed of markets and their potential. Moreover, Nedstack and Intelligent Energy argue that probe experience is relevant for the selection of specific customers. Compared to Plug Power, the three case firms supplying to OEM customers appear to have required more learning from probe applications prior to the identification of specific market segments and customers. The case firms with OEM customers engaged in a broader scope of market segments, apparently to develop their value propositions. From this perspective, the search and learning process to identify and develop a firm's value propositions, drives the breadth of the firm's probing process.

Finally, what is the role of a firm's value proposition in the identification of markets for developmental probing? Each of the case firms responded to the emergence of market demand, apparently irrespective of prior probes and firm specific value propositions. Although Plug Power identified and developed its proposition in back-up power, it has engaged in material handling. Hydrogenics developed its value proposition in material handling but re-engaged in the back-up power market in reaction to customer orders. In all cases, the emergence of market demand appears to dominate firm decisions, irrespective of the firms' value propositions.

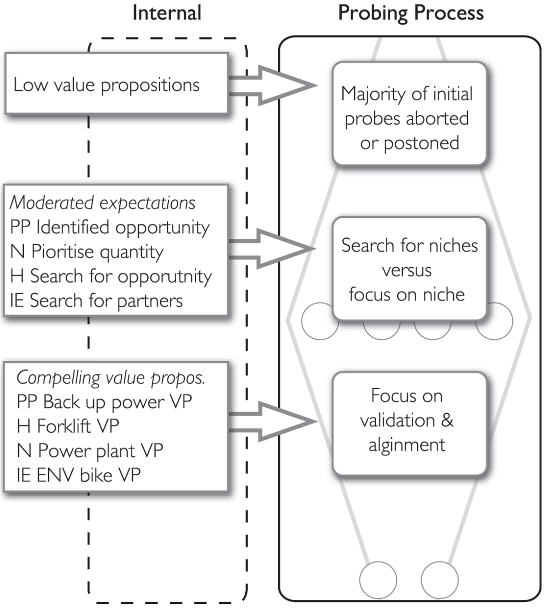

Figure 8.2 Influence of the case firm's value propositions on their probing processes

Ability to Meet Customer Requirements

As firms gain experience in probes, they learn and gain competences to develop and strengthen their value propositions, i.e. their ability to align their technology to customer requirements. Alignment requires technological advances and market competences. The case firms all describe the relevance of physical prototypes in facilitating the dialogue with customers to better understand specific customer requirements and preferences. How do differences in the development and strength of the firms' value proposition influence probe decision making?

Different approaches to the development of the firms' value propositions are observed. Plug Power pursued iterative probes to find out exactly what customers want and to align to these requirements. Similarly, Intelligent Energy suggests that aligning to customers requires 'intensive dialogue and that it is important to become *"intimately involved with applications to know how it will really be used"* (Hayter 2005). These companies have focused their developments to align to specific market requirements. By contrast, Nedstack applies similar stacks to various applications. Nedstack argues that, with some exceptions, customer requirements in different markets are similar because each market requires improved price, performance and reliability. Nedstack, uses data from the PEM power plant to align to bus market requirements and strengthen its value proposition in this market. This difference in approach, between focused learning about specific customer requirements and cross-over learning to advance technology and align to requirements is reflected in the breadth of the firms' probing processes.

Furthermore, can differences in the current level of the firms' value propositions be observed? A high value proposition has been described as a firm's ability to provide a cost-effective solution to a customer's problem. The case firms all claim to provide near cost-effective solutions to emerging markets. Nevertheless, the firms differ in their level of probe experience, which may indicate a difference in technical maturity and their ability to meet customer requirements. It is difficult to say if this level of experience provides an advantage in terms of technological competences or in the ability to convince customers. Differences between the firm's value propositions are also observed in the emphasis, for example, between i) technically oriented value propositions targeting cost reduction and customised systems for OEM customers and ii) market oriented value propositions targeting the needs of end users. This study finds that it is therefore difficult to compare the levels of value propositions. Finally, the case firms appear to have identified 'unique' value propositions in terms of highly specific markets that fit the firms' technologies such a, Nedstack in the chlorine electrolysis plants and Intelligent Energy in aeronautical applications. The case firms appear to develop their value propositions in order to differentiate themselves from other FC firms.

In conclusion, the data suggests that the case firms learned to identify market opportunities and align to customer requirements through probe applications. The comparison suggests that variable levels of value propositions in early periods of probing may have driven differences in the breadth of probing and difference in the timing of focus (fig. 8.2). However, for explaining probe decisions, there appears to be a fine line between a firm's value proposition and the way a customer perceives the firm's capabilities. A different construct is expected to be influential: customer familiarity with the firm and its technology.

8.1.5 Level of Customer Familiarity

Customer familiarity has been proposed as an external construct. Chapter 6 suggests that under the influence of customer unfamiliarity, firms are likely to conduct probes for demonstration and validation. This construct may explain both similarities and differences in probe decision making. A customer's level of familiarity with FC technology in general is likely to have a similar effect on firms in the FC industry. The level of customer familiarity with an individual case firm may influence the firm's probing process.

Each of the case firms faced a lack of a general awareness of FC technology and each of the case firms pursued probe applications for this purpose. Ballard's first bus demonstration in 1993 was instrumental in generating awareness about the technology and the potential. Similarly, Plug Power's early demonstrations appear to have benefited the FC industry in general. This observation is in line with Aldrich and Fiol (1994) who suggest that in the formative years of an industry, firms should collectively develop credibility for the technology. It can be assumed that customer familiarity with the technology in general has had a similar influence on each of the case firms. This construct may explain why the timing and duration of experimental probing appears to fall within similar periods. Although general awareness is likely to have increased during the period of probing observed, this process has taken many years. Intelligent Energy launched the ENV probe to demonstrate and explain FC technology to a general public 8 years after Plug Power's initial probes, conducted for a similar purpose. Aside from these similarities, customer familiarity with the individual firms is expected to differ.

There are differences in the degree to which customers are familiar with the case firms. As a relatively young company in the FC industry, the ENV motorbike can also be explained as an effort to publicise Intelligent Energy. According to Intelligent Energy, the ENV motorbike has put the company on the map as a credible FC developer in the FC industry. It can be argued that in terms of publicity and probes publicised, Plug Power and Hydrogenics are better known than the other case firms. The level of customer familiarity with the individual case firms is a matter of firm legitimacy in terms of two aspects: i) to become known as a company, ii) to become trusted as a supplier. Plug Power is renowned for the large number of installed units and experience in field tests. According to Plug Power, this experience has positioned the company as a front runner in the industry. The technology demonstrators have similarly made Hydrogenics well known to a broad scope of OEM customers. Relatively, Intelligent Energy and Nedstack have conducted fewer probes and rely on further publicity to attract customer interest. This difference in customer familiarity may explain their lower number of customer orders and their slower transition to a developmental phase.

The process of becoming a trusted supplier is common to many industries: it involves a process of trying out one, subsequently a series and repeat orders until eventually the firm receives a position as a trusted supplier. However, the process of validation appears to vary between the case firms. Plug Power has conducted field trials with launching customers. By contrast, Nedstack explains that to become a trusted stack supplier, it has to be involved in an OEM's developments from the start. Similarly, in the case of Intelligent Energy, demonstrations are part of the sales process towards intellectual property agreements involving demonstration, alignment and subsequent field trials. Intelligent Energy, is validating its technology to a select number of customers through customisation. By contrast, Hydrogenics and Nedstack are focused on the generation of operational and reliability data through quantities of FC stacks and systems in operation. The approach to demonstrating and convincing customers depends on a firm's supply chain position and appears to influence the probes pursued.

Plug Power 's early focus on field trials with partners and launching customers. In the same period, Hydrogenics engaged in a diversity of technology demonstrator probes, enabling a wide range of customers to experience and 'try out' the technology (fig. 8.3). In several of these probes Hydrogenics helped OEM customers realise the FC product. Similarly, Nedstack provided system integration services and education to OEM customers. Intelligent Energy finds that the ENV functions as an excellent tool to explain the technology to customers. Thus, the case firms suggest that probes are conducted to educate and convince OEM customers prior to further development and sales. These probe decisions appear to be driven by customer unfamiliarity instead of a firm's value propositions alone. Convincing OEM customers involves demonstration and customer education for customers to learn about the integration of FC technology in their products. Moreover, convincing OEM customers requires operational and reliability data. These case firms appear to depend on the level of OEM customer familiarity, their system integration capability and their willingness to adopt the technology. Intelligent Energy acknowledges that the pace of customer adoption is slow because OEM customers have to learn about FC systems.

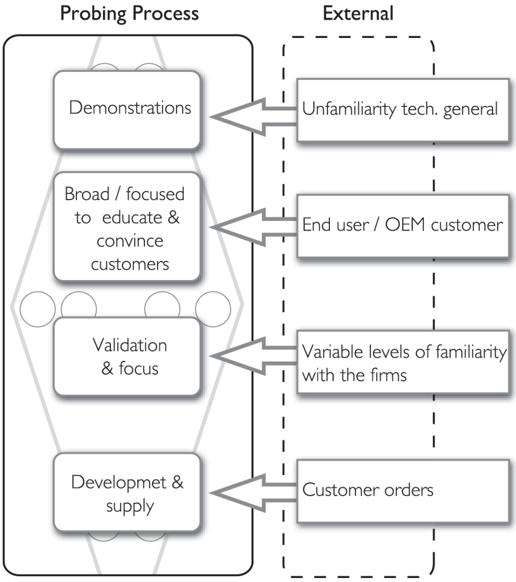

Figure 8.3 The influence of customer familiarity on the case firms' probing processes

Demonstrating and waiting for OEM adoption decisions appears to delay a firm's shift to a developmental phase of probing. OEM customer familiarity appears to influence the breadth of market segments and the transition to development.

The pursuit of probes for demonstrating, explaining and educating OEM customers appears to at least partly explain probing in a breadth of market segments (fig. 8.3). There appears to be a period in which probe decisions are primarily driven by customer unfamiliarity, instead of value propositions, probing primarily to convince and educate customers. Moreover, firms appear to depend on the learning speed of OEM customers. Differences in the level of customer familiarity appear to drive differences in probing behaviour in terms of the breadth of market segments and timing of development.

8.1.6 Industry Expectations

The collective expectations of the young and emerging FC industry are also expected to influence the probe decisions of FC firms. This external construct is suited to explain mimicking behaviour, whereby firms follow generally held beliefs in the industry instead of proprietary strategies and plans. Industry expectations include expectations on market adoption as well as technological dominance.

The potential applications for FC technology have not been a secret. Niche markets and the time frame for market adoption are openly discussed and analysed at conferences and trade shows. Prior to the year 2000 the FC industry held high expectations for near term wide spread market adoption in automotive and stationary power applications[1]. It can be argued that the automotive industry is largely responsible for shaping these expectations. Probe applications around this time caused a modification of expectations. Plug Power states that its early demonstrations have influenced the expectations of the whole industry, by showing how far the large markets really were from adoption. Between 2000 and 2004 industry expectations shifted to niche markets. However, it took several years for a consensus to emerge on which niche markets would emerge at which time. Around 2005 the emergence of critical back-up power as the first commercial

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[1] *These expectations are illustrated by figure 2.14, discussed in section 3.1.*

market became apparent as a number of FC developers received their first repeat orders. This emergence of demand has shaped industry expectations on niche market adoption[2]. What was the influence of this construct and can it explain similarities and differences between the case firms' probing processes?

Nedstack and Plug Power appear to have followed the 'hype' of industry expectations in the pursuit of their initial probes. Plug Power's adoption time lines, presented in 1999 and published in subsequent annual reports, communicate the company's expectations to the whole industry. This example characterises the industry at the time: there appeared to be more learning between firms of the industry than competition. Although Hydrogenics was comparatively early to target premium niche markets, their initial probes coincide with the period of modified expectations in the industry and the shift towards niche market applications. Intelligent Energy's selection of initial probes falls within this period of niche market pursuit, in which the majority of firms in the FC industry sought near term niche market applications. However, this period is also characterised by a limited clarity of industry expectations on which markets would be first to emerge. In this period, industry expectations appear to have limited influence, as the case firms pursue highly different probing strategies. Subsequently, the emergence of market demand, reflected by customer repeat orders in a number of firms, appears to have crystallised industry expectations for niche market adoption. After the years of probing with limited revenue from commercial sales, it is not surprising that the case firms are targeting the emergent market demand.

In addition to the industry expectations on market adoption, expectations on the dominance of technological alternatives can be observed in the FC industry. These expectations appear to coincide with the decisions to focus on R&D in the case firms. Decreased expectations for onboard fuel reforming are likely to have influenced Plug Power's decision to abort probes for this application. Expectations of the potential of PEM FC technology for widespread application, compared to other FC technologies, is likely to have influenced Nedstack's and Hydrogenics' focus on PEMFCs.

The case firms suggest that on the one hand the FC firms and their probe applications shape industry expectations. On the other hand, FC firms appear to follow industry expectations in terms of market adoption and technological dominance. In particular, industry expectations appear to have influenced the selection of initial probes, determining the boundaries within which the firms sought and selected probes. Industry expectations regarding niche market adoption did not crystallise until recent years and instead of following each other, firms appear to have sought and pursued niche markets in their own way. Now that industry expectations have crystallised, in terms of the first niche markets to emerge, most case firms appear to follow these expectations. Nevertheless, there were also case firms probing in these markets prior to the emergence of market demand and crystallised industry expectations.

8.1.7 The Role of Explanatory Constructs Over Time

The case study data has been analysed along the explanatory constructs to asses the role of these constructs in explaining probe decisions. Throughout the probing process, the case firms gained experience and the external environment changed, providing a different point of departure for subsequent probe decisions. The probe applications and the probe outcomes change the input for subsequent probe decisions. Table 19 provides an overview and a comparison of the input constructs and the changes throughout the firms' probing processes that appear to have influenced probe decisions.

The case firms show similarities and differences in terms of the explanatory constructs. First, the firms appear to react similarly to industry expectations, whereby industry expectations primarily appear to influence initial probes. The level of customer familiarity with the technology has a similar influence on the case firms probing processes in terms of the demonstrations pursued. The case firms appear to go through a similar learning process to develop competences and value propositions, however, the duration of this process

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[2] *These expectations are described in section 3.1, derived from collective discussions and presentations at conferences and tradeshows and reflected in the increasing number of government funded forklift and back-up power field trials (2.3)*

varies. Moreover, the level of customer familiarity with the firms and the level of required customer learning vary and appear to influence the breadth of probing and time to development. In line with the conceptual model proposed in chapter 6, the analysis suggests that the role of the constructs in the company's probing processes change over time. The differences in explanatory constructs appear to drive different patterns of probing.

Table 19: An overview of the input situation, the probes and the probe outcomes in each phase

Period	Plug Power	Hydrogenics	Nedstack	Intelligent Energy
1. Input	History in utility and mass market ambition Government funding/ support	Start up in FC industry. IPO pressure. FCATS experience. Focus on Premium markets	Akzo material science Mass market ambition. Project subsidies	First in premium markets. Commercialise APS technology
Initial Probes	Large markets: Automotive/ stationary	Portable power / back-up for telecom niches.	Large markets: Micro CHP for residential	Portable power niches
1. Outcome	Reforming technology. modified expectations	Customer education/ market dev. necessary.	Slower than expected	Take longer than expected
2. Change input	Seek value proposition IPO, product platforms	HyPM Technology platform. IPO	Modified expectations Multi applicable stack platform	Modified expectations
Second period	Field trials and partnerships.	Technology demonstrators	Probes and supply to diverse markets with platform.	Diverse demonstrations and the ENV
2. Outcome	Data, market feedback Value proposition backup power	Identified value proposition	Stack improvements. Market learning.	Publicity, market information, positive feedback
3. Change input	Market potential larger than initially expected	Potential forklift Supply order	Necessity to validate and build up production capacity	Value proposition ENV, credibility boost
Third period	Focus Back-up power	Focused niche markets	PEM power plant	ENV dev. and select customers in niches
3. Outcome	Emergence commercial market.	Increasing number of repeat orders	Reliability data	Partnerships

8.2 Comparison of Market Segments over Probing Histories

The probing processes of the case firms differ. This section compares the probing histories of the case firms in terms of market segment involvement. A comparison of the firm's probing histories shows similarities and differences in the markets segments pursued over time. To analyse these differences and similarities, the analysis will refer to the explanatory constructs discussed in the previous section. This study expects various constructs to have influenced the selection of market segments over time. On the one hand, the analysis is likely to demonstrate how firms learn to identify and select market segments. On the other hand, the pursuit of market segments may be explained by opportunistic behaviour or mimicking behaviour. The market segments the case firms have engaged in, are discussed separately and are illustrated in figure 8.4[3]. A key difference in initial probe engagements: Plug Power and Nedstack targeted large scale markets in automotive and residential CHP, whilst Hydrogenics and Intelligent Energy targeted premium niche markets in portable power. Before the year 2000, Plug Power and Nedstack were interested in similar markets: automotive and residential/commercial CHP.

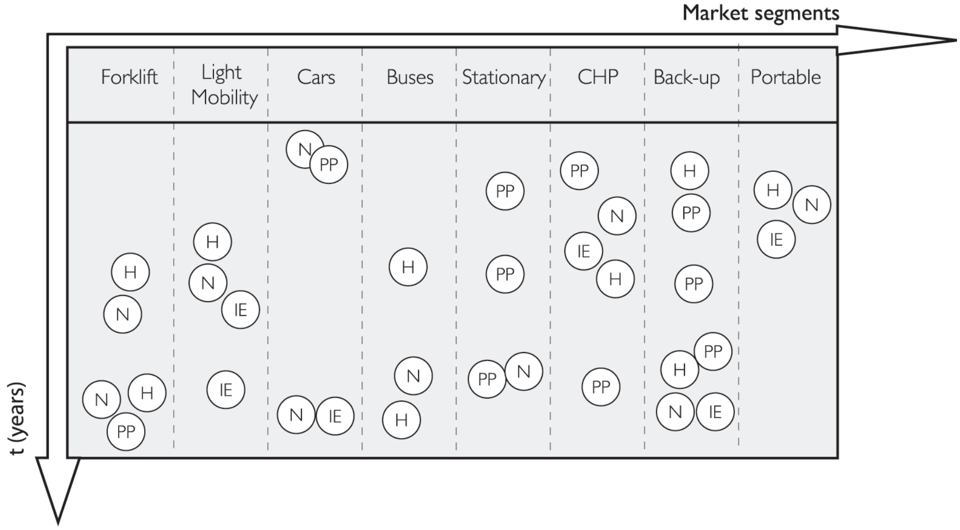

Figure 8.4 Comparison between the case firms on market segment engagements. Abreviations used include. PP: Plug Power, N: Nedstack, H: Hydrogenics, IE: Intelligent Energy

Automotive

For two years Plug Power conducted R&D probes towards automotive power. The company subsequently aborted its probe activities in this market segment. Nedstack was founded with similar expectations for automotive applications, inherited from Akzo Nobel, but directly after founding Nedstack made the decision to shift away from the automotive focus. In subsequent years, Plug Power aborted automotive engagements. By contrast, Nedstack strategically positioned itself as a supplier to automotive companies in subsequent years. What explains this difference? Plug Power's access to governmental funding for an automotive R&D programme and the opportunity to engage in this partnership appears to explain the company's initial automotive probes. Additionally, industry expectations for automotive adoption appeared to be promising. The subsequent abortion of probes may be explained by Plug Power's value proposition in this market. The firm's value proposition was based on reforming competences that became insufficient when onboard fuel reforming became less popular. Additionally, Plug Power explains that its main competitor, Ballard, already targeted the automotive market. By contrast, Nedstack did not engage in early automotive probes but continued R&D. The company's stack technology was further developed to meet automotive requirements and compete with Ballard. Similar to Nedstack, Intelligent Energy has targeted automotive companies for longer term markets and engages in strategic partnerships. By contrast, Hydrogenics' strategic alliance with GM disabled the company from entering the automotive market. Hydrogenics also argues that around the year 2000, there were more advanced companies targeting PEM fuel cell technology for automotive than Hydrogenics.

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[3] The case firms cover a wide range of PEMFC applications. The case firms have not engaged in a number of other possible segments such as, portable electronics (e.g. Altran and Jadoo), power FC systems and mobile generators for specific applications such as mobile homes, yachts and construction sites (Voller and Protonex), lower power mobility such as wheelchairs and bicycles (Suzuki prototype and Masterflex). The illustration does not include submarines, an early probe application for FCs pursued by for example, Ballard and Nedstack.

Stationary and Residential CHP

Around 2000, Plug Power and Nedstack expected residential CHP to be the first large market for PEM fuel cell technology. This belief was generally held in the FC industry at the time, therefore, the industry's expectations may explain the firms pursuit of residential CHP. Furthermore, Plug Power's selection of the CHP residential market can partly be explained by the firm's historic antecedents in utility. Nedstack's history has no direct relation to the CHP market other than the firm's historic ambition to target large markets and produce large quantities of FC stacks. The initial CHP probes in both firms were funded by governmental subsidies. After the initial probes both companies modified their expectations to other market applications. The market was further away than expected. Partnerships and shareholders appear influential in explaining Plug Power's continuation and focus on stationary niches. Plug Power continued to engage in a linear path of CHP developments despite setbacks. First, Plug Power found that the application would not be cost-effective on the near term, yet the EU funded Virtual Power Plant project enabled continuation. In subsequent years, probe activities were continued despite the mismatch Plug Power found between the temperature PEMFCs provide and the temperature current residential homes require. The EU funding and Vaillant partnership appear to have determined the repeated continuation of this CHP probe path. Nedstack was not part of such large CHP projects and although the company continues to R&D for this segment, it diversified its attention to probes in a wider range of applications by 2003.

Around 2003 Intelligent Energy developed a CHP probe and in 2004 Hydrogenics supplied to a CHP application in Japan, however, both companies did not actively pursue this market segment. It can be argued that by this time industry expectations for CHP were moderated. Additionally, Hydrogenics explains that its technology is not ideally suited for the CHP market. Nedstack on the other hand, claims that their stack technology can be applied to both CHP and other applications. Apparently, Hydrogenics' preference is also a matter of technology fit and company culture. Intelligent Energy states that it in the future it may consider reengaging in CHP probes, but then from a different position, as other firms have advanced in this sector.

Plug Power's continued engagements and probes in other stationary markets appear to be influenced by the partnership with GE and Detroit Energy as shareholders. In comparison, the other firms do not have historic ties to stationary markets. Both Plug Power and Nedstack have engaged in the market niche for remote residential power. However, in comparison, Nedstacks shows less continuity and commitment to this market. For Plug Power, the remote power market is a key niche market to establish itself in the premium power market for residential and light commercial markets. Thereby, Plug Power expects that the GenCore will pave the way for the GenSys premium power product. By contrast, Nedstack has primarily engaged in project based probes, such as the development of an autonomous uninterruptible power supply system. The continuous support from the military and government as early customers, appears to, at least partly, explain Plug Power's continuous engagement in this market. Nedstack's involvement in this market has increased over the years through supply agreements. For example, following the demonstration of a 50kW stationary system at the Olympics in Torino 2006, Nedstack continues to supply stacks to this customer. Through the PEM power plant project, Nedstack is also considering large scale stationary generation in specialised markets. With funding from the Canadian government, Hydrogenics has been involved in the development of a 50 kW stationary power generator since 2000, but the market has not become a focus market. In comparison, it can be argued that Hydrogenic's HyPM module demonstrated in a variety of vehicles is more suitable for dynamic operation. Intelligent Energy's lack of stationary probes in the 50 kW plus range is noteworthy. This may be explained by the lack of an appropriate technology platform and technological competences for this market.

Portable Power

Both Hydrogenics and Intelligent Energy started with probes in portable power applications for military customers. In the case of Hydrogenics, there is a relation between these military probes and the military background of one of the founders. However, the military can also be considered as an early adopter of FC technology in general, as the other case firms also engaged in early probes for the military. Nedstack, for example, initially developed DMFC portable power packs for the military. Moreover, Hydrogenics' decision for portable power around 2000 is likely to be explained as an act of strategic positioning. As a start up company in the industry it selected premium power niches to differentiate from firms targeting the large markets. Intelligent Energy's involvement in this niche market two years later is more likely to be explained by the general trend towards niche market engagement in the FC industry around 2003. Additionally, it can be argued that portable power was a practical showcase of Intelligent Energy's technology.

The portable power market probes were not followed up and have not become an area of focus for Hydrogenics or Nedstack. Hydrogenics aborted the HyPort probe path when commercial feasibility turned out to be further away than expected. Nedstack focused on PEM FC instead of DMFC. Furthermore, both companies shifted their focus to higher power platforms, too heavy for portable power applications. In line with the experimental probe strategy of these case firms, a platform specifically for portable power would be less broadly applicable and contribute less to realising 'volume'. Plug Power's lack of portable power probes can similarly be explained by their technology platform, the 5 kW power range is unsuitable for portable power. These case firms suggest that portable power probes fell out of the firms' portfolios as they focused their scope of technology developments. Thereby, Plug Power, Nedstack and Hydrogenics aborted probes in the portable market segment despite the *"generally accepted belief that these markets are nearest to commercialisation"* (PwC 2006: p.4). The firms appear to have left the portable market to others FC firms, as an increasing number of companies focused on portable markets in 2005 (PwC 2006) and various FC firms emerged targeting portable niche markets (described in section 2.5). By contrast, Intelligent Energy continues to develop technology platforms in the low power range. For example, the FC system in the ENV can be used as a portable generator. On the other hand, Intelligent Energy suggests that it may not continue developments in the 100 W power range, as these systems require a different technology platform.

Back-up Power

Currently, the critical back-up power market is generally expected to be the first commercial market for FC technology. However, Hydrogenics and Plug Power were involved in this market prior to the crystallisation of such industry expectations. In this market segment, Hydrogenics pursued its initial probes. Thereby, it was the first case firm to present a back-up power unit for telecom at tradeshows and conferences in 2001. The selection of the telecom probe came forth from the partnership with GM. It is likely that GM's experience in niche market opportunities for FC technology strongly influenced the selection of this market. A year later than Hydrogenics, Plug Power engaged in the back-up power market. According to Plug Power, they recognised the need for back-up power. It can be argued that both North American case firms were inspired by the North American 'hype for back-up power' in this period. In contrast to Plug Power, Hydrogenics did not continue in the back-up power market until several years later. This difference may be explained by the level of the firms' technological competences and value propositions. Technically, Plug Power's Gencore can be explained as a niche market spin-off from prior technological experience and GenSys developments. A private/public partnership enabled a feasibility study with Nyserda and Verzion, to asses and demonstrate technological feasibility and market opportunity. By contrast, Hydrogenics supplied the system integration expertise, but not the stack technology for the back-up power probe. Moreover, the probe targeted the 25 kW power range instead of Plug Power's 5 kW power range that meets the requirements of telecom providers. Apparently, Hydrogenic's proprietary value proposition in this market was not as strong as Plug Power's in the same period.

Nevertheless, Hydrogenics was approached by a major client for AC back-up power in data centres several years after its back-up power probe with GM. Apparently, where Plug Power's back-up power decisions were based on probe experience and the internal development of its value proposition, Hydrogenics decided to re-engage in this market in response to customer orders. Since 2004 Plug Power and Hydrogenics have begun to receive repeat orders in this market segment. Plug Power argues that it is a front runner in the back-up power market because of its extensive field trials and operational data. But then what explains Hydrogenic's repeat orders in this market? The company argues that its experience from the initial demonstrations and light mobility technology demonstrators has given the company legitimacy and credibility in the back-up power market. Apparently, Hydrogenics' HyPM technology and experience in light mobility is transferable to the back-up power market.

The other case firms addressed other niches in the back-up power segment, such as Nedstack's diesel genset project for remote back-up power and IE's remote back-up power probes in South Africa. Despite a limited probe history in the back-up power market for telecom, these case firms have also become involved in the emerging market for critical back-up power. As critical back-up power for telecom operators and data centres emerged as the first commercial market for FC technology, each of the firms became involved in this market segment. This homogeneity appears to show mimicking behaviour in response to market demand, however, a closer look shows that the case firms target different positions and different subsegments within the back-up power segment. Plug Power covers various back-up power subsegments including the Gencore to telecom and broad band customers. Plug Power has also received government funding to develop an emergency critical back-up power unit. Besides the DC back-up power market for telecom providers, Hydrogenics is targeting the AC back-up power market for data centres, supplying directly to a marketing partner. Nedstack has not developed further 'probes' in this market, but supplies to back-up power system integrators. Intelligent Energy became engaged in back-up power for telecom once it had identified a niche application within this market that suits the firm's technology and business model. Intelligent Energy is involved in partnerships with OEM customers to supply technology for what goes into a cabinet rather than what powers an entire base station for a mobile network.

Thus, on the one hand, industry expectations and the emergence of market demand appear to explain homogeneous behaviour among the case firms. On the other hand, the case firms appear to have established strategic positions and unique value propositions within the back-up power market with respect to their technological core competences.

Transportation

After 2003, the case firms engaged in several niche markets. Whilst Plug Power focused on stationary applications and the GenCore in particular, the other case firms engaged in a diversity of markets including light mobility applications, such as neighbourhood and specialty vehicles. Intelligent Energy was involved in the development of the microcab and in later years the ENV. Nedstack additionally became involved in the development of a neighbourhood vehicle and is currently developing high power transport applications. Hydrogenics engaged in the largest number and broadest diversity of light mobility applications such as a neighbourhood vehicle and a midi bus, higher power vehicles such as a delivery van and a bus as well as the material handling segment. What explains this diversity of light mobility probes?

In 2003 Hydrogenics became involved in the specialty vehicles segment through the orders from customer Deere. Relative to the other case firms, Hydrogenics was early to engage in light mobility applications. The company realised that it could address multiple light mobility applications with the same module in the 10kW power range. Moreover, the GM agreement limits Hydrogenics' engagements in the automotive market. Therefore, the pursuit of light mobility appears to be a strategy to address the transportation market through other applications. For example, the midibus probes enable Hydrogenics to approach the automotive market through buses. In the mean time, Hydrogenics continues to supply to the vehicle demonstration market. The light mobility probes by Intelligent Energy, Nedstack and Hydrogenics are mostly characterised by a short duration without follow up. This can be explained by the project based nature, typically subsidised for demonstration purposes[4]. The light mobility applications are popular for demonstration as they tend to speak to the public's imagination. The demonstration value of the light mobility segment is reflected in Intelligent Energy's ENV motorbike. Thereby, it is the only case firm that has developed a dedicated design for the motorbike market segment with the ambition to showcase their technology. According

[4] *Such as the HyChain project described in section 2.3. The Hydrogen Village in Toronto, Ontario, is also an example of various light mobility applications for demonstration.*

to Intelligent Energy, a motorbike is more effective to explain the technology and enthuse customers than, for example, portable power. Hydrogenics and Intelligent Energy explain that light mobility is a good sector to demonstrate a firm's FC technology and convince potential OEM customers, because it requires high energy densities and dynamic operation. The pursuit of probes for market development appears to explain the selection of light mobility applications and characterise this period of probing.

Intelligent Energy is the only case firm in the aeronautical market segment. This engagement can be explained by the opportunity to engage in a joint development agreement with a large customer, Boeing. In contrast to Intelligent Energy, Nedstack has been involved in higher power transportation applications including a bus module, submarine, ferry boat, a delivery truck and a train. Through these high power transport applications Nedstack achieves quantity. This example once again reflects the influence of the firms' business models on their probing strategy. As suppliers of modules and stacks respectively, Hydrogenics and Nedstack are both forming supplier-OEM customer relationships with forklift manufacturers.

Three of the case firms, Hydrogenics, Plug Power and Nedstack, are currently involved in material handling. Similar to the back-up power engagements, this is not a coincidence but a response to the emerging market for material handling. In contrast to the back-up power market, Hydrogenics developed a value proposition through probing in this market and Plug Power 'stepped into' the market. Through experience gained in the 'technology demonstrator' probes, Hydrogenics developed its value proposition: the company identified the forklift market segment for the HyPM module technology[5]. By contrast, Plug Power did not announce probes in the forklift segment, except for some 'quiet' developments on a 'GenDrive' system for material handling in 2005. Instead, Plug Power has become involved in the forklift market through the acquisition of two FC developers focused on material handling. Apparently, Plug Power's proprietary technology for stationary applications is not suitable for and transferable to this market segment. By contrast, Hydrogenics and Nedstack are able to apply their technology platforms to both markets, driven by the following key requirement: back-up power requires reliable modules or stacks and material handling requires durable modules or stacks. With technology applicable in this market, Nedstack will pursue opportunities in the material handling market once capable OEM customers are found. Intelligent Energy has not reported any involvement in this sector. This may be explained by their lack of probes and systems at the required power level and/or a lack of appropriate and committed partners to pursue forklift applications within their business model.

The case study suggests that engagement in the material handling market can be explained by, i) an internally derived value proposition based on probe experience, ii) technology applicable/ transferable to this market and iii) the availability of resources to acquire the competences and capabilities for this market.

Unique Value Propositions

Although the case firms appear to have converged to a selection of similar markets, each case firm also appears to have developed 'unique' value propositions, i.e. unique abilities to identify specific market segments and meet customer requirements. Plug Power is the only case with field trial experience on-scale for the premium power market. With this experience and proprietary reforming technology as well as relations with and knowledge of current GenCore customers, Plug Power appears to be developing a proprietary value proposition for this market. Hydrogenics' experience with multiple light mobility applications, supplying to demonstration vehicle markets and partnership with Deere, positions the company for future markets in light mobility. Nedstack is one of the only firms in the FC industry targeting the market for large scale stationary production of electricity in chlorine electrolysis plants[6]. The company's historic ties to Akzo

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[5] General Hydrogen and Cellex Power were early to focus on the forklift market. Nevertheless, these companies faced similar difficulties to identify and develop their value proposition. General Hydrogen initially picked 'the wrong' forklift class, it took time to identify which specific forklift segment would most likely adopt PEM FCs first. Cellex Power identified opportunities in a specific forklift segment, but had difficulty to select which technological approach would match customer requirements.

[6] Another FC firm involved in this market segment is Nuvera. The historic background of this company is also in the electrochemical industry.

Nobel appear to explain the identification of this highly specific niche market. The firm's ability to manufacture the required volume of kWs and the market competences in this industry provides a unique value proposition. Intelligent Energy is the only case firm targeting the commercialisation of a premium consumer niche market, the ENV bike. Thus although mimicking behaviour is observed in response to the emergence of market demand, FC firms have also developed unique value propositions in specific niche markets.

Conclusion on Market Segment Histories

The comparison of probing histories, in terms of market segment involvement over time, gives insight into the differences and similarities of the probing processes. The comparison suggests that the market segments for initial probes appear to coincide with industry expectations at the time of probing. It is noteworthy that the majority of these initial market segments are not directly followed up. A period follows in which the case firms pursued a diversity of market segments. A notable characteristic of this period is that the case firms are engaged in a highly variable breadth of market segments. Some market segments in this period, particularly the light mobility segment, were pursued primarily for demonstration and market development purposes. The selection of subsequent market segments is at least partly a consequence of learning from the experience gained in the probes. Following the period of heterogeneous market engagements, each of the case firms shifts to similar market segments, suggesting mimicking behaviour in response to the emergence of market demand. The firms are all engaged in the critical back-up power segment, apparently irrespective of prior probe experiences. This ability to shift appears to primarily depend on the application diversity of the firms' technology. In this final period it is also observed that the case firms engage in fewer market segments. From the comparison of the probing histories, patterns of probing appear to be emerging. The following section will discuss these patterns and compare them to patterns from theory.

8.3 Characterisation of the Probing Process

Patterns of probing are emerging from the analyses of explanatory constructs and comparison of probing histories. This section will compare the case firms' probing processes to identify these patterns. Thereby this section will address the research question: what characterises a firm's probing process? Chapter six proposed a descriptive model of the probing process, as a manner to describe and represent a firm's probe decisions. The model is based on variation in the breadth of market segments and the length of probe paths over time. The descriptive model enables comparison between the probing processes of the firms, to learn more about the process of probing and variable patterns of probing.

The case firms were selected on the basis of a variable breadth in market probes and different technologies central to their probing processes in order to analyse and explain different strategies of probing. This section will analyse and compare the case firms along the variables of the descriptive model, breadth of market segments and length of probe paths, to derive patterns of the probing process. Based on concepts from theory, chapter 6 conceptualised possible probing patterns. The conceptual model suggests that firms go through three phases of probing characterised by different modes of decision making and learning: an exploratory phase of initial probes, an experimental phase and finally a developmental phase of iterative probe development. In addition to these phases, the experimental phase is expected to show patterns of 'cross-over learning' between market segments. The breadth of market segments is expected to increase and subsequently decrease over time and the length of probe paths is expected to increase over time. Paragraph 8.3.1 will compare the firms' probing processes to analyse if similar phases of probing can be observed. Subsequently, paragraph 8.3.2 will compare differences in the probing process.

8.3.1 Comparing the Characteristics of the Probing Processes

Phases

Three phases of probing have been proposed, defined by the mode of learning and decision making. The conceptual model suggests that over time probing shifts from chaotic to orderly, through a divergent process of new market segments followed by a convergent process of selective development.

The case firms all show divergence and convergence in the number of different market segment engagements over time. Regarding early probe applications, it is observed that the breadth of initial probes in each case firm is limited to two or three different market segments. Plug Power targeted two large scale markets: automotive and residential stationary. These two markets differ strongly in product requirements and sector characteristics. Nedstack concentrated developments on combined heat and power for the residential market, although developments and seed projects were ongoing for the military and bus segment. Hydrogenics engaged with customers in military portable power and telecom back-up power. Similarly, Intelligent Energy engaged in niche markets for military and remote portable power. These initial probes are demonstrations of the firms' technological competences, with a small number of units. This limited number of probes may be explained by resource limitations in the young FC firms. The probes are used to make themselves known to external actors and communicate that the company is ready to start moving from R&D to applications. Under these conditions every beginning is likely to start small.

These initial probes show the characteristics of a phase described as explorative and chaotic: i) learning is gained from the variety of probes and does not follow a linear process, ii) several probes are not followed up, iii) the probes show little consistency and dominance in the selection of technologies and markets. The majority of the initial probe engagements do not correspond to the main probe engagements in later years. Each case firm shows a similar pattern: the probe paths initiated in the first phase of probing show the highest degree of abortion and postponement. For example, Plug Power aborted its automotive probe path and Intelligent Energy did not continue with the development of its initial portable power units. Nedstack slowed down its engagements in CHP and Hydrogenics did not engage in telecom back-up probes for some years. Feedback and information on the initial probes did not fit with the firms' initial expectations: the time to adoption was too far away. Consequently, each case firm changed their probing strategy. Apparently, the potential and outcomes of the initial probes were difficult to predict.

The shift between the initial probes and subsequent probes is noteworthy. Following initial probes, the four case firms show an increase in the breadth of probe engagements as well as shifts to new market segments (fig. 8.5). These shifts can be interpreted as a phase difference between the initial probes and subsequent probes, consistent with the shift to an experimental phase predicted in the conceptual model. Plug Power aborted probe engagements in the automotive market and chose to focus on stationary markets. Within this market, Plug Power diversified to several market segments. Hydrogenics shifted from probes in portable power to a breadth of market applications, several in light mobility. Nedstack shifted away from its initial focus on CHP to a wide range of applications. Intelligent Energy continued to apply their initial technology, but also engaged in a wider scope of probe applications. In this period, the firms show short and long probe paths and increased engagements in new market segments. These characteristics support the concept of experimental probing: the pursuit of probes in a variation of market segments and learning by discovery. It can be argued that if the case firms had stayed in the initial markets, they would not have 'survived', because market adoption was too far away. From this perspective, experimenting in new markets and probes was necessary for two reasons: i) to gain market insight in order to identify and develop a firm's value propositions and ii) to stimulate and develop markets to reduce uncertainty in the external environment.

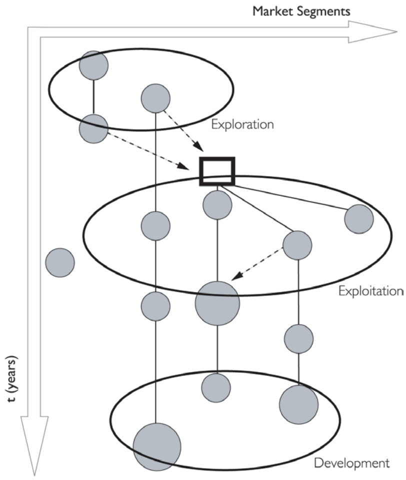

Figure 8.5: Three phases of probe decision making

For each case firm, the increasing breadth of market probes coincides with the development of technology platforms. This pattern can be explained by technology and market development with limited resources: with standard platforms the case firms were able to serve different customers with limited development effort. The case firms show similar experimental behaviour in new market segments through applications of their technology platforms.

Subsequently, each case firm shows a decrease in the breadth of market segments and new probe engagements and the case firms focus on developing a select number of probe paths. In a select number of market segments the paths of iterative development, become longer and more linear. Plug Power began to prepare the commercial roll out of the GenCore through probes with launching customers. Hydrogenics began with field trials in the forklift market and with development and supply to back-up power application. Nedstack continued developing (a larger) PEM power plant in successive probe demonstrations and Intelligent Energy focused on the realisation of the ENV and a select number of customers. Apparently, some degree of focus appears to be necessary to transition to a phase of development. Additionally, the focus may be explained by the emergence of market demand as customer orders and repeat orders increase in a select number of markets. For example, Plug Power and Hydrogenics received sizable repeat orders from customers, reducing the uncertainty of market adoption considerably. Thus, the probe applications in this period show the predicted characteristics of a developmental phase: the focused development of a select number of probe paths, iteratively developing the technology towards optimisation, refinement and production.

Probe **paths** have been proposed as a concept to describe the continuation of probe applications in the same market segment. Probe paths are represented as vertical lines, indicating iterative development and exploitive learning. Throughout the probing process, the lengths of these probe paths are expected to vary. In the first period, the case firms show short paths, consisting of one probe without follow up or with a single follow up. This observation is consistent with the predicted characteristics of an explorative phase, characterised by predominantly explorative probes in new market segments. As the firms diverge into a wider range of probe applications, a similar rate of abortion is observed. For example, a small number of Hydrogenics' technology demonstrators were followed up and several of Nedstack's subsidised demonstrations were not continued. In contrast to the initial period, the short paths in the period shows a high degree of technical cross-over learning between market segments, feeding experience from one market segment into a probe path in another segment. This observation supports the concept of cross-over learning and characterises the experimental phase of probing.

The longer paths for iterative development are observed in two different periods. Fist, longer probe paths are observed as the firms decide to focus on the development of a select number of probes, for example, the iterative development of Hydrogenics' forklift and Intelligent Energy's ENV bike. Second, longer probe paths are observed in partnerships targeting developments for future markets. Plug Power, for example, shows long probes paths for CHP with Vaillant and the Home Energy system with Honda. In some of these long paths few probes are realised. The case firms indicate that these market segments were not aborted but 'left aside', to keep the options open for future engagement. Most of these' postponed paths' originated in the first phase of probing.

In conclusion, the case firms show similar phases and patterns of probing as proposed in chapter 6. First, the case study suggests that these similarities can be explained by the level and process of learning in the case firms. Second, the case study suggests that uncertainties in the environment influence these phase of probing. The observation of similar patterns in the probing process is consistent with the findings of Van de Ven et al. (1996: p.17) on the similarities between the innovation processes in firms, *"the innovation journey entails many of the same core processes"*. However, the selection of cases was based on variable probing strategies, therefore, differences have also been observed in the probing and learning processes.

Table: Comparison of breadth variation and path length

Breadth/ Length	**Plug Power**	**Hydrogenics**	**Nedstack**	**Intelligent Energy**
Breadth 1st period	2 main segments. Stationary and Automotive (1997-1999)	2 main segments Portable power, military and back-up (2000-2002)	1 main segmen CHP developments, diverse interests (2000-2002)	2 main segments Portable power military / remote (2002-2003)
Breadth 2^d period	4 main and 7 subsegments. Several paths in stationary	8 main segments Breadth of technology demonstrators	8 main segments Breadth of supply and applications platform	4 main segments Breadth of applications with customers
Breadth 3^d period 2004-2006	Focus on 2 segments. Commercial roll out back-up	Focus on 2 main segments	4 main segments Power plant pilot and bus interest	3 main segments ENV platform and automotive platform
Linear path	Early field trials, product line development	Forklift path after technology demo	PEM power plant	ENV development
Aborted	Automotive, GenSite	CHP, portable power	DMFC	CHP
Postponed	CHP, GenSys	Back-up power	CHP	Automotive
Path shifts-cross-over	GenSys to GenCore	Mobility to back-up	Power plant to bus	Limited

8.3.2 Differences in Overall Pattern

In addition to similarities, the four case firms show differences in the breadth of market segments and the length of probe paths. The case firms were selected on the basis of variance in breadth. Additionally, the case firm selection was based on different technologies, to study how the probing process varies for different technologies applied. On the basis of the case study data, this paragraph addresses what explains the variation of breadth (RQ 3b), and what different patterns of probing can be identified (RQ4b)? In a comparison of the case firms, figure 8.6 illustrates variation in the breadth of probing over time. Figure 8.8 illustrates variation in probe length. To facilitate the comparison of patterns in this paragraph, the timing of initial probes is aligned to compare the probing processes from initial probes to current probes.

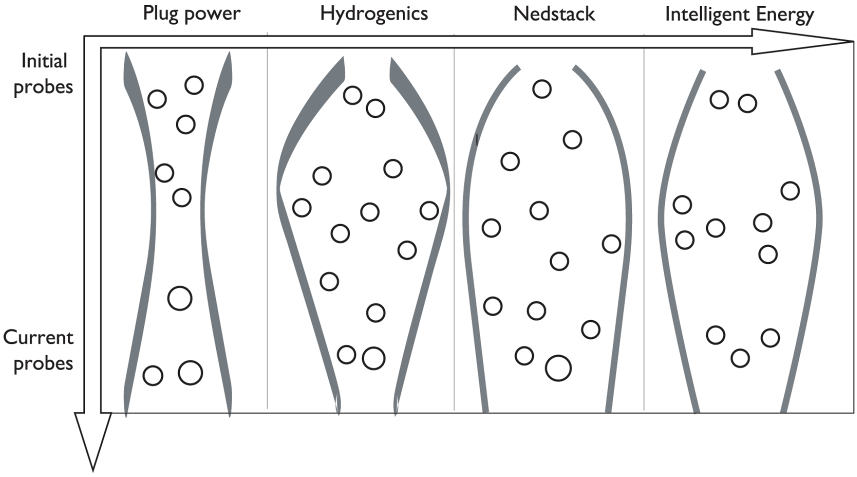

Figure 8.6 Comparison of case firms along breadth of market segments from initial probes to current probes

The case firms show a variable degree of focus and breadth as well as divergence and convergence over time. Plug Power, developing an end product, shows the highest degree of focus throughout the process. Hydrogenics, the developer of a FC module for OEM clients, shows the highest degree of convergence from a wide range of market segments to focused niche markets. Nedstack, the developer of stacks, shows the lowest degree of convergence. Nedstack continues to supply and engage probes with a diversity of OEM customers. Intelligent Energy, partnering towards IP agreements shows convergence to a select number of customers and the development of a showcase.

The application of stacks and systems appears to require more breadth in an experimental phase of probing than the application of endproducts. With potential customers in a wide range of market segments, Hydrogenics, and Nedstack used a breadth of probes to attract the interest of potential OEM customers and to identify specific customers. Moreover, supplying to OEM customers instead of end users, the companies put more effort into educating customers for system integration. Furthermore, to convince potential OEM customers to change to FC technology, the companies required reliability data and operational data prior to further development. Hydrogenics and Nedstack's probing processes suggest that data from one market segment was transferable to another market segment. By contrast, Plug Power conducted market assessments and feasibility studies in a specific market segment prior to probe applications. Enduser customers appear to require more effort to understand specific customer preference and product requirements at an early stage of probing, whilst OEM customer require more effort to explaining and validating the technology.

Although the case firms all show some degree of focus in the final phase, the degree of focus varies. Plug Power became highly focused on the commercial roll out of the GenCore, but subsequently acquired two companies in a different market segment, material handling. Similarly, Hydrogenics chose to focus on the development of two similar market segments, the forklift and back-up power market. Although Nedstack focused its probe efforts on the PEM power plant, it remains involved in a wide range of applications. Similarly, The ENV bike and platform became the 'face' of Intelligent Energy, but projects with key customers in a variety of market segments continue. Apparently this difference can be explained by a focus on the development of probes versus a focus on supplier relations and strategic partnerships.

The case firms additionally show variance in probe path length (fig. 8.7). Plug Power shows long linear probe paths of iterative developments with long-term partnerships and the highest degree of continuity. By contrast, Hydrogenics and Nedstack show a multiple short paths and the linear development of a selection of these paths. Intelligent Energy shows long linear probe paths with partners as well as short probe paths for various projects. The cases reveal two different patterns of iterative development: 1) the development of a product through a linear iterative probe path and 2) iterative improvements of a technology platform through short probe paths in a diversity of markets. Thereby, cross-over learning is observed, explaining the firms' ability to engage in a diversity of markets and their flexibility to shift between markets. The different probing strategies suggest that there may be archetypes for probe decision making. The cases primarily show a difference in breadth of market segments in the experimental phase and a difference in the degree of focus moving towards the developmental phase. Additionally, two approaches to iterative development are identified. The case data suggests two archetypes for probing:

1. Focused market analysis and probing through early field trials and long paths of iterative developments,
2. Probing in a breadth of markets to specify markets and iterative developments through cross-over learning.

These archetypes illustrate how the process of technology application differs for applying products and subsystems. The differences between these archetypes appear to be explained by the different learning processes for the development of a firm's technology and market insight. Moreover, the differences appear to be explained by a difference in the required approach to market development.

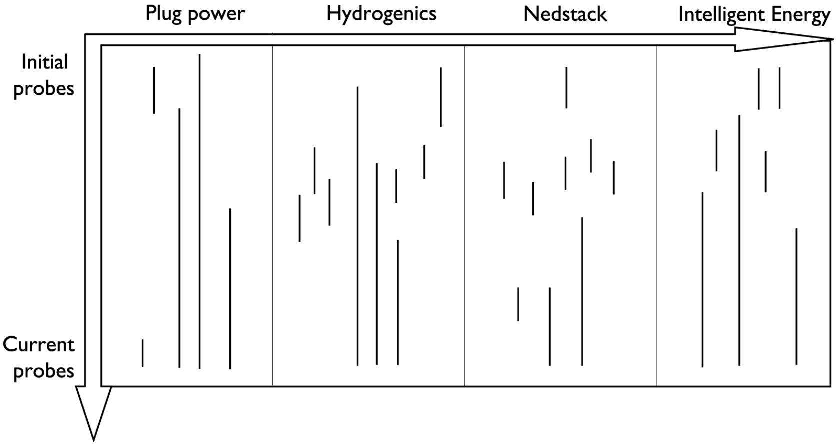

Figure 8.7 Comparison case firms variable path length

8.4 Comparing Probing Strategies

Similar phases of probing and different patterns of probing have been discussed in the previous section. This section will take a closer look at the similarities and differences in these probing patterns and discuss what drives these different patterns. A comparison will be made of probing process details including the technology platforms applied, the types of probes pursued, the number probes realised and the timing of probes. The analysis again refers to the explanatory constructs discussed in section 8.1, including the firm internal and external constructs. In addition, drivers may emerge to enable us to understand what drives the differences in probing processes.

8.4.1 Technology Platforms

The cases have been selected on the basis of variation in technologies applied and breadth of market segments. The technologies applied are represented in a firm's technology platform. The previous section suggests that these differences represent different probing archetypes. This paragraph describes the technology platforms in detail to better understand these archetypes of probing. The technology platforms differ in supply chain position and power range (fig. 8.8).

Plug Power's GenSys and GenCore platforms are stationary products platforms in the range of 5 kW, for business to business end-users. This focused power range is reflected in the firm's focused probing process. By contrast Nedstack applies a FC stack platform available from 2 to 100 kW, modularly applicable to applications up to MWs. In 2005 Nedstack has also presented a system platform with a net rated electrical power of 100 kW. Both stack and system platforms are supplied to OEM customers. This broad power range is reflected in the company's broad probing process. Hydrogenics's first technology platform was based on a 20 kW module, from which the 10 kW module was derived. This 10 kW module was broadly applied and the portfolio of modules was extended to include modules in the power range of approximately 5 to 70 kW nominal power. Intelligent Energy developed a system for automotive applications of 65kW but the power range of the other platforms is lower: between 100 W and 2 kW, a 10 kW system for PSA Peugeot Citroen and a 25 kW system for Boeing. Intelligent Energy's platforms and dedicated systems are developed and applied in partnered developments with customers. What explains these differences in platform technology and power range?

Each case firm has positioned itself in a proprietary power range to address a particular range of market segments. The case firms appear to have strategically positioned themselves with respect to their technological core competences and competitors in the industry. For example, Hydrogenics and Intelligent Energy's technology is most suitable for applications requiring compact design and dynamic operation. Plug power has specialised on stationary systems in the 5 kW power range. However, power range positioning may not be an entirely strategic decision. It can be argued that Hydrogenics was 'forced' into the sub-70 kW range for niche market applications under the GM alliance. Nedstack and Intelligent Energy's broad power range of stacks and systems are developed to serve a variety of prospective customers, apparently a 'technology push approach'. It can also be argued that their broad power range results from the pursuit of opportunities to supply or form partnerships rather than strategic intent.

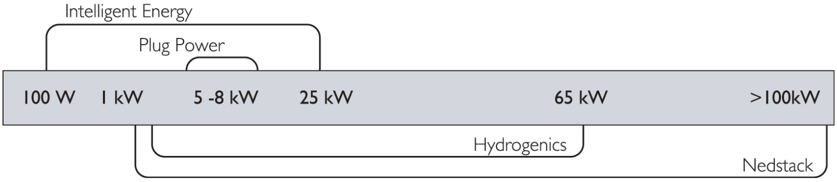

Figure 8.8 Power ranges technology platforms of case firms

In addition to the differences in power range, the firms' technologies vary in supply chain position: product platforms for end users or subsystems for OEM customers. The platforms coincide with the archetypes described in the previous paragraph. End products fall within a product category and are typically developed for a particular market segment. Plug power probed the end product GenCore in a variation of subsegments within the back-up power segment. By contrast, FC subsystems, modules and stacks are not bound to a product category: the platforms can be applied to a variety of markets segments with similar operating requirements. What explains this difference in supply chain positioning?

Plug Power transferred technology from the early GenSys platform to develop the GenCore product. Firm history appears to have influenced this decision: the company was founded with the ambition to produce on-site power products. According to Plug Power, the GenCore product focus was pursued because the company identified a market opportunity that fit their technology. Moreover, this study observes pressure from external investors to realise short term product sales. In contrast to Plug Power, Hydrogenics and Nedstack applied a standardised subsystem to diverse market segments and the companies were founded to serve various markets. The standardised platforms can be explained as a strategy to achieve quantity, to validate production and serve a variety of OEM customers. Moreover, the quantity of standardised systems can be explained as a means of validation to OEM customers. By contrast, Intelligent Energy develops customised systems for customers. Thereby, Intelligent Energy does not target quantity through a standard module but prioritises alignment to customer requirements. This approach can be explained by the firm's strategy of joint development partnerships and licensing agreements. Nevertheless, the case firms express uncertainty about their supply chain strategies. Hydrogenics suggests that in some markets, such as the AC back-up power market, they may approach endcustomers directly in order not to rely on the pace of OEM adoption. Intelligent Energy is further developing the ENV bike internally, expecting to generate more value from licensing the end product than the subsystem alone.

The technology platforms appear to determine the degree of cross-over learning. The technology platforms appear necessary for technology development through cross-over learning by gaining and transfering operational data between markets. Intelligent Energy's experiences suggest that technical cross-over learning between market segments becomes less likely when several platforms are developed at the same time, for example, one platform may develop faster than another. Intelligent Energy, Hydrogenics and Nedstack expressed the need to focus on one technology platform to further develop this platform. Moreover, limitations to the applicability of technology platforms in other market segments are observed: stationary generation and automotive power, for example, have contrasting operating requirements. These limitations are likely to influence the breadth of the firms' probing processes. Nevertheless, in the experimental phase, probe applications by Hydrogenics and Nedstack suggest that their standardised modules and stacks could be applied to both markets, despite limited suitability. Apparently, limitations were acceptable in this phase. By contrast, the platforms appear to require more dedicated designs in the transition towards development.

In the transition to a phase of development, the opposite of standardisation takes place: the case firms develop platforms for specific markets. This trend coincides with optimization to meet specific customer requirements. Plug Power launched different Gencore versions for different subsegments, developing variations of technological specifications. Hydrogenics launched two modules specified for the material handling and back-up market. It can be argued that the development of specialised modules is necessary to meet requirements of customers beyond the early adopters markets. In the case of end product platforms the design of versions to meet specific customer requirements appears to be necessary at an earlier stage than in the case of subsystem platforms, explaining the focused archetype of probing.

8.4.2 Types of Probes

The observed differences in patterns of probing are likely to involve different types of probes. This paragraph analyses the different types of probes involved. The case study data suggests that the case firms pursued similar types of initial probes. The subsequent experimental probes show various types; what explains the similarities and differences in probe types? The initial probes in each case firm are characterised by a small number of prototypes to demonstrate functionality and technical achievement. For example, Plug Power and Nedstack presented their initial probes as a demonstration of their R&D competences. These 'proof of concept' probes were subsidised by government grants for R&D. The initial probes presented by Hydrogenics and Intelligent Energy were prototypes developed for early adopters and demonstrations to showcase their initial platforms. Apparently, initial probes can, at least partly, be explained as public relation efforts demonstrate and convince external actors such as investors and early customers.

In the subsequent period of probing the case firms engaged in various types of probe applications. In contrast to the other case firms, Plug Power began by building manufacturing capacity instead of generating customer interest to validate manufacturing investments. As Van der Heyden in section 7.1, *"we did it the other way around"*. Plug Power's main probes in the experimental phase were field trials with a pre-commercial product platform to generate feedback and operational data. The field trials were primarily conducted with several units and subsequently on scale. This approach provides more information on the focused archetype of probing. The approach also reflects Plug Power's ambition to address commercial markets as soon as possible. Plug Power chose to focus the allocation of its resources. It can be argued that Plug Power's approach requires considerable financial resources. Therefore, Plug Power's access financial resources may explain the firm's decision to pursue this type of experimental probing.

Hydrogenics' experimental probes are characterised by a different type of probe. In contrast to Plug Power's focused field trials, Hydrogenics applied the integrated HyPM module to a wide range of 'technology demonstrators'. With this approach the company generated operational data and market feedback from a diversity of market segments. Hydrogenics explains the twofold objective of this type of probe: to identify compelling value propositions and marketing to OEM customers. The technology demonstrator strategy represents the concept of probing in practice, i.e. probing in a variation of market segments to learn about and select markets for development. Hydrogenics appears to prioritise market development and the formation of partnerships above early product development. In comparison, Plug Power's field trial strategy is more similar to a classic product development process. The company departs form a perception of customer needs and probes with a variety of product variations and subsegments, iteratively developing the product platforms to meet specific customer requirements. These observations further clarify the archetypes of probing: focused probing in iterative developments to align to specific customer requirements and a breadth of probes for market development and technology development through cross-over learning.

Similar to Hydrogenics, Nedstack applied standardised stacks in a diversity of market segments. However, Nedstack's demonstrations and development projects, partly funded by government subsidies and typically conducted in consortia, illustrate a different type of probe. This strategy appears to be characterised as 'probing with the opportunities that came along'. Among these projects, the PEM power plant probe is an exception, this probe became Nedstack's proprietary pilot to apply a large number standardised stacks for reliability testing. This type of probe can be explained by the necessity to validate and convince OEM customers. Thereby, Plug Power and Nedstack target a different type of volume: scaled field trials with multiple platform products to validate a product versus a stack platform applied on scale in a single application to validate stacks.

Intelligent Energy probes are characterised by yet a different type of probe: to showcase their technology. The company's business model explains why the company focused on developing a showcase for its technology. With this probe, Intelligent Energy aimed to demonstrate the status of its technology, catch people's attention and explain the technology potential to customers. The ENV probe has provided Intelligent Energy with sizable publicity and credibility. In the case of Intelligent Energy, the showcase probe was instrumental in developing partnerships. Similar to Hydrogenics, Intelligent Energy's probes were not based on economic value propositions, but on a marketing and market development rationale. The case firms appear to have probed in a breadth of markets to realise probes for various purposes including: operational data, market development, reliability testing, initial revenue, customer education, partnership formation and demonstration. Differences between the types of probes pursued appear to be a matter of priority setting. The variety of different probes is most apparent in the experimental phase of probing and is primarily observed in the case of OEM customers. A firm's position with respect to customers and the familiarity of customers with the firm and its technology appear to influence the variable patterns of probing.

8.4.3 The Number of Units

A closer look at the patterns of probing requires a comparison of the number of units realised in the probing processes. The numbers of units and probe applications realised vary considerably between the case firms. Plug Power and Hydrogenics have engaged in more probe applications than Nedstack and Intelligent Energy. What explains this difference in the number of probes realised? The difference in financial resources, discussed in paragraph 8.1.2 suggests that this difference is likely to be explained by firm size: Plug Power and Hydrogenics are significantly larger than Nedstack and Intelligent Energy in terms of personnel and financial resources. With 300 employees, a firm can address more probe applications than with 40 employees. Considering the allocation of limited resources to time consuming and costly probe applications, the number of probe applications a firm can realise is likely to be directly related to the resources available to the firm. Regarding firm internal resources, the larger the firm, the more personnel and resources available to realise probe applications. It can also be argued that larger firms have more legitimacy in terms of 'brand recognition' than smaller firms and therefore, perhaps, more access to external resources. From this perspective, the number of probes conducted is not entirely a decision variable of a firm.

Plug Power has conducted probes with a larger number of units than Hydrogenics. Through Plug Power's focused field trial strategy more than 600 units were applied. At an early stage, Plug Power invested in a manufacturing facility to build a pre-commercial product line for probe applications. By contrast, Hydrogenics has waited for customer orders to validate building manufacturing facility. Apparently, Hydrogenics and Plug Power allocated their resources differently. Whilst Plug Power allocated resources from initial public offerings on building manufacturing capacity for stationary power products, Hydrogenics spread its IPO resources over two business units: commercial sales of the test and diagnostic systems and development of PEM fuel cell modules. Additionally, the companies are currently of a similar size, however, the number of employees at the end of the year 2000 shows a very different ratio: Plug Power with 500 employees compared to Hydrogenics with 74 employees. Besides, Hydrogenics' employees were spread over two business units. Apparently, the variable number of probes can at least partly, be explained by the difference in growth rate and size of the companies, in terms of resources to allocate, and the commercialisation expectations conveyed to investors. Probing with a large number of units in a single market segment appears to characterise focused probing towards product development.

8.4.4 The Timing

In the previous paragraphs, the probing processes have been aligned to compare patterns of probing. This paragraph will compare the probing processes in absolute time to observe differences in timing of the patterns observed. Figure 8.9 shows the probing process of the four case firms, enabling a comparison of timing, illustrating the differences in timing. What explains the differences in timing? The timing of initial probe decisions, the timing of divergence through experimental probes and the timing of focus for development are discussed.

Although a similar phase of explorative probes is observed, the case firms began probing in different years. Plug Power realised initial demonstrations at least two years prior to the other case firms. On the one hand, funds and partnership opportunities were available for probing. On the other hand, Plug Power's initial public offerings directly followed the company's initial demonstrations. Apparently, the initial probes played a role in demonstrating the firm's potential and convincing investors. The Hydrogenics case similarly suggests that investors influenced the timing of initial probes. However, in contrast to Plug Power, the timing of initial probes is 3 years later and after the initial public offering. The case study suggests that in the first five years after founding, Hydrogenics focused on its FC test business and was still in the process of developing its PEMFC competences during its initial public offering. Nevertheless, the company experienced pressure from investors to move the R&D in PEMFC to market applications during this period. Hydrogenics also explains that the company waited for early adopter customers to engage in premium niche markets. Therefore, in comparison, Plug Power used initial probes to grow fast and position itself as a FC manufacturer for short term markets whilst Hydrogenics positioned itself as a FC test and diagnostic business and used initial probes to move its R&D in PEMFCs to premium niche markets.

Similar to Hydrogenics, Nedstack did not engage in probes until several years after founding. Nedstack was run as a R&D company and did not move towards the development of applications in the initial years. In the period that Plug Power presented probes, Nedstack did not invest in early demonstrations. Nedstack explains that the company was able to wait for applications to emerge, because it did not need to invest in early demonstrations to attract investors. The subsidised projects in subsequent years may suggest that the limited availability of funds for demonstrations additionally explains the relatively late pursuit of initial probes. Intelligent Energy was founded 3-5 years later than the other firms, explaining why the company was relatively 'late' to present initial probes. In comparison to the founding years of other FC firms, Intelligent Energy was a newcomer in a rapidly growing industry[7]. With the technology inherited from APS, Intelligent Energy demonstrated its proprietary technology in portable power prototypes shortly after founding. The initial probes were presented at tradeshows and conferences and were primarily realised for demonstration and public relations.

Differences in the timing of initial probes appear to be related to differences in firm objectives, growth ambitions, investor pressure and the availability of external resources. Whilst Plug Power was run as a company targeting near term commercial markets, Nedstack was run as an R&D company targeting large markets, waiting for applications to emerge. Hydrogenics waited to realise initial probes for premium markets, whilst Intelligent Energy chose to showcase its technology directly after founding. It is observed that initial probes are either pursued with the objective of showcasing the firm's technology or delayed to further develop the firm's technology. The timing of initial probes appears to be driven by investors and public relation efforts and largely depends on the availability of resources from government grants or early customers.

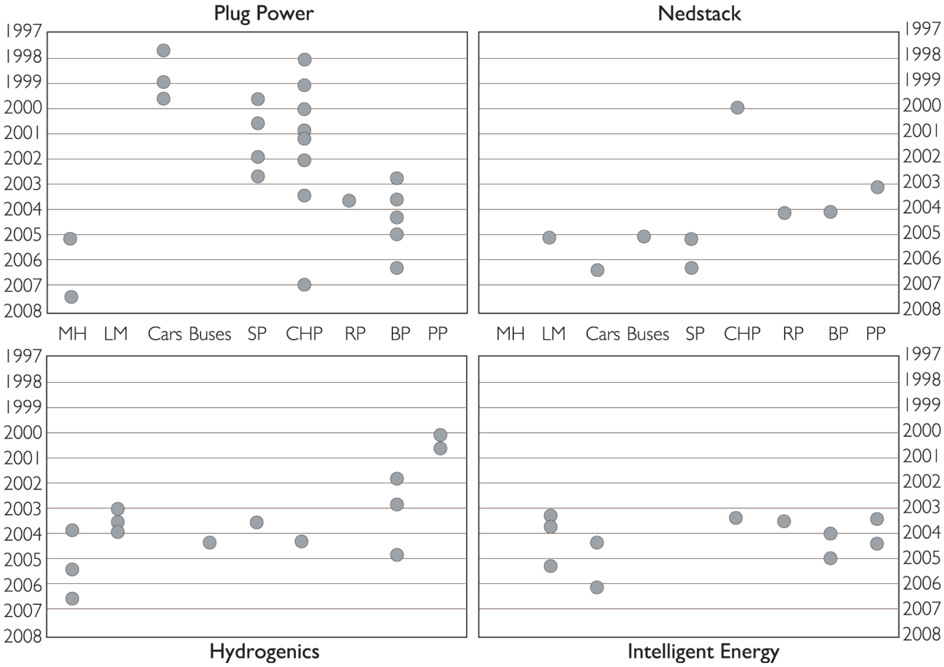

Figure 8.9 Comparison of timing in the case firms' probing processes. Abreviations stade for, MH: Material Handling, LM: Light Mobility, SP: Stationary Power , CHP: Combined Heat and Power, RP: Remote Power, BP: Back-up Power and PP: Portable Power

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[7] *The industry evolution in paragraph 2.5.2 suggests that after the founding of Ballard in 1989, various independent FC firms emerged around 1995*

Timing of Divergence: Experimental Probing

The timing of the shift from initial probes in an explorative phase to an experimental phase of probing again differs between Plug Power and the other case firms. Plug Power modified its strategy and diverged from a residential generator to applications of the GenSys, Gencore and Gensite between 2000 and 2003. After Plug Power's early initial probes, the company was also early to moderate expectations and shift to new markets. With milestones set by the IPOs, the company targeted the development of commercial products for short term profit. The other case firms did not begin their divergent phase until after 2003. The launch of the HyPM module in 2003 marks the divergent phase of Hydrogenics' experimental probe applications. Similarly, Nedstack began to apply its stack platform to a diversity of applications around 2003. Intelligent Energy's diverse probe applications followed shortly after the presentation of its initial probes in 2003. Thus, Plug Power's phases of probing appear to be a few years ahead of the other case firms. The company was early to build manufacturing capacity and was early to gain experience in field trials. In comparison to the case firms, Plug Power's historic ambitions and investors appear to have pushed the company towards the identification and development of near term markets at a faster pace. These constructs appear to explain Plug Power's focused pattern of probing[8].

Timing of Convergence: Towards Developmental Probing

Plug Power was also the first to announce the commercial roll out of their product: the Gencore in 2004. Around 2005, Hydrogenics focused developments on the commercial sales of HyPM modules for two markets: material handling and back-up power. Nedstack and Intelligent Energy also show more focus after 2005, however, their developments target the generation of reliability data and partnership formation respectively. Nedstack and Intelligent Energy appear to be in the experimental phase transitioning towards development whilst Plug Power and Hydrogenics appear to have moved into a developmental phase. This difference is supported by the relative number of repeat orders. For Plug Power and Hydrogenic, sizable repeat orders have reduced the uncertainty of market adoption to a level that validates investments and focused development. Nedstack has received initial repeat orders, but is in the process of validating its technology to form stronger supplier-customer relationships. Intelligent Energy is also in the process of forming and strengthening partnerships to focus developments. The difference in timing may be explained by the differences in the firms' level of probe experience to validate their technologies. Also, end users and OEM customers appear to require a different process of convincing. These observations suggest that a firm's level of customer familiarity and trust influences the timing of probing towards development.

8.4.5 Conclusions on the Comparison of Probing Processes

The four case firms were selected on the basis of variance in probing strategy. The previous paragraphs took a closer look at the differences in their probing processes including the technology platforms, the types of probes, the number of probes realised and the timing. The explanatory constructs have been addressed to better understand, what explains these differences?

The technology platforms have in common that they enable firms to realise early applications and facilitate technical learning by focusing technological developments. The case firms have developed different technology platforms and this difference is reflected in the focus and breadth of their probing processes, i) a large number of focused probes are realised through scaled field trials with a product platform, ii) a breadth of market segments is pursued through module platforms and stack platforms and ii) various platforms for customised system designs. The application diversity of these platforms is variable, determining a firm's flexibility to engage in new market segments and abort prior paths. Platform decisions are a matter of strategic positioning with respect to customers. These decisions appear to be driven by i) firm history and ii) experience gained in initial probes. The firms show differences in their inherited ambitions and haste towards market applications, at least partly explaining the pursuit of end products or subsystems. Additionally, initial probes enabled the selection of a technological focus and ideas on how to approach

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[8] In comparison to Ballard, both companies had a few hundred employees around the year 2000 and both companies shifted to near term markets such as back-up power in the same period. In 2002, Ballard introduced the 1kW Airgen, a FC generator uninterruptible power.

early customers. Technology platform decisions appear to be a matter of strategy, on which technology to provide and how to reach customers.

Throughout the probing process, the case firms pursued various types of probes. Initial probes appear to be conducted primarily for PR and demonstration purposes. This type of probe can be explained by the firms' lack of legitimacy and customer unfamiliarity with the firms and their technology. By contrast, a subsequent period shows a large variation of probe types: field trials with a product platform, technology demonstrators, customised systems, demonstration projects and showcase products. This diversity of probe types is reflected in the different probing strategies pursued in this period. The probes in this period appear to be driven by two constructs: i) the level of a firm's value propositions and ii) the level of customer familiarity. Experimental probes are conducted to identify and develop compelling value propositions for a firm's technology. In addition, experimental probes are conducted for market development. The case studies suggest that probes are of central importance in generating awareness, educating customers and validating the technology in this phase of probing. Consequently, the heterogeneity in the probing processes can at least partly be explained as a variable effort to demonstrate the technology and educate customers. Thereby, convincing OEM customers appears to require particular effort for demonstrations, trials and education. Therefore, customer unfamiliarity appears to explain the breadth of probes pursued. Moreover, considering the various types of probes in this period, the heterogeneous strategies may be explained by differences in priority setting. Firms may choose to pursue probes for short term revenue, partnership opportunities, market development, validation or technical learning. Different probing patterns are, for example, observed for the pursuit of diverse short term projects funded by customers and subsidies or focused developments with partnerships in long probe paths.

The firms appear to go through similar phases of probing, however many differences are observed in the timing of these phases. The case study data suggests that primarily initial probe decisions differ. Some choose to probe immediately after founding, whilst other wait for early customers or applications to emerge. Partly, a firm's ability to realise initial probes depends on resource availability, however, this does not explain why firms with access to resources choose to wait. More important are the differences between the firms' haste to realise demonstrations. The firms appear to experience a variable pressure and need to demonstrate their technology in relation to their ambitions for firm growth and development.

The pursuit of early initial probes appears to give a head start in terms of probe experience and legitimacy. However, the case data suggest that this advantage may be limited because: i) probe experience and legitimacy is primarily gained in experimental probes and ii) the emergence of market demand in the FC industry takes time and appears to be largely irrespective of a firm's initial probes. Nevertheless, it is noteworthy that the larger case firms have realised more probes and that this level of experience appears to be related to a difference in timing: the smaller firms are taking longer than the larger firms to make the transition to a developmental phase. Apparently, the quantity of probe experience is instrumental in convincing customers.

In conclusion, the similarities observed in the firm's probing processes appear to be driven by industry expectations and the level of customer familiarity with the technology in general. Differences between the case firms' probing processes, in terms of breadth and path length, are largely driven by firm internal priority setting. Decisions appear to be both strategic and opportunistic. On the one hand, firms pursue probes to identify and develop compelling value propositions or form partnerships; on the other hand, firms show opportunistic behaviour in the pursuit of probe applications. Finally, differences between the firms in terms of timing also appear to be driven by the level of customer familiarity and trust with the individual firm.

8.5 Explaining Probing Processes

The case studies show similar patterns as well as differences in the selection of probes over time. Various constructs have been analysed that may explain these similarities and differences. Chapter 6 presented propositions to predict probe behaviour and the dominance of constructs in explaining probe decisions. The previous analyses will be brought together to test these propositions. Additionally, new findings and propositions are derived from the case study data. The analysis in the following paragraph addresses how and why firms have selected probes and why probe paths were pursued or aborted. First, the propositions are tested on the basis of the case study data. Subsequently, the questions on probe decision making, posed in paragraph 6.6.2 are addressed. Using the case study data as a point of departure, new propositions are proposed.

8.5.1 Testing the Propositions

In this paragraph the propositions proposed in paragraph 6.7.1 are analysed and tested on the basis of the case study data. The propositions are separately discussed to address the following topics:

1. The selection of initial probes (P1).
2. The consequence of initial probes (P2).
3. The necessity of experimental probing (P3).
4. The continuation of probe paths (P4).
5. The selection of probes for development (P5).

The Selection of Initial Probes

In the context of uncertainty and with limited experience in applications, how do firms select initial probes? The conceptual model suggests that although a firm's history and technological skills influence the selection of initial probes, industry expectations of market adoption are expected to dominate.

P1. Industry expectations are more important than firm internal factors in explaining the selection of initial probes

This proposition suggests that in a certain period, firms will select similar markets by following expectations of the industry. The case firms selected initial probes more or less inline with industry expectations at their time of initial probe engagement. The industry moved from a period of expectations of large scale market adoption to a focus on niche market development. Consistent with these periods, Plug Power and Nedstack engaged in probes targeting large scale markets whilst Intelligent Energy and Hydrogenics targeted probes in niche markets several years later. Plug Power engaged in automotive probes before 2000. Both Plug Power and Nedstack engaged in the residential CHP market before and during the year 2000. These case firms explain that the residential CHP market was generally believed to be the first large market before the automotive market. Industry expectations of market adoption, rather than firm internal assessments, appear to explain the firms' pursuit of these initial probes.

After 2000, industry expectations for large scale adoption were moderated and shifted towards expectations for niche market applications. In this period, Intelligent Energy presented its portable power probes, in line with the niche market expectations of the FC industry. In the same period, Plug Power and Nedstack moderated their expectations for residential CHP and began to address niche markets, despite their ambition to target large scale markets. In line with the proposition, industry expectations appear to have dominated probe decisions above firm internal factors. Hydrogenics' initial probes may oppose this proposition. The company was relatively early to engage in niche market applications compared to the other case firms and compared to industry expectations. The firm's history and partnership opportunities appear to have influenced this decision. On the one hand, it can be argued that as a new start up in the industry, Hydrogenics strategically positioned itself in premium niche markets because experienced FC developers were already targeting large markets. On the other hand, Hydrogenic's relatively early back-up power probe for telecom is likely to be explained by GMs experience in niche markets. Thereby, opportunities to form partnerships with established companies appear to have dominated the influence of industry expectations in the selection of Hydrogenics' initial probes.

In conclusion, the case firms largely confirm that initial probe decisions follow expectations of the industry at the time. The construct explains the pursuit of similar market segments in the same periods. An exception is observed where the potential to form strategic alliances dominate industry expectations. Nevertheless, in all cases, industry expectations appear to influence the scope of markets the firms considered to select for their initial probes.

Consequence of Initial Probes

The experience from initial probes is expected to influence subsequent probe decisions. How does experience from initial probes influence subsequent probe decisions? The following proposition was proposed:

P2 A low value proposition, resulting from the evaluation of initial market probes, will cause firms to search for alternative market applications

With experience gained in initial probes, the firms were able to assess the fit between their technology and the market pursued. This feedback provided a reality check of the time to adoption. Initial expectations were moderated, influencing the decisions to engage in subsequent markets. Apparently it was difficult to make the right decisions in an early phase of technology application. In each case firm these moderated expectations impacted subsequent probe decisions and, in line with the proposition, the case firms show a similar behaviour of shifting to alternative market segments. Plug Power and Nedstack moderated their expectations for large scale markets and shifted to niche market applications in line with the moderation of industry expectations, described above. Initial probes appear to have provided the firms with market insight to evaluate their value propositions. Similarly, Intelligent Energy and Hydrogenics show a divergence to new market segments following the evaluation of their initial probes. In contrast to the other case firms, their 'reality check' can be explained by modified expectations of niche market adoption: customers were not readily following the early adopters markets. This discrepancy appears to be similar to Moore's (2002) 'chasm', a gap between early adopters and subsequent early majority adopters. The firms' ability to evaluate their value propositions, resulting from the evaluation of initial markets, appears to have driven their subsequent search for alternative niche markets.

The firm's perception of their value propositions, resulting from the assessment of initial probe outcomes, appears to have driven subsequent experimental behaviour in the case firms. The firm's value propositions were low in terms of their ability to identify niche markets, predict market adoption and align to customer requirements. Therefore, on the basis of the case study data, the proposition holds: the case study shows that the outcomes of initial probes motivated a process of learning by discovery.

The Necessity of Probing Alternatives

Firms were subsequently challenged to identify and develop market opportunities. Theory suggests that under high degrees of uncertainty, classic market research methods have limited value. Instead, market competences are gained through experimentation and probing. This study has questioned the necessity of probing alternatives to identify and develop a firm's value propositions. Probing alternatives has been observed as a successful management practice for new technologies. This research, therefore, proposed that:

P3 Probing alternatives is a necessary condition to develop a firm's value propositions

This proposition assumes that firms identify value propositions by learning from probes. All the case firms probed alternatives, to some degree. Hydrogenics, Nedstack and Intelligent Energy developed market insight and educated customers through a breadth of experimental probes. Hydrogenics' technology demonstrator strategy particularly illustrates probing as a vehicle for learning to identify and develop the firm's value propositions. Hydrogenics engaged in diverse market segments in order to: i) specify niche markets with compelling value propositions and ii) stimulate market development by demonstrating the technology to a wide range of potential customers. In line with the innovation literature on market learning, it can be argued that stimulating customer interest and educating stakeholders is necessary to receive reliable market feedback for shaping a firm's value proposition. By contrast, Plug Power's early field trials in a select number of market segments appear to contradict proposition three. However, Plug Power also probed alternatives, although less broad and largely within market segments. Apparently, the divergent experimental probes were necessary to generate feedback from customers and develop the firms' value propositions.

In contrast to proposition three, the case data suggests that market insight is not only developed through probes. Market information is also gained from activities other than 'probing'. For example, Plug Power conducted market assessments prior to probing, contributing to the identification of specific market opportunities. Plug Power explains that by talking to potential customers, it was able to specify its value propositions. Thereby, the market assessments appear to have reduced the need for probing alternatives. Moreover, partnerships appear to play a role in the identification and development of a firm's value propositions. For example, in the case of Hydrogenics, its partnership with John Deere shaped the firm's value proposition in the light mobility market. Furthermore, Nedstack and Intelligent Energy also conducted various probes for the purpose of partnership formation, initial sales or subsidise. Therefore, probing in a breadth of market segments cannot only be explained by the search for a firm's value propositions. These observations suggest that there is a limit to the breadth of probing, necessary to develop a firm's value propositions. Additionally, these observations suggest that an 'unnecessary' breadth of alternative probes may be avoided through complementary means of gaining market insight.

The necessity of probing alternatives has been compared to direct market engagement. It can furthermore be questioned if the firms could have waited until market demand emerged instead of probing alternatives. The case data suggests that firms develop their value propositions through probing alternatives, as their technology develops and market experience is gained. These value propositions appear to influence a firm's strategic position and ability to identify specific partners and customers. In conclusion, the cases suggest that a phase of learning by discovery and market development is necessary in order to develop and focus their value propositions. Nevertheless, the 'effective breadth of probing' in terms of learning is limited and is likely to require complementary sources of learning.

The Continuation of Probe Paths

The case firms were faced with decisions on which probes to continue and which to abort. What explains the continuation of probe paths? It was proposed that:

P4. The availability of external resources dominates the decision to continue probes for mid and long-term applications

Market segments are aborted or postponed when market adoption proves to be further away than expected. Long-term markets appear to be sustained by government funds and strategic partnerships. Therefore, the case data suggests that decisions to pursue longer term markets depends on the availability of such external resources. The continuity of Plug Power's probe paths appears to be explained by long-term partnerships and continuous government support. The LIPA partnership continued to provide a test bed for Plug Power's product platforms and although the GenSys path is taking longer than anticipated, the government and military continue to support field trials. Similarly, Intelligent Energy is involved in long-term markets under customer contracts and the company's long probe paths can be explained by these partnerships. By contrast, Nedstack's relatively short probe paths appear to be related to the short term nature of government subsidies at the time. Similarly, the majority of Intelligent Energy's short probe paths are related to subsidised projects of limited duration. The continuation of Nedstack's PEM power plant project with continued and successive support from subsidies emphasises the influences of subsidy duration of probe path continuation.

Despite the postponed expectations for widespread market adoption in residential micro CHP, Nedstack and Plug Power continued developments in this market. Thereby, Plug Power continues in the Vaillant partnership with European R&D funding. Nedstack continues to be involved in CHP probes and developments to serve OEM customers in this market. Most of the continuous developments at Nedstack for longer term markets are 'hidden' behind supply chain relationships, to supply a variety of OEM customers with FC stacks. Similarly Hydrogenics continues to supply to customers in mid-term markets such as the specialty vehicle manufacturer John Deere. Additionally, Hydrogenics continues to supply to demonstration projects. These markets are not cost-effective in the short term and their continuation depends on government support in creating 'protective niches' and stimulating local demand through regulatory support.

In conclusion, proposition 4 appears to hold. The decision to continue probes that are not likely to be cost-effective in the short term depends on sources of external funding from strategic partnerships or government funds. This proposition is related to the second proposition, predicting the behaviour of firms in response to their low value proposition. A combination of the propositions implies that

In response to the evaluation of a low value proposition, firms will search for alternative markets and abort initial probe paths unless external sources of funding are available to continue in this market segment.

The Selection of Probes for Development

As the firms' probing processes proceed, a select number of probes are continued for development. How do firms select market applications for development? It can be argued that firms probe and learn towards a unique value proposition in a specific market segment. Nevertheless, it was proposed that the emergence of market demand is more influential and that mimicking behaviour would dominate the experience a firm has gained in prior probe applications:

P5 The emergence of market demand is more important than probe experience in explaining the selection of probes for development.

The short term market opportunity for critical back-up power has become widely recognised as a first commercial niche market. This is the first market where repeat orders have been made and the cost-effectiveness as well as the potential revenue is calculable. Various firms in the FC industry are targeting this market[9]. The case firms have also become involved in the back-up power market. Hydrogenics, Intelligent Energy and Nedstack have engaged in the back-up power market with limited prior probe experience in this market segment. Hydrogenics re-engaged in the back-up power in response to customer orders. By contrast, Plug Power has extensive probing experience in back-up power. However, the company has limited experience in the material handling market, whilst this market is also expected to emerge in the short term. Apparently in response to this immanent opportunity, Plug Power has acquired two FC developers in material handling. Plug Power and Hydrogenics appear to be mimicking each other. All the case firms appear to show some degree of mimicking behaviour in response to the emergence of market demand, irrespective of their probing histories. This behaviour is not surprising considering that finally opportunities are emerging for commercial sales and revenue. Therefore, the proposition appears to hold: the emergence of market demand dominates the case firm's experience and competences gained in prior probes.

An argument opposing the dominance of market demand is the apparent role of a firm's probe experience and unique value propositions in the selection of specific subsegments within the emergent markets. The case firms appear to have developed 'unique' technological competences and identified specific customers through the experience gained in probes. This technological competence also influences a firm's ability to shift to emergent markets. Therefore, although firms are likely to change plans and respond to market demand, their probe experience appears to be highly relevant in their ability to shift.

[9] For example, Ballard, Electro Power Systems, Relion and UTC

The arguments from the case study, comparison supporting and opposing the propositions, are summarised in table 8.3.

Table 8.3 Testing the propositions

Propositions	Support	Opposing arguments
P1. Industry expectations are more important than firm internal factors in explaining the selection of initial probes	Largely confirmed by market segment selection at time of industry expectations by Plug Power, Nedstack and Intelligent Energy	Hydrogenics was relatively early to probe in niche markets with early adopters. Partnership opportunities also appear to influence initial probe decision making.
P2. A low value proposition, resulting from the evaluation of initial market probes, will cause firms to search for alternative market applications.	All case firms moderated market expectations and changed strategy to search for niche markets.	Hydrogenic's and Intelligent Energy began in niche markets. The search for niche markets appears to be related to the low level of customer familiarity.
P3. Probing alternatives is a necessary condition to develop a firm's value propositions	Largely confirmed by Hydrogenics' technology demonstrators and Nedstack's diversity of probes. Plug Power probed alternatives within stationary The cases suggest that probing was also necessary for market development.	Plug Power's early focus. Value propositions also identified through other means of market learning. There appears to be a limit to the necessary breadth. Probing is also a 'survival' necessity
P4 The availability of external resources dominates firm decisions to continue probes for mid and long-term applications	Confirmed Plug Power and Intelligent Energy's dependence on partnerships for longer term developments & regulatory support for probes Nedstack and Hydrogenics	Plug Power and Nedstack suggest that probe paths are also continued with limited investment, to keep options open.
P5. The emergence of market demand is more important than probe experience in explaining the selection of probes for development.	Each case firm pursues the back-up power market for telecom, and 3 in forklift, also without prior probes in this market.	In each of the cases probe experience is determinant for strategic positioning and provides unique value propositions.

8.5.2 Deriving New Propositions

The previous paragraph tested the propositions stated in chapter 6. This paragraph sets out to induct new findings and propositions from the case study data. The questions on probe decision making, posed in paragraph 6.7.2 guide the analysis:

- The timing of initial probes: What explains the timing of initial probes? (RQ 3a)
- The breadth of experimental probes: What explains a firm's breadth of market segments? (RQ 3b)
- The transition from variation to selection: What factors determine when a firm stops probing variations and focuses on development? (RQ 3c)
- Shifts to new market segments: What factors explain decisions to shift to new market segments without prior probe experience? (RQ 3d)

The Timing of Initial Probes

The cross-case analysis suggests that the selection of initial probes can largely be explained by industry expectations. But what explains the difference in timing of initial probes? The conceptual model suggests that several factors may explain the difference in timing including competence level, firm history, the availability of external resources and customer unfamiliarity. The case study data is analysed to determine which factors are most influential in explaining the timing of initial probes.

The case study data suggests that initial probes are primarily conducted to showcase and demonstrate the firm's technology. However, differences in the timing of initial probes can be observed relative to the year of founding and IPO. Although Plug Power, Nedstack and Hydrogenics were founded in the same year, Plug Power developed probes for demonstrations two years prior to the other case firms. Plug Power's initial probes were not commercially sensible: instead they were used to showcase and prove their technology prior to the firm's IPO In this period, Plug Power was a relatively large company, run as a company targeting profitable short term commercial markets. Intelligent Energy was founded as a spin-off to commercialise prior R&D activities and demonstrated this technology soon after founding. In contrast to Plug Power, Nedstack and Hydrogenics were small companies with PEMFCs in R&D, waiting for applications to emerge. Thus, although initial probes where conducted for a similar purpose, there appears to be a difference in the pressure to demonstrate a firm's technology, relative to the firm's growth phase and haste to move from R&D to market applications.

Shareholders appear to have influenced Plug Power's haste to move from R&D to applications. Founded to commercialize its proprietary technology, Intelligent Energy also felt pressure from investors to demonstrate soon after founding. With a relatively late entrance, Intelligent Energy appears to have used these probes to establish a position in the rapidly growing FC industry. This explanation is a matter of establishing a firm's legitimacy. In contrast to Plug Power and Intelligent Energy, Hydrogenics established legitimacy through its FC test and diagnostic business. This may explain why the company was relatively late to realise initial probes. The timing of Hydrogenics' initial probes can furthermore be explained by the pressure experienced to realise applications after the company's IPO. By contrast, Nedstack argues that it was able to continue R&D because investors did not pressure the company to demonstrate pre-mature versions of its technology. However, it can also be argued that Nedstack did not conduct early probes because there were limited funds available to realise such demonstrations. The availability of government funds and grants to realise PEMFC demonstrations in the US was years ahead of Europe at the time. In the case of Plug Power, for example, subsidised programmes, grants and early government related customers were instrumental in realising the initial demonstrations before the year 2000. However, this does not explain the relatively late entry of the other North American case firm, Hydrogenics.

If initial probe decisions were primarily determined by the availability of external resources, it can be argued that initial probe timing would be more opportunistic than strategically planned. However, the case firms suggest that initial probe applications were primarily instrumental in building firm legitimacy and customer familiarity to access external resources, and convince investors and early customers. Based on the observations of the case study firms, the following proposition is stated:

New P6 Investor pressures combined with pubic relations are the dominant reasons to engage in initial probes

Each case firm expresses the necessity to develop legitimacy and credibility through probe applications. Yet, the case firms show variable haste towards demonstrate their technology. Some firms conduct initial probes long before their technology was capable of meeting market requirements, to present early demonstrations. Other firms waited until their value proposition 'made sense' and chose to initial probes through partnerships. This proposition addresses the issue of order of entry and entry strategies (e.g. Lambkin 1988, Lieberman and Montgomery 1988) and raises new questions such as, should a firm start probing as a pioneer, an early follower or late entrant?

The Breadth of Experimental Probes

The case firms were selected on the basis of variance in their breadth of probing. The cross-case comparison of probing patterns and strategies shows differences in the breadth throughout the firms' probing processes. This paragraph addresses what causes this variance in breadth and subsequently discusses if there is a necessary or effective breadth of probing.

The case firms show the largest variance in the breadth of market segment engagements period characterised as an experimental phase. Although Plug Power and Nedstack started in similar markets, they subsequently followed completely different probing strategies in terms of breadth and focus. Where Plug Power focused on the development of product platforms and a select number of niche markets, Nedstack developed a FC stack platform to address a diversity of niche markets. Similarly, Hydrogenics and Intelligent Energy started in similar markets but then took on different experimental probe strategies. Where Hydrogenics focused its technological developments on the HyPM to address a wide range of markets, Intelligent Energy's probe applications were based on multiple technology platforms for a select number of customers. What explains this difference in breadth? The experimental probing strategies appear to be related to a firm's strategic position with respect to their technological competences and customers.

The process of probing with subsystems for OEM customers appears to require more breadth than probing products for end customers. Where Plug Power's end products are applicable to a limited number of market segments, the Hydrogenics module is applicable to a wide range of markets. Where Plug Power is focused to identify and align to specific end-user requirements, the supply to OEM customers appears to require a different type of customer learning. Hydrogenics and Nedstack have used the diversity of probes to identify, educate and convince a wide range of OEM customers. A diversity of experimental probes is conducted on the one hand, to identify specific niche market opportunities and OEM customers and on the other hand, to stimulate market demand and educate customers. The case firms suggest that it requires considerable effort to educate OEM customers and convince them to replace their incumbent energy solution with FC technology. This observation is consistent with literature describing the resistance of established companies to radical change (e.g. Christensen 1997). Similar to recommendations from high technology marketing literature (Shanklin and Ryan 1987), Hydrogenics and Nedstack have supplied stacks and systems to OEM customer to let them try out and learn about the technology. In contrast to market development through a breadth of probes, Intelligent Energy has focused on a single probe application to showcase, demonstrate and explain its technology. This approach is explained by the firm's business model, the company sought an interactive and effective way to explain the technology and attract a diversity of potential customers for partnering.

Probing with products and subsystems additionally differs in the process of technology development. Section 8.3 describes how Plug Power developed the GenCore in linear probe paths whilst Hydrogenic and Nedstack developed their platforms through technical cross-over learning from a breadth of probes. In these cases, breadth is explained as a tool for technology development. Nedstack and Hydrogenics in particular engaged in a diversity of niche markets, in order to realise stack 'volume' and operational data. By contrast, Intelligent Energy had difficulty to transfer experience and data from one market to another. Moreover, the Hydrogenics modules are considered to be more suitable for some segments than others. A breadth of experimental probes may be explained as a strategy for technology development, but there appear to be limitations to the number of technology platforms applied and the ability to transfer data between market segments.

The case study data also suggests that the breadth of probing is a matter of setting priorities. It is observed that probing in a breadth of markets may also be explained by the pursuit of short term revenue or partnership opportunities. These projects are typically of a limited duration. For example, Nedstack took on projects proposed by customers and engaged in several subsidised projects in consortia and Hydrogenics supplied to a diversity of one-off projects. These observations are similar to Klofsten's (1997) findings, that

YTB firms typically depend on external resources and have difficulty to prioritise longer term objectives above short term revenue. Opportunistic behaviour and resource dependency may, therefore, explain 'short' engagements in a breadth of market segments. Such decisions based on random external opportunities for revenue, are expected to result in broader and shorter probe engagements than decisions departing from strategic intent.

In conclusion the cross-case analysis suggests that a breadth of probes is pursued for market development, customer education and technology development. As proposition 3 suggests, probing alternatives appears to be necessary in a phase of probing characterised by uncertainty. However, considering these functions of probing, the necessity of probing in a breadth of markets differs according to the technology applied, the type of customers and the required customer education. Products to endcustomers are likely to require more focus and subsystems compared to OEM customers who are likely to require more breadth. However, the breadth of probing can also be explained by the pursuit of opportunities for short term revenue and the formation of partnerships. This 'opportunistic' explanation of breadth suggests that for effective probing, in terms of learning and market development with minimal investment, there is a limit to the 'necessary' breadth.

To probe 'effectively', there appears to be a limit to the necessary breadth of probing. How can a firm limit their breadth of probing? The discussion on proposition 3 suggests that market insight is not only developed through probing in alternative markets. Some of the case examples suggest that market assessments are useful to asses markets and customers before probing. Both an engineer's approach to technology application and a marketer's approach to technology application is observed in the case firms. Plug Power's GenCore and Intelligent Energy's ENV motorbike were developed taking customer needs as their starting point. The diverse applications of Hydrogenics' and Nedstacks' systems were primarily based on technology potential. This difference in point of departure, either from technology push or market pull, may additionally explain the breadth of market probes. Market pull implies that product innovation starts from the assessment of latent, unsatisfied customer needs in the market place whilst technology push implies the use of exploratory market approaches (Herstatt and Lettl 2004). Plug Power and Intelligent Energy suggest that market assessments prior to and in addition to probing appear to result in more focused probing. Considering the established markets of replacement technologies, this study expects that the breadth of probing can be limited through market assessments prior to probe selection, particularly in the form of conversations with prospective customers. On the basis of these observations, the following proposition is stated:

New P7 Market assessments prior to probing decrease the breadth of probe applications necessary to identify and develop compelling value propositions.

The Transition from Variation to Selection

On the basis of the literature reviewed, the experience gained by probing in alternative markets is expected to facilitate the evaluation of markets and the identification of a firm's value propositions. However, at a certain point in time, probing focuses and iterative development becomes more important to commercialise a new technology. There is limited theory to understand when firms begin to converge from experimental probes to more focused developments. This research, therefore, questions: *What factors determine when a firm stops probing variations and focuses on development?*

The above paragraphs suggest that experimental probes are conducted for various reasons: learning about markets, market development, technology development and opportunities for partnership formation and initial revenue. The case data suggests that there are two reasons to continue probes in a variation of markets: i) internal uncertainty due to a lack of information to asses the most compelling value propositions and ii) external uncertainties due to a customer's unfamiliarity or perception of risk. During the experimental phase, Hydrogenics used the HyPM module to shift between markets, for learning and market development. Similarly, Nedstack offered stacks to a wide range of customers, in some cases primarily to generate initial revenue. A variable timing and approach to this transition from experimental behaviour to more selective and focused probing is observed in the case firms. Plug Power was relatively early to focus developments of the GenCore once its value proposition was identified and initial orders received. Based on this end-user interest and market potential, Plug Power became selective. Hydrogenics, on the other hand, did not become more selective until after the technology demonstrators. In comparison, Nedstack and Intelligent Energy are less selective of market segments, but have become more selective of their customers. Their transition from variation to selection appears to depend on the formation of supplier relations and partnerships. The ENV bike boosted Intelligent Energy's credibility and confidence and consequently, attracted customers and gave access to new customers. Following the credibility boost and publicity from the ENV, the company was able to focus on a select number of customers. Similarly, Nedstack has received significant publicity with its PEM power plant, validating the reliability of its stacks. In the same year, Nedstack began to receive repeat orders in the range of 40/50 stacks. Thus, customer familiarity appears to influence when firms are able to become more selective of their probe engagements.

Market assessments and early field trials may explain why Plug Power was relatively early to analytically asses and focus on the back-up power market. Comparatively, the other case firms made a later transition to more selective probe decision making. The uncertainty of OEM customers appears to have influenced this relative delay. OEM customer familiarity not only appears to influence the breadth of experimental probes, but also the duration of experimental probing. Even though a firm has identified a compelling value proposition, selective probe decision making depends on the degree to which customers understand, are convinced by, and willing to adopt a firm's technology. Firms are expected to become more selective and less reactive to the external environment once customers have become familiar with the firm's technology and customer uncertainty is reduced. Based on these observations it is proposed that:

NewP8 Customer familiarity and acceptance is the dominant factor driving selective probe decision making

A firm's level of probe experience appears to influence a customer's familiarity with the firm. The discussion on customer familiarity in paragraph 8.1.5, suggests that this process is an issue of establishing firm legitimacy as a trusted supplier and that this process can take time. This influence of external uncertainty on the transition to selective probe decision making is consistent with the model of learning proposed by Van de Ven et al. (1999), where a firm's activities start to converge once environmental uncertainty is reduced.

Shifts to New Market Segments

Experimental probing involves trying out applications in various market segments. The concept of probing and learning suggests that companies will abort and select market segments based on experience gained in probes. However, this concept fails to explain how firms appear to entirely change strategy and shift to market segments irrespective of prior probes. *What explains a firm's ability to shift to new market segments without prior probe experience?*

Hydrogenics argues that it was able to return to the back-up power market because this market requires similar technology to the firm's prior probe applications. Plug Power, on the other hand, has acquired two FC developers specialised in material handling. Plug Power's specialised stationary power competences are apparently not directly applicable to the material handling market. This can partly be explained by the governing requirements of these markets: whilst durability and efficiency requirements govern the stationary market, material handling requires stacks with higher densities, dynamic load following and intermittent use. The lack of an applicable technology platform for material handling appears to explain Intelligent Energy's lack of probes in this market. By contrast, Nedstack is able to design and supply stacks to both markets. Apparently, the ease of switching markets can be explained by the degree to which a firm's technology is either diversely applicable or optimised for specific market segments. Nedstack argues that the durability and efficiency requirements for stationary power in the PEM power plant are similar to the requirements for the bus market. Similarly, Hydrogenics states that its development path in back-up power and material handling will enable them to cover a broad range of applications. By contrast, Plug Power's specialized systems are optimized for specific market requirements, explaining their limited ease of shifting markets.

Platforms are likely to become more specified and optimised to specific market requirements. Therefore, technically, the application diversity of platforms is likely to be reduced as the technology and applications develop further. Moreover, as markets develop and crystallise, a firm's level of market competences, network and credibility in specific market segments are likely to become more influential to a firm's ability to shift to other markets. For example, in comparison to firms new to the back-up power market, Plug Power has developed market competence, operational data, a reputation and customer relations. Intelligent Energy suggests that it will not be easy to re-enter the CHP market with the same approach, because, in the meantime, competition has grown in this area. However, as yet, the case firms are capable of validating their technology in one segment, with data from other segments. Nedstack, Hydogenics and Intelligent Energy show that they are able to transfer their credibility to other markets. Moreover, the case firms have plans to shift to other niche markets as they emerge. In this phase, market competences do not appear to determine a firm's ability to shift. Based on the case data the following proposition is stated:

NewP9 Technological competence is more important than market competence in explaining a firm's ability to shift to emergent niche markets.

In conclusion, the case firms' response to emergent markets suggests that their ability to shift is determined by: i) the applicability of a firm's technology, ii) the firm's ability to transfer technology from one market to another iii) the availability of resources to acquire the technology for the targeted market. Either way, the case firms are capable of shifting between markets. The first two approaches suggest that 'cross-over learning' enables flexibility and shifting between markets. In the early phases of technology application and niche market emergence, a firm's technological competence appears to determine a firm's ability to shift to new markets. From this perspective, probing experience provides FC firms with a competitive advantage above new entrants in the FC industry.

Figure 8.11 summarises the propositions derived from the case study data. Considering the inductive approach, the propositions are preliminary. The relationships proposed require further verification. Thereby, Eisenhardt (1989: p.542) suggests that *"it is important to discover the underlying theoretical reasons for why the relationship exists".* The propositions are further discussed in chapter 9. However, the possible scope of verification within this study is limited. Besides, the propositions are likely to give rise to more questions. Therefore, the propositions derived from the case study data will also be discussed in terms of the possibilities for further research.

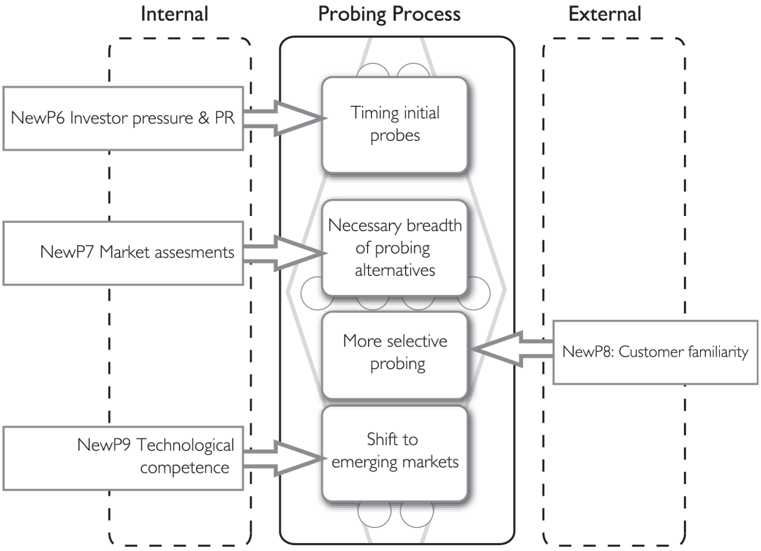

Figure 8.10 New propositions derived from the case study data, predicting the influence of factors on the probing process

Chapter 9: Conclusions and Recommendations

Resource constraints and uncertainties of timing complicate decision making with regard to the market application of FC technology. Given the challenges and uncertainties associated with managing the application of FC technology and radical technologies in general, this research addressed the following central question:
How do firms apply their technology to market applications and how do they develop the ability to do so?

To approach the central question the following research questions were proposed:

- What challenges do FC firms face in selecting and developing applications for their technology? (RQ 1)
- How do FC firms manage the process of technology application? (RQ 2)

To further specify the research problem and focus, the first part of this study addressed these research questions, first, through the characterisation of FC technology in chapter 3 and subsequently through a literature review of innovation and market literature in chapter 4. The characterisation described the application of FC technology, prior to commercial sales, as a lengthy process in which FC firms pursue multiple early applications and niche markets. Within this process, young FC firms face particularly challenging decisions on which applications to pursue at which time. For young FC firms, with limited resources to allocate and multiple markets to choose from, the application of FC technology involves strategic choices on which markets to engage as well as which competences and partnerships to develop. Considering these findings, this study chose to focus on: the selection of early applications by young FC firms. Chapter 4 subsequently reviewed literature on the uncertainties of radical technology application. Literature suggests that firms manage the application of radical technologies through a process of experimental applications and learning. The case study research supports these preliminary findings. These findings on the challenges of FC technology application and how firms manage this process, are summarised in section 9.1.

On the basis of the literature review, this study chose the concept of probing and learning to describe and analyse the process and the selection of early applications. The preliminary findings on probing and learning by Lynn et al. (1996) require further study. This study argues that although probe applications are time and resource consuming, there is a limited understanding of how probe decisions are made. Therefore, a focus was chosen on 'probe decision making' in firms, i.e. how probe decisions are made and how the experience gained in probes influences subsequent decisions. Additionally, more general patterns of probing processes have not been identified in prior studies. Therefore, this study has also focused on the characteristics of and differences in probing processes and the factors that drive these patterns of probing. Through a case study research of FC firms, the following (revised) research questions have been addressed:

- What explains probe decision making in young FC firms? (RQ 3)
- What characterises a FC firm's probing process? (RQ 4)

These questions address the central research question through a conceptual model, based on theoretical constructs, applied to case study research in the FC industry. The propositions and the conceptual model to explain probe decision making are discussed in section 9.2. These findings lead to the findings on characteristic patterns of probing. To better understand how firms apply their technology to markets, section 9.3 describes and explains the observed probing patterns. Subsequently, the scope of generalisation to other technologies and industries is discussed and topics for further research are presented (9.4). This chapter concludes with recommendations for practice and academics (9.5).

9.1 Fuel Cell Technology Application

This study began with the case of FC technology, to better understand the phase of FC technology applications prior to widespread commercial sales. This section summarises the findings on the challenges FC firms have faced and how FC firms have managed the process of technology application. The probing histories of FC firms between 1997 and 2007 provide an overview of the early FC applications pursued and realised prior to commercial sales. The case study suggests that in a first period, market expectations were modified and most initial probes were aborted. This observation characterises the early applications of FC firms at the time. Apparently, the FC industry overestimated the speed of performance improvement and cost reduction as well as the rate of customer adoption. For example, several firms focused on widespread adoption of FC vehicles with limited attention to the status of cost and performance competitiveness. Similarly, the micro CHP market for residential applications was targeted, whilst the technology was far from cost competitive. Moreover, the FC industry appears to have underestimated the time it would take to educate and convince customers. Consequently, feedback from early probe applications provided several FC firms with a 'reality check'.

- The case of FC technology illustrates how difficult it is to make the right decisions in an early phase of technology application and suggests the importance of applying immature versions of the technology to gain information and feedback from early markets and customers.

A period of over-enthusiasm is common to the starting stages of the technology commercialisation process and the creation of new industries. Jolly (1997) describes how the overall process of technology commercialisation involves bouts of enthusiasm, disappointments, delays and enthusiasm again. Gartner's renowned hype cycle[10] additionally suggests that prior to productivity, new technologies go through a peak of inflated expectations followed by a trough of disillusionment. The peak and subsequent downfall of expectations appears to follow a similar cycle as the 'Garnter hype cycles' (Fenn 1995) observed in other industries.

A second observation of FC technology application refers to the process of niche market accumulation described by Geels (2002). FC firms sought for niche market opportunities and pursued a diversity of niche market applications. Although most applications of FC technology are known, it took several years to specify which markets would come first. In this period, prior to the emergence of niche market demand, FC firms pursued diverse early applications.

- The young FC firms illustrate the difficulty of determining the timing and order of niche markets. It has been particularly challenging to determine when and which niche market would emerge first.

Applications were 'probed' in a breadth of market segments with multiple variations of the technology. Thus, this period can be characterised by diverse alternatives and variations. The characteristics of diverse designs and frequent product changes are consistent with the 'fluid phase' of technology development (Utterback and Abernathy1975) and 'the era of ferment', characterised by multiple technological alternatives and a diversity of markets (Tushman and Anderson 1986).

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[10] The hype cycle was introduced by Jackie Fenn of the Gartner Group1995

A third observation is that young FC firms have engaged in a diversity of applications with immature versions of their technology. Lynn et al. (1996) have described this as a process of probing and learning: 'probing applications', learning from these applications, and probing again. The process of early applications is a learning process. The outcomes of probe applications include: feedback from markets and customers, experiences with applications in practice, operational data, publicity and awareness. Probes were pursued for early revenue, technology and market development and customer education. Probe applications have also been instrumental in generating awareness, explaining the potential and validating the technology to convince prospective customers.

Furthermore, this study observed that the young FC firms responded similarly to the emergence of niche market demand: shifting from prior probe paths to the emerging markets. For most young FC firms these markets provide the opportunity for initial commercial sales. It is notable that many FC firms are able to shift to the emerging markets without prior experience in that market. At the same time, prior experience gained in probe applications appear to determine a firm's position in the emerging markets, in terms of specific sub segments, customers and supply chain position.

Finally, this study observes that firms apply their technology differently. FC firms have managed the process of probing and learning in different ways. The case firms were selected on the basis of different probing strategies in terms of a broad or a focused scope of market segments, to illustrate different approaches to probing. These cases additionally varied in the technology applied: products to end users or subsystems to OEM customers. Furthermore, the following differences were observed between the probing processes of the case firms:

- The timing of initial probes. Some firms engaged in early probe applications years before other case firms. These applications were far from commercial realisation. Other firms engaged in initial probes years later and continued with R&D in the meantime.
- Different market segments.The case firms engaged in different market segments at different times.
- Short term revenue or longer term developments. Some firms engaged in several projects for short term revenue whilst others prioritised longer term developments.
- Quantity or customisation This study observed firms targeting quantities of standard units versus a limited number of customised systems. The total number of probes conducted varied considerably.

Thereby, this study shows how young FC firms pursue different strategies to select and develop niche markets. To date, a 'best practice' cannot be identified. Designing a probing strategy is challenging, considering the trade-offs, the diversity of possible applications and the uncertainty of their outcome. Firms can decide to probe: too early or too late, too broad or too focused, too long or too short.

This summary of observations suggests that firms go through different periods of probing and learning with different probing strategies. In these periods, FC firms are influenced by several factors within the firm and external to the firm. These empirical observations of the FC case firms have been analysed and compared to a conceptual model of probe decision making, discussed in the following section to better understand what drives probing processes and the selection of probe applications.

9.2 Explaining Probe Decision Making

To extend and integrate innovation literature on the application of radical technologies, this study has built on the concept of probing and learning and aims to better understand what explains probe decision making in young FC firms. This study presents a conceptual model of constructs that are expected to drive probe decision making over time. A multitude of factors are expected to influence decision making. Starting from a dynamic capabilities perspective, the model proposes that technology application decisions are related to various factors, including firm internal factors and factors external to the firm. Particularly in the case of YTB firms, the development of the firm is expected to interact with a dependence on external resources and partnerships. Consequently, different factors may explain probe decision making:

- Firm and competence development. Decisions based on what the firm is strategically and competitively most capable of.
- Expectations of an emerging industry. Probes are selected by following a majority of firms in an industry, irrespective of the firm's internal competences and strategy.
- Resource dependency. Grasping probe opportunities for revenue irrespective of strategic intent or industry expectations.

These perspectives relate to the classic debate on strategic decision making, discussed in paragraph 5.2. This study argues that probe decision making cannot be explained by a single driver. Rather the role of these drivers changes as a firm learns and the environment changes. Although dynamic capabilities scholars propose this dynamic perspective, there is a limited understanding of the relative influence of factors over time. This study proposes that the role of factors in explaining probe decisions will change over time. Therefore,

➢ The core message of the conceptual model is that in different periods of probing, different factors drive probe decision making.

The case study data has been analysed to validate the conceptual model and test the propositions. In the following paragraphs, the propositions on probing and the role of the constructs in probe decision making are primarily discussed. Subsequently, conclusions are drawn on the conceptual model of probe decision making.

9.2.1 Discussion of the Propositions

The conceptual model suggests that the weight of factors explaining probe decision making varies over time. The propositions have been proposed and tested in order to predict probing patterns and the constructs that drive probe decision making over time. In paragraph 8.4.1 the propositions were tested on the basis of the case study data with supportive and opposing arguments. This paragraph finishes with the status and strength of these propositions. Where considered necessary, modifications are proposed.

Initial probes

To explain the selection of initial probes in the explorative phase of probing, the weights of internal and external factors have been compared. The model suggests that initially, YTB firms have limited market competences and experience in market applications and are expected to follow industry expectations. It was proposed that:

P1 Industry expectations are more important than a firm's internal factors in explaining the selection of initial probes.

This proposition was largely confirmed in the case study: industry expectations dominated a firm's internal factors during the selection of initial probes. FC firms engaged in a similar scope of markets in the same period and appear to have followed the expectations of FC industry. Before the year 2000, industry expectations for automotive markets appear to have 'blurred' realistic expectations of market adoption within several firms. The dominance of industry expectations can be explained by the enthusiasm and 'hype' in the industry at the time, motivating firms to follow what 'the others' in the industry expect and do. The dominance of industry expectations in initial probe decision making can also be explained by the difficulty of rational assessment in the uncertain environment. With limited internal capability and experience to assess the market potential and adoption timeframes, firms appear to have followed shared expectations. This observation can be supported by an institutional perspective, whereby firms are likely to mimic each other and follow the beliefs of the industry when faced with uncertainty (e.g. DiMaggio and Powell 1983). Industry expectation is an 'institutional factor', referring to expectations of an industry as a social structure, in contrast to the beliefs of an individual firm.

In the uncertain context of a young and emerging industry, literature suggests that firms learn from other firms in the industry (Miner and Haunschild 1995, Ingram and Baum 1995). Industry learning, or population level learning, implies that there is a close relationship between learning and expectations within the firm and the industry. It can therefore be argued that industry expectations do not only shape a firm's internal expectations, but the opposite also takes place. Similarly, the case study research suggests that the probes of the pioneering firm influenced the formation of industry expectations. This observation is in line with Garud and Rapa (1994) who argue that there is an interaction between the beliefs and expectations within a firm and the expectations of the industry. Nevertheless, the case study suggests that initial probes are selected within a scope of industry expectations at a particular time. From a dynamic capabilities perspective, industry expectations shape a firm's path, i.e. the strategic options open to a firm.

Thus, industry expectations appear to shape a firm's initial expectations of market opportunities rather than a firm's inherited ambitions. This proposition can explain similar behaviour among YTB firms in early periods of probing.

In addition to industry expectations, strategic alliances with large companies appear to have influenced initial probe decisions. This influence was most apparent in the start-up case firm without formal ties to the FC industry at founding. It can be argued that with limited legitimacy, no prior network and limited experience at founding, start-ups rely more on the formation of strategic partnerships with established companies than spin-off companies with some kind of inherited experience and network.

To verify and generalise this proposition and analyse the relative role of strategic alliances, further research is necessary. There is limited innovation literature to validate the influence of industry expectations in a young industry. However, literature on new industry creation and development addresses this topic (e.g Aldrich and Reuf 2006, Audretsch 1995, Klepper and Graddy 1990). The influence of strategic partnerships relates to the field of organisational growth and new business development (e.g. Bhidé 2000, Garnsey 1998). In further research, these disciplines should be addressed to complement innovation studies.

Consequence of initial probes

As the concept of 'probing and learning' suggests, experience from initial probes influences subsequent decisions. The feedback from initial probes was expected to result in a 'reality check' and cause a search for new market applications. To address how experience from initial probes influences subsequent probe decisions, the following proposition was proposed:

P2 A low value proposition, resulting from the evaluation of initial market probes, will cause firms to search for alternative market applications.

The case study data suggests that the outcomes of initial probes caused firms to search for new and alternative markets. The behaviour of searching for near term niche markets was primarily caused by modified expectations of large scale market adoption. In contrast to literature in section 4.3, which suggests that technology application begins small and in niche markets, two FC case firms began by targeting large scale markets. The previous paragraph suggests that these firm appear to have followed industry expectations of large scale markets. The other two case firms have engaged in niche markets, but show modified expectations with respect to OEM customer adoption, in terms of the required duration and effort to convince and educate OEM customers. Thereby, the case of FC technology illustrates the difficulties involved in applying a replacement technology. Although most market applications for FC technology were known, the time frame and order of market adoption was highly uncertain. With feedback from initial probes, firms appear to have assessed the realism of achieving cost and performance targets as well as the time it would take to educate and convince customers.

The proposition implies that initial probes are difficult to select and evaluate beforehand. Apparently, the chance of identifying and selecting the 'right' initial market application is small. Experience in initial probes provides firms with insight into the status of technology and market development. After these initial probes the case firms began their own search for alternatives and diverged into new market segments. Thus, for the case of FC technology this proposition holds. The proposition implies that due to the modified expectations, firms are likely to shift to other market applications and reconsider their strategy. These findings suggest that a search for new opportunities may explain divergent and experimental behaviour in a firm's probing process.

Necessity of Probing Alternatives

Given the possible cost and risks of experimenting with applications in various market segments, the necessity of this approach has been questioned. According to Lynn et al. (1996) firms learn to identify market opportunities and meet customer requirements through probing and learning. Therefore, on the basis of these findings, the following proposition was proposed:

P3 Probing alternatives is a necessary condition to develop a firm's value propositions.

This proposition predicts that probing in a breadth of market segments is desirable and necessary when there is uncertainty about which markets to pursue at which time. The case study data largely supports this proposition. Three explanations for this necessity are observed. First, the case study suggests that the experience gained from a variety of probes is valuable and contributes to the identification and development of a firm's value propositions. Second, probes are pursued for market development and customer education. Particularly in the case of OEM customers, probe applications appear necessary to enthuse, educate and convince customers. Third, some case firms diverge into alternative markets for technology development, to achieve quantities and validate the technology. Thereby, data from a probe in one market segment is used for probes in other market segments. These observations are in line with Van de Ven et al. (1999), who argue that a divergent phase of learning by discovery and market development is necessary before the firms are able to focus developments and set goals and priorities. However, opportunistic behaviour is also observed, suggesting that probing alternatives is not only a strategic decision to manage technology application, as the findings of Lynn et al. (1996) may suggest. This case study finds that probing alternatives is also a survival necessity, whereby probes in short term projects and niche markets provide young FC firms with initial revenue. This observation suggests that there are limits to the effective breadth of probing in terms of learning and market development. Moreover, the necessary breadth to fulfil these functions appears to be variable.

However, contrary to this proposition, it is observed that information and competences to identify and develop new value propositions are also gained through sources other than probing, such as conversations with clients, market assessments and partnerships. Apparently, probing alternatives is necessary, but not the only method to develop market insight into the timing of adoption and potential of market segments. Furthermore, the case study data suggests that some firms choose to minimize probing, focusing on development early in the process of technology application. The necessity of probing can also be challenged by the possibility of waiting for markets to emerge, as new FC industry entrants directly focusing on specific niche markets illustrate. As yet, it is not possible to asses the success of new industry entrants in comparison to the firms with probing histories and experience.

In conclusion, the proposition partly holds. This study finds that probing is necessary, but not the only method or strategy to apply FC technology. Moreover, there appear to be limits to the necessary breadth of probing in terms of learning and market development, considering that probing is also a survival necessity. A future ex-post study of successful and less successful firms in the FC industry may provide more insight into the necessity of probing alternatives compared to the focused pursuit of applications or a later entrance. The findings suggest that the variable necessity of probing alternatives is likely to explain variation in the breadth of probing processes.

Continuation of Probe Paths

To explain the continuation of probe paths, both internal and external factors have been analysed. On the basis of literature it was assumed that there is a low level of managerial choice in the adolescent phase of a firm's growth. It was proposed that:

P4 The availability of external resources dominates the decision to continue probes for mid and long-term applications

In line with the above proposition, the case study suggests that firms rely on external funding and support to continue with probes that are not likely to be adopted in the short term. These external sources of funding include customers, strategic partnerships or government funds. This reliance on external funding is particular for YTB firms and their phase of growth. For further research on this topic, literature on firm growth is likely to provide valuable input on the relationship between the innovation process and the growth of YTB firms (e.g. Penrose 1995, Garnsey 1998, Kazanjian and Drazain 1990).

The proposition implies that YTB firms rely on external sources of funding to engage in mid and longer term applications. Therefore, a firm's longer term strategic planning largely relies on external commitment and support. Consequently, the influence of strategic intent on probe decision making in YTB firms appears to be limited to the pursuit of short term markets. Furthermore, the proposition implies that long probe paths are typically driven by the availability of external resources. Within the firms' probing processes, differences in probe path length can, therefore, at least partly be explained by differences in sources of funding.

Developmental Probe Paths

Considering the lengthy and uncertain process of early applications, the emergence of market demand is expected to dominate probe decisions and outweigh a firm's experience in prior probes. The following proposition was proposed:

P5 The emergence of market demand is more important than probe experience in explaining probe selection

The case study firms show similar behaviour in response to the emergence of market demand. Most firms appear to shift to the emergent markets irrespective of prior probe engagements. Thereby, a firm's probing history does not appear to determine a firm's decisions to pursue probes for development. Apparently, the emergence of market demand dominates a firm's internal strategy and competences. However, this proposition does not entirely hold. The case study data suggests that probe experience plays a significant role in the selection and pursuit of emergent markets. A firm's probe experience appears to determine a firm's technical ability to engage in emergent market segments. Moreover, probe experience determines how the case firms strategically position themselves in these markets. The influence of market demand, therefore, does not imply that probe experience is trivial. Nevertheless, the influence of market demand on probe decision making is likely to explain shifting and homogeneous behaviour in the firm's probing processes.

9.2.2 Propositions Derived from Case Study

The propositions predict probing behaviour and the dominant constructs explaining probe decisions in various periods. The case study provides insight into other factors that appear to influence probe decision making and may explain the difference in probing patterns. Through an inductive process, further findings have been derived from the case study data. The cross case analysis in paragraph 8.4.2. introduced new propositions that address the following questions: what explains the timing of initial probes, the breadth of experimental probes, the transition to more selective probing and a firm's ability to shift to new markets?

Timing Initial Probes

The timing of initial probes is relevant considering the cost of early probes and the risks of, for example, damaging a firm's reputation and causing unrealistic expectations. The case firms show differences in the timing of initial probes. The case study data was analysed to address what explains these differences in timing. In each of the case firms, pressure is observed to demonstrate applications. However, initial probes for demonstration were timed differently. The case study suggests that this difference in timing of initial probes can be explained by variable pressure from investors and a variable need for PR.

The pioneering case firm suggests that early demonstrations were necessary to acquire and access resources. Moreover, two of the case firms had grown to a substantial size and investor pressure appears to have driven the firms' haste to move from R&D to applications. Differences in the phases of firm growth account for the difference in timing between these North American case firms. Their location in North America may explain why these firms were relatively early to engage in initial probes, compared to the European case firms: the FC industry was a step ahead and investors had begun to exert more pressure. Thus, differences in the phase of firm growth and industry development appear to explain a variable pressure from investors to demonstrate and move from R&D to applications.

Furthermore, initial probes were realised largely for demonstration and PR. In particular, the later entrant of the case firm sample, felt pressured to demonstrate the firm's technology shortly after founding. In contrast to the other case firms, the company was not founded as an R&D company, but founded and funded to commercialise and license prior R&D experience. The relatively new firms in the industry appear to rely on demonstrations for PR: to establish a position in the industry, generate awareness of their existence and legitimacy and develop relationships with stakeholders and partners. This necessity of demonstrations to develop legitimacy and relationships can be explained by the vulnerability of entrepreneurial firms to the liabilities of newness (Freeman 1983, Singh et al. 1986). Based on the above observations, the following proposition was proposed:
New P6 Investor pressures combined with pubic relations are the dominant reasons to engage in initial probes

Under investor pressure and PR ambitions, it can be argued that firms may probe 'too' early. In terms of probing and learning effectiveness, 'too' early would mean that the outcomes are of limited value in terms of learning and market development. However, there are also advantages of being early or the first, such as having a head start in building experience and legitimacy. The pioneering firm in this case study has built a reputation as a front runner in the industry. Moreover, their probes contributed to shared beliefs and expectations in the FC industry. This observation supports Sawhney (2005), who argues that pre- market branding for new technologies is likely to provide pioneering firms with 'thought leadership'[11]. However, the case study suggests that the advantage in terms of customer orders is limited: later entrants received a similar number of repeat orders at a similar time. Moreover, the FC firms still run the risk of 'burning out', (Olleros 1996), irrespective of their initial probe timing. Therefore, the longer term competitive advantage of early initial probes is not apparent in this case study. The relation between investor pressure, PR and probe timing points to literature on firm growth and entry timing. This study suggests that further research and discussion requires input from literature on order of entry and entry timing (e.g. Lambkin 1988, Lieberman and Montgomery 1988, 1998) and the role of firm legitimacy throughout the phases of firm growth (eg. Aldrich and Auster 1996, Fichman and Levinthal 1991).

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[11] A thought leader is a term used to describe a person or firm who is recognised for innovative ideas and demonstrates the confidence to promote or share those ideas. http://en.wikipedia.org

Breadth of Experimental Probes

Innovation studies suggest that the application of radical innovations require experimentation and a process of probing and learning (section 4.5). However, probing does not imply blind 'trial and error'. This study suggests that there are limits to the necessary breadth of probing in terms of learning and development. To explain the pursuit of probes in a breadth of market segments, this study observed firms with variable probing strategies in terms of breadth.

This study finds that firms probe alternatives for market development, customer education and technology development (proposition 3). Considering these functions, it is argued that the necessity to focus or to probe in a breadth of markets depends on a firm's supply chain position with respect to its customers and the novelty of the technology to customers. For the cases that develop end products, there are limited market applications to choose from. For the case firms supplying technology platforms to OEMs, there are multiple possible market applications and customers. To identify the most compelling value propositions from these options, a broader scope of probes is pursued for learning and market development. Additionally, customer education and technology validation requires considerable effort. It is furthermore observed that a breadth is necessary to apply a volume of subsystems in various small markets.

A larger breadth can also be explained by a less proactive attitude towards pursuing applications. From this approach, firms keep options open to serve and supply customers. Furthermore, a breadth of market segments can be explained by the pursuit of various opportunities for short term revenue, such as sales to early customers and projects. It can be argued that developers of subsystems typically depart from engineering and scientific expertise and initially put less effort into market assessments and marketing than product developers. These characteristics suggest that firms may pursue a broader range of market segments than necessary for learning and market development. As the discussion on proposition 3 suggests, some of the case firms conducted market assessments besides or prior to probing applications. These case firms appear to have engaged in a more focused scope of probe applications. Based on this observation this study suggests that:

New P7 Market assessments prior to probing decrease the breadth of probe applications necessary to identify and develop compelling value propositions

This proposition, derived from the case study data, is in line with innovation studies that emphasise the relevance of the interaction between engineering and marketing activities and technical and market related competences for innovation success (e.g. Cooper and Kleinschmidt 1987, Moenaert et al. 1995, Song et al. 2005). This proposition implies that although traditional marketing techniques are argued to be misleading and inaccurate (section 4.4), market assessments can play a valuable role in the application of a new technology. Particularly in the case of replacement technologies, where established technologies provide benchmark requirements, market assessments are expected to facilitate the pre-selection of probing opportunities. The proposition implies that the breadth of probing strategies is likely to vary strongly prior to the emergence of market demand: firms may minimise their probing breadth through market assessments or maximise their probing breadth to generate revenue and sales. From this perspective, a variable breadth can be explained by a technology or market oriented approach.

Transition to Selective Probe Decision Making

The case study analysed when firms stopped diverging by probing alternatives and transitioned to a selection of applications for development. OEM customer familiarity appears to have a strong influence on the timing of this transition, whereby customer adoption depends on the degree to which firms have educated and convinced OEM customers. This observation implies that FC firms depend on the development of customer familiarity and emphasises the role of probe applications in market development. Probing alternatives for market development and customer education may outweigh and delay a firm's strategic intent to focus probe developments.

The case study data suggests that firms reduce their variation of probes and become more selective as customer uncertainty reduces. Moreover, the firms are gradually able to become more selective of customers to pursue probe applications. The influence of external uncertainty on the transition to selective probe decision making is consistent with the findings of Van de Ven (et al. 1999). These scholars suggest that a firm's activities will only start to converge through adaptive learning cycles once environmental uncertainty is reduced. The dependence on customer uncertainty additionally relates to studies on the diffusion of technologies. The communication perspective in particular, addresses the psycho-sociological processes of customer perception that affect the adopter's decision making (Rogers 1995).

The construct customer unfamiliarity refers to both the firm and the technology. The case study suggests that it may be necessary to treat familiarity with the firm and familiarity with the technology as separate constructs. The process of generating awareness about a technology and its potential is, at least partly, a collective process of numerous different probes and activities in the industry. By contrast, achieving legitimacy, credibility and trust with a customer is the responsibility of an individual firm. The first type of customer familiarity strongly influences the phase of the FC industry in general. As a consequence, FC firms appear to shift towards development in a similar period and respond to the emergence of market demand similarly. The differences of timing towards selective probe decision making appears to be related to the level of customer familiarity with and trust in the individual firms. Moreover, the case study suggests that some degree of focus was necessary to validate their technology to prospective customers.
Therefore, this study expects that the transition to selective probe decision making requires a certain level of customer familiarity and trust with the FC firm and the subsequent focus is driven by the need to validate the technology to customers. On the basis of these observations, the following proposition is proposed:
NewP8 Customer familiarity and acceptance is the dominant factor driving selective probe decision making

This proposition relates to customer adoption behaviour and firm legitimacy. For further research on the influence of customer familiarity and firm legitimacy on probe decisions, this study suggests a combination of findings from diffusion literature (Rogers 1995) and literature on the development of firm legitimacy (e.g. Aldrich and Fiol 1994, Singh et al. 1986, Zimmerman and Zeitz 2002).

Shifting Markets

The case firms show shifting behaviour between market segments and to new market segments. This study questioned what factors determine a firm's ability to shift to new markets. The case firms show a similar response to the emergence of market demand, i.e. shifts towards these markets. Apparently, the firms are able to shift between markets irrespective of their prior probe paths and experience. The case study suggests that technological competence determines the case firms' ability to shift to other market segments, more so than the firms' market related competences gained in prior probes. Thereby, technical 'cross-over learning' enables firms to shift between markets and their technical experience in probes provides flexibility. On basis of their technological competences, firms are able to position themselves in the emergent market. Apparently, during the period in which initial market demand emerges, a firm's market competences are less important than a firm's technology. On the basis of case study data the following proposition is proposed:
NewP9 Technological competence is more important than market competence in explaining the shift to emerging niche markets.

This observation emphasises the importance of developing technical legitimacy and credibility through probe applications. The proposition appears to contradict the emphasis of market competences in innovation studies. Apparently, the legitimacy of YTB firms is primarily determined by its technological core competences and technical experience in probe applications. Particularly in the case of OEM customers, technical validation is of primary importance to convince customers This explains why firms are able to shift to emergent markets and convince customers in these markets without prior probe experience in that market. As markets develop, the industry matures and becomes more market driven (Shanklin and Ryan

1987) and partnerships become more structured, the relative importance of technological competences compared to market competences is expected to change. It may become more difficult to get a foothold in markets without prior market related experience and relationships. This proposition therefore primarily holds for the early phases of industry development and technology application. Moreover, in the case of new industry entrants, lacking technical validation through probe experience, market competences are expected to be more important for entering a new market. New entrants are expected to require a more in-depth understanding of markets to seek out unique niche markets and gain a foothold in the FC industry. Therefore, this proposition primarily holds for YTB firms with probing histories during the phase in which niche markets begin to emerge.

9.2.3 Conclusions on Probe Decision Making, Conceptual Model

It can be concluded that the case study data largely validates the conceptual model. The case study data additionally provide new findings to further develop this model. The model of probe decision making suggests that probe decision making is influenced by both factors internal and factors external to the firm and that the role of these factors in probe decision making changes over time. The propositions made predictions on probing behaviour and the influence of factors on probe decision making over time. The following patterns have emerged from the discussion.

Initially, probe decision making appears to be driven primarily by industry expectations. Industry expectations shape the scope of markets from which a firm selects initial probes, causing homogeneous behaviour in the selection of initial probes. Moreover, in the same period, customer unfamiliarity with the technology and the industry in general has a similar effect on firms: probes are primarily pursued in small numbers for demonstration purposes. Although the FC firms depend on external stakeholders to fund initial probes, differences in the timing of initial probes appear to be explained primarily by different levels of investor pressure and PR strategies.

On the basis of the experience gained in initial probes and modified expectations firms set out do identify new value propositions by probing alternatives and learning from these probes. A firm's internal factors appear to determine this search for alternative market segments. Moreover, probes are pursued for market development, partnership formation and initial revenue. Therefore, internal factors including the level of a firm's competences and capabilities as well as diverse strategies and priorities appear to drive a second period of probing, causing different strategies and a variable breadth of market segments. In this period, the type of external funding appears to influence the length of probe paths. A breadth of short probe paths is partly caused by the pursuit of opportunities for short term revenue. Partnerships and external sources of funding appear to largely explain long probe paths for mid and long-term markets. Furthermore, the duration of this period differs, apparently due to the variable level of customer familiarity with the individual firm.

Finally, the emergence of market demand drives similar behaviour, apparently irrespective of prior probe experience. Nevertheless, a firm's technological competences and experience in probes are what explains a firm's ability to shift to emergent markets. Thereby, probing experience provides legitimacy and validation to convince customers and this experience is transferred from one market segment to another.

9.3 Characterising the Probing Process

To conceptualize the process of radical technology application, this study has built on the concept of probing and learning. The case study research validates prior findings of Lynn et al. (1996): firms probe with immature versions of their technology in market experiments and develop market insight through these probes. Lynn et al., present this concept as a successful management practice. By contrast, this study finds that all firms probe and learn to some degree. This study argues that probing and learning is not only a management decision or management practice that by definition, leads to success. *Probing and learning is also a survival necessity for YTB firms.* Therefore, this study found that to derive a more general model of the application of radical technologies, the concept of probing and learning was a useful point of departure.

To derive a more general model of probing and learning, a structure was proposed to describe and analyse the probing histories of firms. This **descriptive model** is based on the concept of 'probing and learning' (Lynn et al. 1996) and the concepts of exploration and exploitation (March 1991). The model proposes that probing processes can be represented on the basis of two decisions: i) the decision to engage in a new market segment and ii) the decision to continue or abort developments in a market segment. Thereby, this study characterises the process of probing along two variables:

- The breadth of market segments (horizontal axis)
- The length of probe paths (vertical axis)

Probe applications are represented as circles on these axes. These probes are variable in function and size. In this manner, the main publicly presented probe applications of a firm have been mapped out. Thereby,

- ➢ This study presents an approach to describe a firm's application decisions over time. This synoptic representation of probe decision making in firms provides an overview of probe decisions, their consequences and interrelations.

The case study research supports the applicability of this model for describing and analysing probe applications over time. This descriptive model provides an overview of a firm's application decisions and enables comparison between probing processes. The probing processes reveal patterns of probing.

On the basis of theory, probing patterns have been predicted along these variables of breadth and length. The probing histories of the case firms, described and analysed along this descriptive model, suggest patterns of variable breadth and length. The cross-case analysis compared the predicted patterns and the patterns emerging from the case study. The analysis along the constructs and the conceptual model gave insight into the factors that may explain these patterns. Similar and different patterns of probing have been observed. In the following paragraphs, first findings on the similar patterns of probing and subsequently the variable patterns of probing are discussed. With these findings, the fourth research question can be answered: what characterises a firm's probing process?

9.3.1 Patterns of Probing

Predicted patterns have been compared to the case study data. In the process of analysing and explaining probing behaviour, patterns of probing have emerged. Section 9.2 identifies three periods in which probe decision making is driven by different constructs as firms develop and the external environment changes. The conceptual model suggests that over time:

1. Initial probe decisions are driven by industry expectations,
2. Subsequent decisions are driven by heterogeneous firm strategies and priorities,
3. Finally probe decisions are driven by market demand.

The first and third period are characterised by similar probing behaviour and the second period is characterised by heterogeneous probing behaviour in terms of the market segments pursued, the breadth of market segments and the length of probe paths.

Within these periods, probes are conducted for different reasons and their outcomes provide different types of probe experiences. This study observes that probing and learning is a vehicle for technology development, developing market insight and stimulating market development. Over time the firms' priorities change and the type of learning pursued differs. The three periods are characterised by a dominance of the following objectives for probing and learning.

1. Fist period: demonstration and customer education for market development
2. Second period: the pursuit of alternative probes to identify niche market opportunities
3. Third period: iterative development to align technology specifications with markets requirements

Considering these three characteristic periods of probe decision making and learning, this study finds that firms go through three similar phases of probing.

Three phases of probing are identified, characterised by different modes of probe decision making and different modes of learning. The phases have been conceptualised on the basis of theoretical concepts: i) exploration and exploitation (March 1991) and ii) learning by discovery and adaptive learning. The phases are defined by a dominance of explorative or exploitive activities and the type of learning.

1. Exploration: initial explorative probes in new markets
2. Experimentation: explorative probes in new markets combined with exploitive probes in continuation of probes in prior market segments
3. Development: primarily exploitive probes to iteratively develop applications in a selection of market segments.

The probing process proceeds through three phases, from divergent and chaotic to convergent, orderly and adaptive. First, a process of learning by discovery is observed, characterised as a divergent and experimental process of probing alternatives and new market segments. Within the phase of experimentation, learning makes a transition to more selective probe decision making and adaptive cycles of learning, characterised by the iterative development of probe paths. These findings support the findings of Van de Ven et al. (1999) on learning in the innovation process.

The probing strategies of individual firms have been described and compared, showing similarities in the overall duration of the phases. The conceptual model suggests that this can be explained by external factors, related to the phase of industry and market development. The similar phases therefore not only characterise the probing process of an individual firm, but also appear to represent phases of industry development. These findings are consistent with the model of technology and industry development proposed by Utterback and Abernathy (1975), describing a fluid, transitional and specific state of development. The findings of this study present a more in-depth understanding of the firm level management challenges and the different types of decisions and learning involved in this innovation process. In addition, this study has observed various differences between the probing processes of firms.

9.3.2 Variable Patterns of Probing

The comparison of probing processes reveals differences in timing as well as differences in the breadth of market segments pursued and the length of probe paths. The case firms were selected on the basis of different probing strategies in order to compare and identify different patterns of probing. The differences between the firms prevail in the experimental phase of probing. Based on these observations, probing process archetypes have been identified for different probing strategies and technologies applied.

- ➢ This study identifies the probing process archetypes of focused probing in a select number of market segments versus probing in a breadth of markets. Focused probing is characterised by market analysis prior to probing, early field trials and long paths of iterative development. Probing in a breadth of markets is characterised by market development efforts, a search for specific markets, and iterative developments through cross-over learning.

The conceptual model suggests that these differences can be explained by heterogeneous strategies and priority setting. Thereby, the archetypes are primarily related to the fundamental strategic choice of supply chain position: choosing to probe with an end product or choosing to probe with a subsystem. End products and subsystems show different development patterns. The iterative development of product platforms is characterised by linear probe paths within market segments, where the feedback from a probe is incorporated in a subsequent probe. Product platforms are probed in subsegments of a market segment. By contrast, subsystem platforms can be developed through applications in a breadth of markets. Thereby, a high degree of 'cross-over learning' between market segments takes place: operational data from various market segments is used to further develop the subsystems. Cross-over learning is particularly observed between markets with similar product requirements. Thus, subsystems are further developed through applications in a breadth of markets whereby, cross-over learning determines the effectiveness of this breadth.

- This study identifies two patterns of probing and learning: a linear path of iterative developments or cross-over learning from one market segment to another.

Furthermore, the time scale in years on the vertical axis reveals differences in timing. The case firms differ in, first, the timing of initial probes, second, the timing of the transition from divergence to convergence, and third, the timing of the transition to a developmental phase. Some firms engage in initial probes earlier than others, some take longer to transition to a developmental phase. Thus, the duration of phases is variable across firms. Coopers (1983) and Buijs (1984) similarly find a variable duration of innovation steps across firms. Based on the variations, these authors identify various clusters of patterns, with their own characteristics. For example, Buijs identifies a divergent and a convergent strategy formation process. This study expects that such clusters of patterns can be derived for probing and learning. For example, the probing archetypes described above, suggest a market oriented process and a technology dominant process. However, a larger sample is required to determine and verify clusters of such patterns.

Variable patterns are also observed in the length of probe paths. Some cases show longer probe paths and more continuity than other case firms. Long probe paths are observed in partnerships and under continuous government funding. Short probe paths with a low continuity are observed in firms that engage in various project-based probes or supplies for short term revenue. This variance is a consequence of the observation that probes are conducted for a multitude of reasons and firms set different priorities.

9.4 Rival Explanations

Multiple factors influence probe decision making. This study attempts to understand which factors dominate probe decision making over time. However, the variety of factors involved implies that there may be rival explanations. Departing from a dynamic capabilities perspective, this study suggests that probe decision making can be explained by a combination of internal and external factors with a variable role over time. Other perspectives ascribe more weight to either internal or external factors or appoint entirely different factors. Referring back to the decision paradigms described in section 5.2, on the variable rationality and influence of external factors assumed in decision making, various theoretical perspectives are discussed that may challenge the findings of this study.

This research suggests that probe decision making is explained by strategic intent as well as factors external to the firm. A rival explanation of probe decision making is that the institutional environment overrules the strategic intent and rationality of an individual firm. Arguments for this perspective include: the commercialisation of FC technology is influenced by regulatory support such as emission legislation and government grants. It can be argued that firms lack the information to rationally evaluate markets themselves, whilst the industry has formed collective expectations over time. From this perspective, scholars may argue that mimicking behaviour and institutional factors overrule rational behaviour and strategic intent in explaining probe decisions. Although study has observed homogeneous behaviour in the selection of initial probes and the pursuit of emerging markets, institutional factors do not explain the diverse strategies pursued in the experimental phase. This study suggests that in the experimental phase, a firm's internal factors are more important than institutional factors to explain the divergent process of probing alternatives. Moreover, in this period, the young FC firms do not solely rely and react to developments in their environment. The young FC firms are actively involved in the development of their market and the institutional environment. The role of demonstration projects in stimulating political change is also described by Karlstrom and Sandén (2004). In this context, it is not surprising that firms have influence on the formation of the institutional environment, because institutional routines, standards and norms are still being developed.

It can furthermore be argued that probing behaviour is primarily driven by the shared outlook of a network or partnerships. The idea of a shared outlook of engineers was developed by Nelson and Winter (1982) and Dosi (1982), referring to the notion of a technological regime to account for the problem solving activities of engineers. These scholars suggest that firms within a technological regime are blind to technological possibilities outside of this regime. Similarly, Jacobsson and Johnson (2000: p.629) suggest that firms innovate within a technological system and in a network of actors, *"the determinants of technology choice are not only to be found within individual firms, but also reside in an `innovation system' which both aids and constrains the individual actors making a choice of technology within it".* Similarly, from a network theory perspective, the network in which a firm is based is more influential than the individual choice of a firm. Although shared beliefs of the industry influence initial probe decisions, these theoretical perspectives do not explain why firms pursue heterogeneous strategies in the experimental phase of probing. The influence of strategic partnerships has partly been addressed and appears to explain long probe paths. It can also be argued that the case firm's network explains the scope of opportunities a firm has to probe, partner, supply or gain revenue. However, this study finds that a firm's network is being formed throughout the probing process and is likely to have more influence on the probing process in the development phase when relationships become structured and more rigid.

This study finds that a firm's internal factors explain the differences observed in the experimental phase of probing, including firm competences, strategies and priorities. Differences in the experimental phase may also be explained from a cultural theory perspective, whereby probe selection is influenced by the culture of a firm. It was argued that YTB firms are still in the process of developing a culture and routines. Nevertheless, this study finds that firm history influences the strategic positioning of firms and the different strategies pursued in the experimental phase. A firm's culture and history at least partly determine the scope of markets a firm chooses to engage in or not. However, this study did not find firm history to dominate decisions. From a resource based view a firm's unique set of competences drive heterogeneous probe decisions and strategies. Similarly, Teece et al. (1997) state that differences can be explained by unique dynamic capabilities. However, Eisenhardt (2000) argues that the dynamic capabilities themselves are not unique, in high velocity environments they are common learning mechanisms. Rather, the specific experiences gained in the learning process are unique. Similarly, this study finds that firms develop unique probing experiences that may provide a competitive advantage for subsequent commercial development.

This study suggests that despite heterogeneous probing strategies and unique probing experiences, firms end up in similar markets. Therefore, this study finds that the emergence of market demand dominates a firm's internal competence to explain probe decision making. In conclusion, the different factors proposed by various theories play a role in probe decision making in some way or another. Nevertheless, within the context of radical technology application and YTB firms, this study finds that industry expectations primarily drive initial probe decisions, a firm's internal factors primarily drive experimental probing and firms respond similarly to the emergence of market demand.

9. 5 Limitations and Future Research

Research Design

The select number of cases within the FC industry has enabled an in-depth analysis of probe decision making in the FC case firms. However, this approach also poses several possible limitations. First, the research is based on a limited sample of case firms. Within the scope and timeframe of this study and the exploratory objective, the author considers the sample to be sufficient, as this sample has enabled an in-depth analysis of FC firms. However, there are limits to the verification of findings. To further research probe decision making and validate findings, a larger sample of cases in the FC industry is recommended. The focus on cases in the FC industry may be seen as a second limitation. The FC industry focus has enabled comparison between the case firms and an in-depth insight into the FC case firms. In addition, this focus was necessary to minimise extraneous variables. However, the FC industry focus puts limits to the scope of generalisation. To validate findings and compare probe decision making for YTB firms in general, further research should select a sample of YTB firms from various industries. A first step could be to sample and compare YTB firms in the FC industry, PV industry and battery industry. A comparative study of sustainable energy technologies can contribute to a further understanding of the innovation process for sustainable technologies.

Furthermore, it is too early to evaluate the success or failure of the FC case firms. Due to ongoing developments and the early state of commercialisation, the outcomes of probe strategies are yet to be determined as successful or not. A ‘best practice’ analysis, common to NPD and innovation studies, cannot be derived as yet. Instead this study has observed various probe processes and strategies and the analysis has been primarily descriptive and explanatory. A third limitation of this study is therefore the limited analysis of success and effectiveness. A future ex-post study of applications in the FC industry may give insight into the more and less successful probing strategies and ‘best practices’. An ex-post study would additionally facilitate further research with quantitative measures of effectiveness.

Finally, the data and analysis of this study have primarily been qualitative findings, due to the exploratory nature of the study and the limited availability of quantitative data in the emerging industry. This research has taken a qualitative approach to gain an in-depth understanding of the probing and learning phenomenon. To further develop and validate findings, quantitative measures of effectiveness should be derived in future research projects. For example, in an ex-post study, financial data and sales data can be used as measures of success. In the meantime, other measures of success can be used, relative to a firm’s objectives. For example, the outcome of a demonstration probe for publicity can be can be measured through media tracking data. Furthermore, firms may provide more data to quantify the relation between a firm’s resources invested in a probe and the number of customer orders derived from the probe. Survey methods of research can be applied to gain such quantitative firm data from a larger sample of firms. Nevertheless, surveys may provide limited data due to the disclosed and confidential nature of investment decisions. In comparison, subsidised projects are relatively open to the public domain. Therefore, subsidised projects may be a source of data and provide the opportunity to make quantitative comparisons of probe investments and their outcomes. Finally, to further develop the concept of cross-over learning, more quantitative measures are required. A possibility to measure technical cross-over learning is to track the generation and application of operational data from probe applications. Measuring which data and how much of the data is used in other market segments allows us to measure the level of cross-over learning between market segments.

Propositions

The findings of this exploratory study provide a point of departure for future research projects. The propositions derived from the case study data require further research to validate and extend findings. First, to validate the influence of investor pressure on the selection of initial probes, a broader sample of case firms with variable financial structures is required. A future research project, to address the influence of investor pressure on the selection of initial probes, should focus on interviews with financial managers and investors and focus on the collection of financial firm data. Secondly, to validate the necessity of probing alternatives, further research should be conducted on the process of 'probing and learning' with a larger sample of cases from various industries. Probing alternatives is bound to the experimental phase of probing or the fluid phase of industry and technology development. Therefore, a study over various industries should either compare industries that are all in the fluid phase of development, or compare the industries in an ex-post study.

A third topic for further research is the influence of customer familiarity on probe decision making. To focus on customer familiarity in a future research project, the construct should be divided in two : i) a customer's familiarity with the technology in general and ii) a customer's familiarity with a firm. The latter is particularly relevant for better understanding the development of firm legitimacy through the process of probing. Future research focusing on the influence of this construct would require more interviews with customers and data from customers. Relevant topics for future research include the influence of different forms of customer education and market development on the timing and focus of probing processes. Furthermore, a firm's ability to shift between markets requires further research. The case firms appear to be successful in shifting on the basis of their technological competences, however, as yet the long-term consequence and competitive advantage of this probe experience cannot be assessed. Additionally, questions remain on the duration of flexibility: until when is a firm able to shift on the basis of its technological competences and is there a moment in which market competences become determinant for a firm's ability shift to other markets? The success of shifting in relation to a firm's competences requires an ex-post analysis of the shifting outcomes, in terms of market penetration and diffusion success. Furthermore, there are several measures that have received less attention in this study. A firm's network and strategic partnerships are observed to be influential for YTB firms, but require further research. Focusing on the relationship between young developers and large firms in an emerging industry may provide more insight into the influence of partnerships on probing and learning.

A sixth topic for further research concerns the role of market assessment in the process of probing, to asses if and in which cases market assessments reduce the necessary breadth of probing. The sample should thereby include case firms that emphasise market assessments and case firms that emphasise probing in diverse applications. Such a comparison of polar case firms may provide further insight into the most effective combination of market assessments and the breadth of probing. Thereby, this study suggests that there are limits to the advantage of probing alternatives. The long-term advantage of probing alternatives compared to other strategies is not entirely evident. Although some degree of probing can be expected in all firms, the probing archetypes suggest that firms may choose to, for example, conduct market assessments, talk to customers or form partnerships instead. Therefore, the degree to which competitive advantage can be derived from probing requires further research. In an ex-post study, a the relative success rate of firms that primarily pursued probes and firms that primarily conducted market assessments can be compared.

Literature
This study revolved around the technology application process and used literature on innovation and high technology marketing as a starting point. Innovation studies were suitable for a design focused and process based approach. However, in retrospect, the firm level analysis and findings are strongly related to literature on 'order of entry' strategies, firm growth and the emergence of new industries (references in section 9.2). Although this study has referred to related literature, further research may start from a combination of innovation studies and literature on firm growth and new industry creation. These fields of literature are likely to complement each other in further research on the process of technology application, firm growth and the emergence of new industries.

9.6 Scope of Generalisation

This study has made predictions, observations and analyses of the technology application process in FC firms. Regarding the objective to integrate and extend theory, it is necessary to question the degree to which the findings can be generalised. A common criticism of case studies is the difficulty of generalising from one case to other cases, no matter the size of the case study set (Yin 1994). With a study of four cases within the FC industry the previous section has discussed the limitations of this study. This section discusses the degree to which the research findings can be generalised to the application of other technologies and other types of firms.

The scope of generalisation is determined by: i) the variables of the descriptive model and ii) the characteristics of FC technology. Probing processes have been described in terms of the breadth of market segment and the length of probe paths. The variable, breadth of market segments, implies that this model is primarily suitable for technologies applicable to a diversity of markets. The characterising factors of FC technology, discussed in chapter 3, determine applicability of the propositions and the observed patterns to other sectors. FC technology has been characterised as a replacement technology, radical to (OEM) customers and applicable to a diversity of markets. In addition, this study has focused on the YTB firms of the emerging FC industry. Therefore, this paragraph will discuss the scope of generalisation along the following characteristics: i) the application diversity of a technology, ii) the radicality of a technology and iii) the organisational setting, i.e. YTB firms compared to established firms.

9.6.1 Application Diversity

The propositions suggest that probing alternative market segments is necessary to identify and develop value propositions. Additionally, an experimental phase of probing in a breadth of market segments is proposed. These findings are primarily relevant when there are several applications to choose from and the outcome of their pursuit is uncertain.

FC technology has been characterised as a replacement technology applicable in diverse market segments and applications. Replacement technologies are typically applicable to diverse existent markets. Similar to FC technology, PV and batteries have been applied in a diversity of market segments at the same time. By contrast, the case of computer technology illustrates how a new product category was created and that over time the technology was applied in different customer segments within this product category. There are also technologies for which the possible scope of applications and markets are broad but new and unknown. For example, in the case of electricity, Rosenberg (1995: p.175) describes, *"It took many decades to explore applications for electricity after Faraday discovered the principles of electromagnetic induction in 1831".*

This comparison shows that the case of FC technology represents technologies applicable to diverse market segments for which applications are known. This type of application diversity poses particular selection challenges. Probes are selected from a wide range of possible market applications. Thereby, the main uncertainty is related to timing: there is uncertainty about which customers and market segments to engage in at which time. This uncertainty is strengthened when there are diverse short and near term niche markets to choose from and the potential for large scale market application is known. In the case of PV, there is an envisaged large scale market for power generation but the technology was first applied in various niche markets. New battery technologies open up the opportunity to address large scale markets, in the meantime, applications are pursued in niche markets. The probing process for replacement technologies is also characterised by various reasons to engage in probe applications and a wide range of applications to choose from. Therefore, this study expects that the proposed experimental phase of probing alternatives in a wide range of markets segments primarily holds for replacement technologies, diversely applicable to existent market segments.

Finally, probe decision making is challenging when there are multiple applications to choose from and their outcome is uncertain. This uncertainty prevails in the early phases of technology and industry development.

As the technology life cycle models in literature suggest, the wide range of alternatives and variations in the 'era of ferment' (Tushman and Anderson 1986), the pre-dominant or 'fluid state' (Utterback and Abernathy1975) of technology development, cause high degrees of uncertainty. Thus, the research findings can primarily be generalised to replacement technologies, applicable to diverse existent market segments, in the pre-dominant phase of technology and industry development. In the case of more radical technologies, different patterns of probing are expected.

9.6.2 The Radicality of a Technology

FC technology has been characterised as a replacement technology or 'technological innovation' in which the technology is highly novel but the market applications are known. As a replacement technology, there are benchmark requirements to start from and most of the potential applications are known and firms can probe the alternatives. There is therefore primarily uncertainty about the potential and the time frame of market adoption. Similar to FCs, the case of PV technology illustrates the situation where potential markets and customer requirements are known but the customers are slow to adopt the technology. By contrast, 'complex' technologies are more radical: their market applications and the possible alternative markets to 'try out' are unknown. In terms of novelty, a complex technology is more radical than a replacement technology. Computer technology, for example, was 'in search of applications'. In contrast to FC technology, the computer industry shows a somewhat linear emergence of markets (Balachandra et al. 2004). Similarly, Lynn et al. (1996) observe a linear pattern for the application of mobile phones. In the case of complex technologies, the search for applications is expected to involve a more linear process of probing alternatives: finding one, trying it out and on to the next. By contrast, for a replacement technology this study observes a breadth of parallel probes in an experimental phase of probing. Similarly, other 'replacement technologies' such as batteries and PV are probed in diverse probes at the same time. Additionally, the concept of cross-over learning is observed between parallel market segments. Finally, market assessments prior to probing are expected to be more useful for replacement technologies, starting from existent market requirements, than complex technologies.

Furthermore, FC technology has been characterised as radical in terms of customer unfamiliarity and their necessity to replace prior competences and acquire new competences. The case of FC technology suggests that experimentation and divergence is necessary to convince and educate customers. In the case of batteries, many customers have the competences to handle batteries and in several markets, batteries are applied as a 'black box' requiring a minimum of system integration effort. However, the application of batteries in novel electrical systems, such as BE vehicles, does involve a radical change for customers, similar to the design of FC vehicles. Besides, batteries have developed a 'bad image'. PV solar cells face a similar problem. Therefore, similar to the FC case, developers have to put effort into explaining and demonstrating the potential of new battery and solar cell technologies and designs. For technologies that are less radical to customers, firms are likely to pursue fewer probes for market development and customer education. Moreover, the predicted influence of customer unfamiliarity on the breadth and duration of experimental probing is less relevant.

Finally, FC technology has also been characterised as a radical environmental innovation typically involving changes to a complex system of technologies. Such technologies depend on the development of regulatory support and complementary technologies such as infrastructure. These characteristics have not been discussed in the case study. On the basis of limited observations, this study expects that the probe process for radical environmental innovations is particularly long.

Thus, the phases of experimentation with diverse and parallel probes and cross-over learning are primarily applied to 'technological innovations' or replacement technologies. In the case of complex innovations, the process is expected to be more linear and stretched over a longer period of time. Moreover, in the case of technologies that are less radical to customers, the concept of probing for developing market insight and market development is less relevant.

9.6.3 YTB firms - Established firms

The probing process model has been applied to young FC firms. Van den Ven et al. (1999) argue that, in principle, the innovation process shows similar patterns for all organisational settings. However, the characterisation of young FC firms suggests that differences can be expected between probing in established firms and probing in YTB firms. Within the FC industry an illustrative comparison can be made between the car manufacturers and the young independent FC firms.

Car manufacturers are typically large established companies, characterised as system integrators with an elaborate hierarchy of suppliers. Typically, FC developments are a small component of the firms' scope of activities and objectives. By contrast, hydrogen and FC technology are at the core of a young FC firm's business. The car manufacturers have demonstrated multiple prototypes of FC vehicles, however, a majority of the developments take place internally, behind closed doors. Large companies in Japan are rumoured to actively develop FC applications, however, the majority of their 'probes' remain undisclosed. By contrast, for young FC firms, probes play a central role in demonstrations, to develop legitimacy, attract investors and develop relationships with customers and partners. Car manufacturers have allocated sizable R&D budgets to FC technology for internal R&D or outsourcing. By contrast, the young FC firms are limited in resources to allocate to R&D and probe applications. Similar to FC firms, young battery firms face problems of capital investment to build manufacturing capacity. Furthermore, young FC firms have been observed to probe in various markets. For YTB firms, the selection and engagement in various probes and niche markets is necessary to identify and develop short term niche markets. By contrast, car manufacturers are typically focused on the automotive sectors and have less interest in short term market investments. Moreover, established firms are typically less flexible to jump from market segment to market segment.

For established firms in a particular segment, probing in a breadth of market segments is less likely to occur than for YTB firms. Furthermore, the weight of factors to explain probe decision making will differ. In comparison, external factors are expected to have more influence on probe decision making in YTB firms. Moreover, established firms are under less pressure to publicise prototypes and early applications. It may be difficult to historically map probe applications that are developed and kept within an established firm. In conclusion, findings of this research are primarily applicable to YTB firms targeting the application of a new technology

9.6.4 Conclusion on the Scope of Generalisation

The research findings on probe decision making and patterns of probing are more broadly applicable than to the FC industry alone. The scope of generalisation is largely determined by: i) the variables of probe decision making and ii) the characteristics of FC technology. The research findings can primarily be generalised to replacement technologies with diverse applications in existent markets. The application process for replacement technologies involves various parallel probes in diverse market segments. Therefore, research findings on, for example, probing alternatives and cross-over learning are primarily relevant for replacement technologies such as PV and battery technology. In the case of complex technologies, where the scope of applications is new and unknown, the patterns of probing are expected to show a more linear process over a longer period of time. Less radical technologies are expected to show a lower diversity of probes and fewer probes for the purpose of demonstration and customer education. Finally, the research findings are primarily applicable to YTB firms targeting the application of a new technology. Established firms are expected to conduct most probes internally and conduct fewer probes to search for niche markets. Moreover, the influence of external factors, such as industry expectations and customer familiarity are primarily influential in YTB firms.

9.7 Contributions and Recommendations

The structure and approach to this study has been determined by a dual objective: i) to contribute both to practice in the FC industry and ii) theory development in innovation and technology marketing studies. The first two paragraphs will discuss the contributions and recommendations to innovation literature and design methodology. Subsequently, contributions to practice for FC firms and YTB firms in general are discussed, followed by implications for policy makers.

9.7.1 To Scholars in Innovation Management

Findings from innovation studies and high technology marketing literature have been integrated to extend theory on the application of radical technologies. The research findings contribute to an understanding of the innovation process by highlighting how firms manage the process of technology application. The concept of probing and learning, proposed by Lynn et al. (1996), has been extended with: i) a model to describe and analyse the probing process, ii) a conceptual model to explain probe decision making and iii) a characterisation of phases and different patterns of probing. Thereby, the concept of 'probing and learning' has been taken a step further to address the literature gap described in paragraph 4.5.3. Furthermore, concepts of organisational learning in the innovation process (Van de Ven et al. 1999) have been applied and extended to explain innovation as a learning process. By integrating the concept of probing with concepts from organisational learning, the early application of radical innovations is described as a process of learning by discovery.

The findings also complement strategic niche management literature and the concept of niche market accumulation with a firm level perspective on the selection and development of niche markets. Scholars of strategic niche management have recognised the emergence of niche markets in technological transitions, but do not address how these niche markets are selected and developed. These scholars assume that niche markets emerge, are profitable and contribute to the development of subsequent markets. The findings of this study give insight into how these niches are selected and emerge. This study suggests that niche markets do not 'simply' and evidently emerge. For YTB firms it is a challenging process to identify and develop niche markets. Moreover, several 'non profitable' probes are realised prior to the emergence of a niche market and not all probes and niche markets contribute to the development of subsequent niche markets. These findings are relevant for understanding the process of technology application and niche market emergence.

With a focus on YTB firms, this study contributes to the understanding of entrepreneurial firms in innovation studies. This study suggests that although probing and learning is likely to occur in both established and young firms, there are significant differences in managing this part of the innovation process for different organisational settings. This study has reviewed innovation studies and technology marketing as the point of departure. For further research on the probing and learning in YTB firms and the application of radical innovations in general, this study recommends a review of literature on new industry creation and firm growth to complement innovation and marketing literature.

The concept of probing and learning

Lynn et al. (1996) suggest that it is relevant to understand how firms can probe and learn effectively and recommend the development of a methodology for probing and learning. This study provides further input to derive such a methodology. First, in line with Lynn et al. this study suggests that probing and learning should be managed as a 'quasi-experimental' process, i.e. to engage in new experiments based on a strategic assessment and the information available instead of 'blind trial and error'. Second, this study finds that although probing alternatives is necessary, there are limits to the effectiveness of breadth in terms of learning. The effective breadth appears to depend on the phase of probing and the supply chain position of a firm. Third, this study recommends market assessments prior to probing to assess the learning potential and the market opportunity. Also, the assessment of a customer's commitment and capability prior to probing is recommended. Fourth, the effectiveness of probing is largely determined by the post evaluation of probes and the experience gained. In this manner, maximum results can be derived from apparent failure. Thereby, this study suggests that 'cross-over learning' between market segments can enhance the effectiveness of probing with a replacement technology.

A key contribution of this study towards a probing and learning methodology, is the consideration of different phases of probing in which probing should be managed differently. This research suggests that there are different phases of probing and that in these phases firms face different priorities, pressures and temptations. Throughout the process of probing, firms will have to prioritise the selection of probes differently, for example, probes for market insight, probes to stimulate market development and probes to develop an application. Additionally, in each phase firms will have to consider their reaction to opportunities and pressures from the external environment. For example, in the phase of development, firms should select 'wisely' from the opportunities for revenue and partnership formation to avoid distraction. Thus, this study suggests that a methodology for effective probing and learning would require a consideration of different priorities and external influences throughout the phases of probing. The development of a probe and learn methodology relates to the field of design methodology, discussed in the following paragraph.

9.7.2 To Product and Strategic Designers

The research findings concern both technology and product development. There is a fine line between the field of technological innovation and product innovation. Despite the overlap, the fields start from different disciplines and models. Product innovation models typically assume that mature technologies are applied in the design process. The process of probing and learning in FC firms shows how technologies, markets and products co-develop and interact. This study expects that the findings on technology application processes and strategies can complement methodologies of strategic product innovation. Additionally, the role of industrial design engineers in the process of technology application is discussed.

The academic discipline of design methodology has derived several models of the product innovation and product design processes (e.g. Archer 1971, Rozenburg and Eekels 1995). Similar to the application of new technologies, the 'front end' of product innovation (section 4.2) includes the analysis and development of market opportunities. Similarly, the strategic product innovation model by Buijs (1984) describes the assessment of opportunities and threats in the environment and an analysis of the strengths and weaknesses within a company to formulate product innovation strategies for companies. This model addresses new technologies within the external or internal analysis. Nevertheless, this product innovation model does not directly apply to technological innovations, when a new technology is 'the centre of attention', instead of a new product. There appears to be an opportunity to further develop the strategic product innovation model for the consideration of technological innovations. Typically, product innovation and development models apply to mature technologies. Yet, in the case of radical innovations, firms may need to strategically plan their involvement in radical innovations at an early stage of technology development.

Furthermore, this study suggests there is an opportunity to further develop the strategic product innovation models for technology based firms in highly uncertain environments: the strategic design of a firm's probing process with respect to the position a firm wants to be in and the competences it needs to develop to be competitive in that position. The strategic design of a probing process is likely to require a similar phase of assessments, but with more experimental assessment methods. The design of a probing strategy may include a strategy for the purpose, the time, the place, the market and type of product for a company's probe applications over time. Thus, this study recommends the extension of strategic product innovation methodology to include the design of probing strategies and probe applications during the process of radical innovation.

- Based on the findings on the process of probing and learning, there is an opportunity to extend strategic product innovation to include the strategic design of: i) a firm's involvement in radical innovations and ii) strategies for technology based firms

The second contribution to the field of product design and innovation is the role of the Industrial Design (ID) Engineering discipline in the process of technology application. Although the discipline of product design dominates in the phase of product development, after early probe applications, this study expects that ID engineers can play a central role in the development of FC probes and early applications in general. First, identifying and developing FC probe applications requires inter-disciplinary communication and interaction. Due to the inter-disciplinary nature of ID engineering, this discipline is expected to provide a valuable contribution to a team of developers and stakeholders. ID designers can, for example, function as a bridge between technology developers and OEM customers in identifying opportunities and aligning customer requirements to technology specifications. Secondly, this study finds that through product design, ID engineers can contribute to external communication, demonstration and market development in the probing process. Therein, ID engineers are capable of translating the technology into visually attractive probe applications. In addition, the discipline can contribute to the exploration of innovative design concepts for new technologies, as illustrated in paragraph 3.2.4.

New replacement technologies, such as FC technology, can be placed in existent products. However, new technologies also offer opportunities for dedicated and innovative designs, for example, by reconfiguring the engine layout and structure of FC vehicles. Although the majority of FC applications to date have replaced the energy systems in existent products to minimise complexity and cost, innovative design concepts appear to be an effective way to communicate the potential of a new technology, and generate publicity and awareness. The discipline of ID engineering can contribute to dedicated and innovative product designs for a new technology in the process of probing applications. In the FC applications observed, dedicated design requires considerable learning to integrate FC systems in products and design the system/product interface (section 3.2). To ID engineers this study, therefore, recommends close interaction and collaboration with FC developers and customers in the process of FC product design. As applications move towards product development, the role of product design is likely to become more evident. Nevertheless, this study suggests that ID engineers can provide a valuable contribution in the early process of applications.

9.7.3 To Practitioners in YTB firms and FC firms

This study aims to provide FC firms with insight into the commercialisation process of FC technology and the challenges faced regarding technology application. This study has looked back into recent history, providing an overview of the early applications process and the various strategies pursued.

The analysis of probing histories helps to understand what has happened in the FC industry, why it has taken so long and where FC firms are now with respect to prior and future developments. Moreover, the model provides FC firms with an approach to analyse their history of probe applications or strategically plan future probe applications. Generating an overview of the rationale and consequence of their probe decisions may assist FC firms in selecting and learning from probes more effectively. In a similar manner, the models may be useful to YTB firms in general. The generalisation suggests that the probing models are particularly applicable to replacement technologies, when there are multiple applications to choose from under a high degree of uncertainty. The proposed phases of probing can help to analyse a firm's position in the process of application, with reference to prior probes and future plans. For example, an entrepreneur in PV technology can map out its probe and niche market applications to analyse where it has gained experience and relationships, where the company would like to further develop these resources as well as new market segments that may be useful to explore. Thereby, the analysis of a firm's probing process and probe applications can contribute towards the following management challenges:

- Application and portfolio management: choosing smart,
- Timing of probes: timing applications right,
- Developing probes effectively: maximise (cross-over) learning.

In the probing process, firms can at least partly determine which markets they want to be in, with which customers they want to partner and which supply chain position to take. Probing and learning is related to the development of a firm's competences, partnerships and legitimacy. The conceptual model suggests that in the first phase of probing firms need to balance shared beliefs and industry expectations with the firm's beliefs and expectations. In the second phase, firms are challenged to balance priorities between technology and market development, partnership formation and opportunities for early revenue. In addition, the experimental phase requires a high degree of flexibility with respect to customers. Moreover, the development of firm legitimacy should be a central priority in this phase of probing. In a subsequent period, firms should prioritise technology validation to respond to the emergence of market demand. Therefore, probing and learning as a management practice involves developing a firm's competitive resources and competences as well as reacting appropriately to uncertainties and changes in the external environment. In each phase of probing the following practices are recommended:

- Explorative phase: collective learning and marketing in the emerging industry,
- Experimental phase: probing and market assessments to identify compelling value propositions,
- Experimental phase: demonstration and education to convince customers and develop legitimacy,
- Developmental phase: developing unique and validated technological competences to respond to the emergence of market demand.

The recommendations on a methodology for probing and learning (9.5.3) are applicable to YTB firms, including the prior and post evaluation of probe applications. In the case of replacement technologies, YTB firms should assess the market opportunity but also evaluate the expected experiential outcome and the potential for cross-over learning. This study provides the following recommendations to YTB firms:

- Balance the exploration of new markets as well as iterative developments. By searching for new niche market opportunities, a firm maintains its entrepreneurial spirit, necessary for flexibility in the context of uncertainty. At the same time, technology development and iterations are necessary to meet customer requirements and validate a firm's technology.
- Design for cross-over learning. With a limited number of multi applicable technology platforms, experience can be transferred between markets. Thereby, a diversity of probes can contribute to further development.
- Assess the necessary breadth of probing. For the purpose of learning, the recommended breadth of probing depends on the scope of options to choose from and the required effort for customer demonstration and education.
- Pro-active market stimulation whilst maintaining realism. Considering firm dependence on customer perception, probes are instrumental in communicating with and convincing customers. However, 'bluffing' will attract customers that are not willing or able to commit to the risk and costs of probe applications.
- Maximise the competitive advantage of probing, by pre-selecting probes on the basis of the opportunities for learning, integrating specific experiences from probes into the competence base of the firm and using probe experiences to specify unique value propositions.

9.7.4 To Policy Makers

This study describes several challenges YTB firms face in commercialising their technology. Similar to the commercialisation of other sustainable technologies, FC technology requires substantial government support for further development towards commercialisation. The young FC firms do not only need government support for early R&D, but also throughout the phases of probing and learning. In particular, this study suggests that young FC firms and YTB firms in general, require significant financial support and protection during the experimental phase of technology application. This argument is in line with the recommendations to public policy by Van de Ven et al. (1999). According to these authors, YTB firms require an 'incubator environment', not necessarily in the start-up stage of a firm, but during the adolescent stage in which firms are most vulnerable to environmental disturbances. The size and duration of government grants should be designed to meet YTB firms in this phase of technology application.

Government grants are traditionally allocated to fundamental R&D. Applications and demonstrations have been considered the responsibility of market actors. Although recent funding programmes signal a change in this attitude, demonstrations and applications generally receive less funding. However, in practice, the financial investment and risk of early probe applications is too high for many OEM customers. In FC demonstration projects, the cost and uncertainty are typically too high for commercial customers, emphasising the necessity of funding for demonstrations. Moreover, this study demonstrates the necessity of probing alternatives and the duration of the experimental phase of probing. This study suggests that the funding of projects and the duration of funding should take into account the characteristics of this process. In the Netherlands, projects have been funded for a limited period, limiting the continuity of probe efforts. Van der Hoeven (2001) finds that in the case of MCFC technology, the short term funding periods led to an accumulation of promises and unrealistic expectations. Policy makers are, therefore, recommended to consider the necessary duration of probing and learning in the design of funding schemes and the selection of demonstration projects.

Considering the costly and time consuming process of probing, this study recommends the careful selection of probe applications for demonstration. This study finds that the effectiveness of probing relies on the selection of probes, the degree of learning from the probes and the integration of these lessons in subsequent probes. Regarding the selection, development and funding of demonstration projects, this research recommends policy makers to:

- Fund probes with a demonstration value as well as an economic value proposition. Demonstration projects should be selected carefully on the basis of a 'value proposition' analysis, to target probes with demonstration value as well as some degree of commercial realism and potential for continuation.
- Fund probes with a longer term vision. Planning beyond demonstration projects and short term funding, increases the commitment of commercial stakeholders and the likelihood of continuity.
- Clarify the application and technology development objective among stakeholders. This study suggests that awareness of status, costs and risks among stakeholders in consortia, increases the chance of success and continuation.
- Specify the main objective. Probe applications are conducted for several purposes and the benefits for different stakeholders are variable. Projects for public demonstrations may, for example, hardly benefit YTB firms. Currently several FC firms, for example, primarily need support for realising field trials on scale.
- Consider probes as vehicles for learning. To maximise the outcome of subsidised projects, considerable-attention should be paid to the formulation of learning objectives and the post evaluation of the lessons learnt and the consequences. Within a project, the analysis of 'what went wrong' is particularly valuable for the stakeholders involved. For policy makers, the cross- case analyses of projects may help shape a more effective approach to selecting and supporting probe applications.

The application of radical technologies, as technology and market develop through a process of multiple probe applications, emphasises the importance of an interactive and dynamic interface between policy, technology developers and market actors.

9.8 Expectations for FC technology

This research has explored FC technology, the markets for application and the industry as well as the role of FC technology in the context of sustainable development. This research has focused on the process of probing and learning in the FC industry. However, expectations with regard to 'popular' questions can also be addressed with the experience and information gained. Therefore, although the academic argumentation is limited, this paragraph provides the author's opinions and views on such questions.

On Young FC firms

Departing from a concern for the 'survival' of young FC firms in the long process prior to widespread commercial sales, questions on firm survival and success are likely to arise. The author expects a 'shake-out' of young FC firms prior to widespread commercialisation. At the moment, it would not be advisable to proclaim failure over the hard working and visionary firms. The variation in business models suggests that some firms will be more successful than others. Time will tell which decisions in trade-offs, business models and strategies are most successful. Expectations can probably best be derived from the competitive position of firms with respect to each other. At the moment, competence base, experience in applications, network and customer relations appear to be critical points of departure. Ideally firms are prepared for niche markets and positioned for longer term markets. However, in practice, firms are better positioned either for one or the other. Some firms are ready to supply to emergent markets, whilst others will not be able to supply when demand emerges. At the same time a reliance on niche markets is risky because many niche markets are not large enough for long-term survival. A number of other FC firms are well positioned to supply to car manufacturers in the future, in terms of network and the competences, experience and technology required for compliance with automotive standards. Nevertheless, this market is still too far away to rely on.

Technology Commercialisation

The mass market adoption of FC technology is widely questioned. Will large scale commercialisation happen and if so, when? There are ongoing debates on these questions and scenarios have been derived by several institutions. Widespread adoption of FC technology is largely determined by the pace of automotive adoption and the application of mandatory zero emission legislation. FC firms have become careful to predict a time frame for automotive adoption. Moreover, the success of the hybrid electric vehicle and developments in bio fuels, illustrates the fierce competition to become the 'cleaner' dominant solution. A new, and perhaps better, technology is bound to push away the conventional IC engines at some point in time, however, which technology that will be is highly uncertain. Besides, despite several 'hydrogen highway' initiatives, large scale investments in hydrogen infrastructure investments are not taking shape at the pace required for widespread commercialisation. Therefore, in the author's opinion, the widespread application of FC technology is highly uncertain. Most probably, several FC vehicles will be spotted on the road by 2015, however, the timeframe for widespread automotive adoption is expected to be closer to 2030.

Considering the technical challenges that remain, such as cost reduction and hydrogen storage, one may question if these problems can be solved within a reasonable time frame. It has been said that when a technology becomes more and more complex and problematic, the chance of successful application becomes smaller. In the author's opinion, the current solutions for hydrogen storage face problems of this kind. Hydrogen storage at 700 bars, for example, is technically feasibly, but considering the complexity and cost, the solution is all but elegantly simple. There appear to be more elegant solutions on the horizon, for example, the application of nano-structured materials. However, the commercialisation of these developments requires considerable R&D investment and commitment. Despite the timescale and uncertainty of automotive adoption, the author expects to see multiple FC applications of FCs in niche markets.

Market Adoption

The FC industry is experiencing the emergence of initial market demand in niche markets. Will this market be successful and which markets will follow? The order of niche market emergence is largely determined by the required cost per kW. However, the rate of cost reduction and customer behaviour is difficult to predict. Established OEM customers are taking their time to learn and decide. By contrast, dedicated FC OEM firms have emerged targeting niche markets such as back-up power and material handling. The emergence of market demand for back-up power appears promising. However, the speed and momentum of this market may be limited. At the same time, there are a multitude of markets for critical and less critical back-up power. The market for forklift trucks is less imminent, but in the author's opinion the widespread adoption of FC technology in forklift trucks is likely. The European and North American support for field trials in this sector appears to be promising. The early markets for back up power and material handling will initially rely on critical operations in specific markets, typically for business-to-business customers. These markets are characterised by a sense of urgency, due to significant problems with the current batteries. Providing that the cost and performance benchmarks are met and the technology is validated within reasonable timeframes, the author expects widespread adoption of FC technology in these markets around 2015.

Investors and suppliers are keen to find out when commercial developments will commence. In general, the process of development, realisation and testing is taking longer than expected. Moreover, there is a risk that other niche markets will not follow and accumulate towards large scale markets. In the author's opinion, the accumulation of niche markets is likely considering the multitude of possible market applications and the steady improvements in price and performance. For example, other material handling and battery powered specialty vehicles are likely to follow the adoption of forklift trucks. Such applications may be stimulated by developments in urban emission legislation. Portable power is also believed to be one of the first commercial markets that may stimulate the accumulation of niche markets. However, in the author's opinion the widespread adoption of portable power is more uncertain, typically relying heavily on consumer markets where the urgency of adoption is limited. Moreover, the early adoption of FC technology in consumer markets largely depends on how the public interest in sustainable development and climate change develops in the coming years.

Sustainability

FC technology has the potential to play a central role in making the transition towards a more sustainable energy system. However, there are heated debates on the sustainability of hydrogen and the use of hydrogen. The contradicting conclusions from well to wheel analyses illustrate the complexity of assessing the sustainability of hydrogen FCs. In any case, hydrogen production determines the level of efficiency and emissions. In the author's opinion, considerable investment and commitment to the development and commercialisation of novel hydrogen production technologies is urgent. However, blindly applying FC technology to any application is not the way to go. For several applications, FC technology is not the most environmentally friendly solution. In terms of sustainability, the author finds that FC technology should only be applied when the advantages outweigh the energy loss of energy conversions. New battery technologies provide a promising and clean solution for many applications. Besides, hybridisation with batteries typically improves the efficiency of a FC system. Therefore, in the author's opinion, battery and FC technologies should be considered more as 'sisters' in realising zero emission solutions.

Various new and promising technologies are competing to become the dominant cleaner solution. Supporters are lobbying for one technology or the other. On the one hand, this competition increases the uncertainty of fuel cell commercialisation. On the other hand, a more sustainable energy system is likely to require an appropriate mix of energy technologies and solutions. In the author's opinion, fixating on one sustainable energy technology is likely to cause the transition to a more sustainable energy economy to fail. Realising a sustainable energy economy with a smart mix of technologies represents an incredible challenge. Currently, the public interest in sustainable development and climate change provides an opportunity to advance and commercialise sustainable energy technologies. For developers and policy makers alike the challenge now is to sustain this interest.

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Samenvatting

Tussen de uitvinding van een nieuwe technologie en de commercialisering ervan ligt doorgaans een lang proces van diverse demonstraties, prototypes, voege toepassingen en niche-markten. Dit proces omvat belangrijke beslissingen over de keuze en timing van het ontwikkelen en het op de markt brengen van toepassingen voor nieuwe technologieën. De toepassing van nieuwe technologieën is vooral onzeker en uitdagend in het geval van *radicale technologieën.* Deze technologieën zijn nieuw en zouden de huidige gang van zaken zodanig kunnen veranderen, dat bestaande praktijken en vakkennis overbodig worden. Deze studie behandelt hoe bedrijven omgaan met deze vroege toepassingen van radicale technologieën voordat deze wijdverspreid voor commerciële verkoop op de markt zijn gebracht.

Brandstofcel (BC) technologie is een interessant onderwerp voor het bestuderen van de vroege toepassingen van een radicale technologie. Gedurende meer dan een decennium, hebben brandstofcelbedrijven diverse demonstraties en vroege toepassingen ontwikkeld en gepresenteerd. Tijdens dit proces worden brandstofcelbedrijven geconfronteerd met uitdagende beslissingen over toepassingen: er is een divers scala van toepassingen om uit te kiezen, maar vooralsnog is de wijdverspreide adoptie van BC-technologie onzeker. De ontwikkeling van BC-technologie heeft in de afgelopen 10 jaar diverse jonge en onafhankelijke BC bedrijven voorgebracht, die zich uitsluitend bezig houden met de ontwikkeling van BC- en waterstof. Om hun technologie te commercialiseren staan deze jonge BC-bedrijven voor de uitdaging om op het juiste moment toepassingen voor hun technologie te identificeren, te selecteren en te ontwikkelen.

In deze oriënterende studie wordt de selectie en ontwikkeling van toepassingen voor radicale technologieën behandeld. De studie heeft zowel een praktische als een theoretische doelstelling. Enerzijds, is het doel om BC-bedrijven inzicht te geven in het proces van commercialisering. Anderzijds, streeft deze studie naar het integreren en uitbreiden van bestaande theorieën over de toepassing en verspreiding van radicale technologieën. Deze studie bouwt daarbij voort op innovatie en technologie marketing literatuur. Voorgaande literatuur beschrijft fases van technologie ontwikkeling: van diverse alternatieven en snelle verandering tot dominante oplossingen en kleine veranderingen. Verder is de commercialisering van een nieuwe technologie beschreven als een accumulatie van niche-markten. Op bedrijfsniveau worden management praktijken voor radicale technologieën gekarakteriseerd door experimentele toepassingen en leren, in een proces van 'uitproberen en leren'. Dergelijke experimentele toepassingen zijn doorgaans duur en tijdrovend terwijl succes niet gegarandeerd kan worden. Het is daarom relevant om beter te begrijpen hoe bedrijven omgaan met dit proces van uitproberen en leren.

.

Hoofdstuk twee geeft een introductie van BC-technologie en achtergrondinformatie over het empirische domein van deze studie. BC-technologie is toepasbaar in diverse markten en concurreert met diverse andere technologieën om batterijen en verbrandingsmotoren te vervangen. De status van de technologie geeft aan dat er nog verscheidene technische uitdagingen zijn, maar er zijn ook verwachtingen voor niche-markten op de korte en middellange termijn. De evolutie van de BC-industrie laat de oprichting van diverse onafhankelijke BC-bedrijven zien. In hoofdstuk 3 wordt een algemeen overzicht gegeven van de informatie beschreven in hoofdstuk 2. Hiermee wordt meer inzicht verschaft in de uitdagingen die gepaard gaan met het toepassen van BC technologie. Ook worden verscheidene BC projecten beschreven. De projecten suggereren dat de realisatie van vroege toepassingen gekarakteriseerd kan worden als een leerproces voor diverse partijen. Verder suggereert een vergelijking van BC-technologie met andere technologieën dat BC-technologie een soortgelijk commercialiseringproces doorloopt, maar bijzonder breed toepasbaar is. Tot slot worden de uitdagingen voor jonge BC bedrijven verder gekarakteriseerd. Jonge BC-bedrijven hebben doorgaans beperkte middelen en diverse markten om uit te kiezen, terwijl de toepassing van BC-technologie strategische keuzes inhoudt over de ontwikkeling van legitimiteit, competenties en relaties. De karakterisering van BC-technologie en BC-bedrijven specificeert het empirische probleem van deze studie: de keuze van vroege toepassingen in jonge technologiebedrijven.

In hoofdstuk 4 wordt relevante literatuur ten aanzien van innovatie en marketing van technologie besproken. Gradaties van nieuwheid, beschreven in de literatuur, suggereren dat BC-technologie kan worden beschreven als een vervangingstechnologie, radicaal voor diverse partijen gezien van hun onbekendheid met de technologie en de benodigde veranderingen in competenties. Deze radicaliteit veroorzaakt onzekerheid over de ontwikkeling van de technologie en de marktvraag, daarbij wordt het proces van innovatie gekarakteriseerd door een dynamisch proces van leren en parallelle activiteiten in technologie- en marktontwikkeling. Literatuur suggereert een proces van experimentele toepassingen en leren om dit proces te managen. Daarbij wordt het concept van 'uitproberen en leren' uitermate geschikt bevonden om de toepassing van nieuwe technologieën te beschrijven en te analyseren, gedefinieerd als: een serie van toepassingen met vroege versies van een technologie/ product in diverse markten als een manier om te leren. Voorgaande studies over dit fenomeen zijn echter preliminair en hebben meer vragen opgeroepen dan beantwoord. Er is beperkte kennis over: i) hoe bedrijven vroege toepassingen kiezen en ii) wat het proces van uitproberen en leren karakteriseert.

Hoofdstuk 5 bespreekt concepten uit de organisatietheorie over het maken van strategische beslissingen en organisatorisch leren. Een perspectief van dynamische capaciteiten is gekozen om beslissingen over vroege toepassingen te verklaren. Daarbij word verwacht dat interne en externe bedrijfsfactoren de keuze van vroege toepassingen beïnvloeden. Op basis van de literatuur zijn de volgende factoren geïdentificeerd: de bedrijfsmiddelen, de competenties en capaciteiten in een bedrijf en de geschiedenis van een bedrijf. Buiten het bedrijf zijn de verwachtingen van de industrie, de regelgevende omgeving, de relaties en het vertrouwen van klanten hoogstwaarschijnlijk bepalend voor de strategische alternatieven waaruit een bedrijf kan kiezen. Deze diversiteit aan factoren impliceert dat er verschillende verklaringen zijn voor de keuze van toepassingen in BC bedrijven:

- De competenties, capaciteiten en de geschiedenis van een bedrijf, waarbij beslissingen worden bepaald door de strategische bedoelingen en de capaciteiten van een bedrijf.
- Verwachtingen van de industrie, waarbij de keuze van toepassingen wordt bepaald door de verwachtingen van de industrie en bedrijven andere bedrijven volgen, ongeacht de eigen capaciteiten en strategie van het bedrijf.
- Afhankelijkheid van middelen, waarbij keuzes worden bepaald door het benutten van kansen voor opbrengsten, onafhankelijk van strategische intenties of verwachtingen van de industrie.

Toegepast op het proces van uitproberen en leren, verwacht deze studie dat de rol van deze factoren bij het verklaren van beslissingen zal veranderen naarmate een bedrijf leert en de externe omgeving verandert. Dit hoofdstuk bespreekt vervolgens concepten uit organisatorisch leren om te begrijpen hoe bedrijven leren in een innovatieproces. Bedrijven kunnen kiezen om hetzij explorerende, dan wel exploiterende activiteiten aan te gaan. Toegepast op het proces van uitproberen en leren: i) explorerende toepassingen in nieuwe marketen en ii) exploiterende toepassingen om voort te bouwen op voorgaande toepassingen. Het tweede relevante concept van organisatorisch leren in het innovatie proces is dat bedrijven worden verwacht eerst te leren door ontdekking alvorens adaptief te kunnen leren.

In hoofdstuk 6 worden twee modellen van technologietoepassingen gepresenteerd, waarbij bevindingen uit de literatuur worden gebruikt als bouwstenen. Een descriptief model wordt gepresenteerd om de beschrijving en analyse van toepassingsprocessen te structureren. Het uitproberen van toepassingen word beschreven aan de hand van twee variabelen: de breedte van marktsegmenten en de lengte van toepassingspaden. Daarnaast worden fases van uitproberen en leren voorspeld en gekarakteriseerd door de keuze voor voornamelijk explorerende of exploiterende toepassingen en de dominantie van leren door ontdekking of adaptief leren. Uiteindelijk wordt een conceptueel model voorgesteld om de toepassingsbeslissingen van een bedrijf te verklaren. Het model suggereert dat in elke fase van toepassingen, óf interne óf externe factoren bepalend zijn voor de keuze van toepassingen. Vijf stellingen en vier gespecificeerde onderzoeksvragen worden voorgesteld om de analyse van een case study onderzoek te leiden. Vier jonge BC-bedrijven zijn geselecteerd voor een case study onderzoek. Voor de data-verzameling is gebruik gemaakt van interviews met leidinggevend personeel in de case study bedrijven, persberichten en diverse documenten.

Hoofdstuk 7 beschrijft het case study onderzoek. Voor elk bedrijf wordt een historische beschrijving gegeven van de vroege toepassingen. Deze historie van toepassingen beschrijft de redenen achter toepassingskeuzes, de karakteristieken van de toepassingen en de opgedane ervaringen. De case studies laten zien dat vroege toepassingen worden gerealiseerd voor verschillende redenen, waaronder, demonstraties, technologieontwikkeling, de educatie van klanten, de formatie van verbintenissen en initiële opbrengsten. De toepassingen hebben verschillende karakteristieken in termen van grootte, duur, betrokkenheid en doelgroep. De bedrijven ontwikkelen hun competenties en veranderen hun strategieën aan de hand van opgedane ervaringen en terugkoppeling. Elk bedrijf is individueel geanalyseerd om te verklaren hoe en waarom het bedrijf initiële toepassingen heeft gekozen, waarom het bedrijf nieuwe marktsegmenten is ingegaan en waarom het heeft besloten om door te gaan of te stoppen met ontwikkelingen in een bepaalde sector.

Een cross-case analyse wordt gepresenteerd in hoofdstuk 8 waarin de bedrijven worden geanalyseerd en vergeleken aan de hand van de theoretische factoren en de patronen voorspeld in hoofdstuk 6. De rol van deze factoren in het verklaren van toepassingen wordt besproken. De verwachtingen van een industrie lijken bepalend te zijn voor het veld van toepassingen waaruit een bedrijf initiële toepassingen kiest. Het niveau van competenties en capaciteiten in een bedrijf en het niveau van het vertrouwen van de klanten lijkt de breedte van toepassingen te verklaren. Bij de totstandkoming van marktvraag reageren alle bedrijven op een soortgelijke wijze. De geschiedenis van de toepassingen in elk bedrijf wordt vervolgens vergeleken om karakteristieken van het toepassingsproces en toepassingpatronen af te leiden. De analyse suggereert overeenkomstige fases van vroege toepassingen: een explorerende fase van initiële toepassingen, een experimentele fase en een ontwikkelingsfase. De vergelijking laat ook verschillende patronen van toepassingsprocessen zien in termen van de breedte van marktsegmenten en de lengte van ontwikkelingspaden, verschillen in het aantal toepassingen en de timing. Tot slot worden de stellingen getest en nieuwe stellingen afgeleid uit de case study data om de patronen te verklaren.

Hoofdstuk 9 presenteert de conclusies en aanbevelingen van deze studie. De belangrijkste bevindingen zijn: i) een model om de toepassingen van een bedrijf te beschrijven en analyseren over een aantal jaren, ii) een conceptueel model om te toepassingsbeslissingen te verklaren en iii) karakteristieken van toepassingsfases en - patronen. Het descriptieve model verstrekt een aanpak voor het beschrijven en representeren van de toepassingen in bedrijven, en geeft een overzicht van de beslissingen, de consequenties en de relaties. Het conceptueel model suggereert dat in verschillende perioden, verschillende factoren bepalend zijn voor toepassingsbeslissingen. Deze studie concludeert dat vroege toepassingen initieel gedreven worden door de verwachtingen van de industrie, vervolgens door heterogene strategieën en prioriteiten en uiteindelijk door marktvraag. Deze bevindingen verklaren de gelijkenissen en verschillen in geobserveerde patronen. Deze studie suggereert dat bedrijven door gelijke fases van toepassingen gaan: eerste het exploreren van initiële toepassingen gevolgd door experimenten in diverse markten, gekarakteriseerd door een divergent proces van ontdekking. Daarna vind een transitie plaats naar de ontwikkeling van een select aantal toepassingen, gekarakteriseerd door een convergerend proces. Verschillende strategieën worden vooral gevolgd in de experimentele fase. Twee archetypes worden geïdentificeerd: i) geconcentreerde toepassingen in een select aantal marktsegmenten, gekarakteriseerd door lange iteratieve ontwikkelingspaden en ii) brede toepassingen in diverse marktsegmenten, gekarakteriseerd door een zoekproces naar specifieke (niche) markten en ontwikkeling door te leren van toepassingen in verscheidene markt segmenten. Deze bevindingen zijn breder toepasbaar dan in enkel de BC-industrie. De bevindingen kunnen vooral gegeneraliseerd worden voor de toepassing van nieuwe vervangingstechnologieën in jonge technologiebedrijven.

Met inzicht in de toepassing van radicale technologieën, dragen deze onderzoeksbevindingen bij aan het begrijpen van innovatieprocessen. Inzicht in het toepassingsproces kan bedrijven helpen bij het managen van dit proces door het strategisch plannen van toepassingen en het overzien van de consequenties. Voor het managen van toepassingen, is een 'quasi-experimentele' aanpak aan te bevelen door toepassingen vooraf te evalueren en de uitkomsten na afloop te analyseren. Daarmee kunnen jonge technologiebedrijven de breedte van hun toepassingen en afleidingen minimaliseren en de leer-effecten en het competitieve voordeel van opgedane ervaringen maximaliseren. Deze studie concludeert dat het uitproberen en leren van toepassingen niet alleen een management praktijk is maar ook een overlevingsnoodzaak. De case van BC-technologie en jonge BC-bedrijven suggereert dat financiële steun en bescherming van de overheid zeer essentieel is in deze fase van toepassingen voorafgaand aan wijdverspreide commerciële verkoop.

Hanna Hellman

Appendix A: Selected Case Study Firms

Table 1: Characteristics of firms in the case studies in 2006

Characteristics	Plug Power	Hydrogenics	Intelligent Energy	Nedstack
Year of founding	1997	1995	2001	**1998**
Firm size	330	325	70	40
Financial structure	Public	Public	Private	Private
Approximate Financial size	Total assets in 2006 $308 million	Total assets in 2006 $97 million	Raised $11.3 million working capital in 2005	Approximatl €500,000 turnover in 2006
Location headqaurters	Latham, New York	Toronto	Loughborough	Arnhem, the Netherlands
Location subsidiary offices	Washington DC and Apeldoorn, the Netherlands	Burnaby, B.C., Oevel, Belgium., Gladbeck, Germany, Valencia CA. China, India and Russia.	London, Long Beach, California, Albuquerque, New Mexico, Johannesburg, South Africa	
Core FC business	FCs for onsite energy	Module production	License agreements	FC Stack production
Main power range	5-8 kW	2kW-65 kW	100 W-25 kW	2 kW-20 kW (stackable to MWs)

Appendix B: Data Sources

Case Firm Interviews

Company	Who	When	t
Plug Power	Jos van de Hyden, General Manager of European, Middle Eastern and African operations	January 2006	2h
Plug Power	Ellart de Wit, Senior Project Manager	April 2006	1 1/2h
Nedstack	Jan Van der Meer, Director Marketing and Sales	November 2005	2 h
Nedstack	Erik Middleman, CEO and Co-founder	August 2006	1 1/2h
Hydrogenics	Mark Kammerer, Head of Sales, Marketing and Business Development Power Systems.	January 2006	2 h
Hydrogenics	Jon Dogterom, Director Business development, Power Systems	August 2006	3/4h
Intelligent Energy	Andy Eggleston, Project Director of the ENV bike	January 2006	1 3/4h
Intelligent Energy	Dennis Hayter, Director of Business Development	September 2006	1 3/4h

Additional Interviews

Company	Who	When	Note
Axane	Director Marketing and Sales	2005, 2006	Informal discussions
Ballard	Director, External Affairs and business development	May 2007	Interview
Ballard	Sales Account Manager Ballard Power Systems.	December 2007	Email questions
Ceres Power	Commercial Director	December 2006	Interview
Cellex Power	President and CEO	May 2007	Informal discussion
Dynetek	Representative Marketing and Sales	May 2007.	Informal talk
Electro Power Systems	Co-founder and CEO	September 2006	Telephone interview
ECN	Manager PEMFC & Supercaps	December 2005	Interview
Formula Zero	Co-founders and directors	March 2006	Interview
H2 -tech	Marketing Manager	May 2006	Email questions
Hydrogenics	Business Development Manager for Asia-Pacific and General Manager for Japan	November 2006	Interview
LHP	Partnership Manager	December 2006	Interview
LHP	Project Manager	April 2007	Interview
Nuvera	Sales and Marketing Manager,	Februari 2004	Telefphone interview
Spijkstaal	Director Spijkstaal	December 2005	Interview

Main Online databases	Website
Fuel Cells 2000	www.fuelcells.org
Fuel Cell Today	www.fuelcelltoday.com
Fuel Cell Markets	www.fuelcellmarkets.com
Green Car Congress	www.greencarcongress.com
Library House	www.libraryhouse.net
SenterNovem	www.senternovem.nl
Cordis	http://cordis.europe.eu
European Patent Office	http://ep.espacenet.com/

Company /Organisation	Referenced Presentation Hydrogen and FC Conference Vancouver and Tradeshow 2007
Angstrom	Kluyskens, D. F. Hydrogen Is a Competitive Fuel For Portable Power Applications.
US DOE	Devlin, P. US department of energy, market transformation Manufacturing R & D and Market Transformation Activities.
NAIST: National Institute of Advanced Industrial Science and Technology of Japan,	Kogaki Japan's Strategies, Policies and Programs related to the Commercialization of Hydrogen and Fuel Cell Technology. Japan
UTC Hydrogen and Fuel Cell Technology.	Toska, M. Fuel Cells For Transportation Applications, Specifically Public Transport.

List of abbreviations

APC	American Power Conversion Corp.
APU	Auxiliary Power Unit
AR	Annual Report
BE	Battery Electric
CHP	Combined Heat and Power
DMFC	Direct Methanol Fuel Cell
DOE	Department of Energy
DOD	Department of Defense
DUT	Delft University of Technology
ECN	Energy research Centre the Netherlands
ENV	Emissions-Neutral Vehicle
FC(s)	Fuel Cell(s)
FFE	Fuzzy Front End
GE	General Electric
GM	General Motors
H	Hydrogenics
HE	Hybrid Electric
HES	Home Energy System
HFP	European Hydrogen and Fuel Cell TechnologyPplatform
GM	General Motors
IC	Internal Combustion
IE	Intelligent Energy
IEA	International Energy Agency
IDE	Industrial Design Engineering
IP	Intellectual Property
IPO(s)	Initial Public Offering(s)
LIPA	Long Island Power Authority
LHP	London Hydrogen Partnership
OEM	Original Equipment Manufacturer
MCFC	Molten Carbonate Fuel Cell
MEA	*Membrane Electrode Assembly*
N	Nedstack
NPD	New Product Development
NRC	National Research Council
NYSERDA	New York State Energy Research and Development Authority
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PP	Plug Power
PR	Public Relations
PV	Photo Voltaic
PwC	PricewaterhouseCoopers
SOFC	Solid Oxide Fuel Cell
R&D	Research and Development
RBV	Resource Based View
UPS	Uninterruptible Power Supply
UTC	United Technologies Corporation
YTB	Young Technology Based
ZEV	Zero Emission Vehicle

Curriculum Vitae

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In 2003 Hanna Hellman obtained her masters degree in Industrial Design Engineering at the Delft University of Technology, specialising in Technology in Sustainable Development, followed in January 2004 by the start of her PhD research at the department for Design for Sustainability at the same University. During her PhD she supervised 12 graduation projects, in collaboration with companies, on fuel cell product design, sustainable energy in general and the introduction of radically new products. Her special interests include the application and diffusion of radical innovations in the field of sustainable energy, with the ambition to achieve synergy between novel technologies, environmental ambitions and market opportunities. In January 2008 she will continue her career and her passion for international adventures in London.