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Arho Suominen

Notes on Emerging Technologies

Turku Centre for Computer Science

TUCS Dissertations
No 141, November 2011

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To be presented, with the permission of the Faculty of Mathematics and Natural Sciences, for public criticism in the Auditorium 157 on the 11th of November, 2011 at 12:00.

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2011

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ISBN 978-952-12-2647-2
ISSN 1239-1883

Abstract

This dissertation considers the impact of technology foresight in innovation within the context of a technology driven development. The main hypothesis made was that by using different methods of foresight in the industry level significant value could be created. The question was approached through a case study in portable fuel cell technology.

The theoretical background of the study draws from Innovation, Product Development, Management of Technology, and Technology Foresight. The connection within the topics is made by analyzing foresight, not in a policy view as often done in Europe, but in a micro-level. Focusing mostly on how a technology driven development scenario could be analyzed.

The study is based on a bibliometric, extrapolation and patent analysis within the context of a case study. In addition, a large two-year Delphi study was conducted. The study was finalized with a scenario work on the future possibilities of the case study technology. Original publications also consider several methodological issues.

In the context of the case study, the study questions the practicality of establishing a portable fuel cell technology in Finland showing several impractical assumptions has been made. In a more conceptual level, the study makes notions on two underlying factors: policy-push technologies and growth of data.

Policy-push questions in which level a policy effort towards a single technology is practical. The European foresight effort is more directed towards policy decisions in contrast to US foresight, which is to some extent corporate driven. Although the policy-based foresight has produced significant results in the European context, policy led efforts towards a single technology are challenging.

Growth of data argues on the challenges produced by the large-scale application of quantitative measures of foresight. Bibliometric studies and trend extrapolations have been taken advantage of the increasing number of databases made available, and used these as the basis for forecasts. However, the relationship with actual development and quantitative evidence is still unproven.

Keywords: Foresight, Management of Technology, Innovation, New Product Development

Abstrakti

Tässä väitöskirjassa arvioidaan teknologiaennakoinnin merkitystä innovaatioiden, erityisesti teknologiavetoisten kehityskaarien arvioinnissa. Keskeisenä hypoteesina työtä käynnistettäessä oli, että teknologiaennakoinnilla on merkittävä rooli erityisesti mikrotason strategisessa suunnittelussa. Hypoteesia lähestyttiin kannettaviin polttokennoihin liittyvällä tapaustutkimuksella.

Työn teoreettinen tausta on vahvasti sidottu innovaatioihin, tuotekehitykseen, teknologiajohtamiseen sekä teknologiaennakointiin. Aihepiirin yhdistävänä tekijänä on tutkimukselle asetettu mikrotason tarkastelu, jossa ennakointia tehdään mikro- eikä makrotasolla. Lähestymistapa on poikkeuksellinen Suomessa.

Väitöskirjan tutkimusosassa työ keskittyy kvalitatiiviseen ja kvantitatiiviseen arvioon valitusta tapaustutkimuksesta. Työn aikana tehtiin laaja kvantitatiivinen tutkimusosa, keskittyen bibliometriseen arviointiin. Työn kvalitatiivinen osuus keskittyy kaksivuotiseen Delphi-menetelmällä toteutettuun asiantuntija-arviointiin. Kvalitatiivisen ja kvantitatiivisen arvioinnin jälkeen tulosten synteesi esitettiin skenaario-tutkimuksen avulla. Kokoelmaväitöskirja sisältää lisäksi kaksi menetelmiin keskittyvää julkaisua.

Työn tuloksena tapaustutkimuksen kontekstissa arvioitiin kriittisesti kannettavien polttokennojen merkitystä Suomessa. Polttokennoihin liittyvä voimakas positiivinen noste osaltaan perustuen perusteettomiin odotuksiin käynnisti kansallisesti laajan panostuksen yksittäiseen teknologiseen ratkaisuun. Työn kritiikki kohdistuukin erityisesti tehtyihin poliittisiin teknologiavalintoihin (*policy-push*). Konseptuaalisella tasolla työn havaintoina keskityttiin poliittisiin valintoihin sekä ennakoinnissa käytettävän kvantitatiivisen tiedon määrän kasvuun.

Poliittisten teknologianennakointeja tehtäessä tulee arvioida kriittisesti voidaanko rahoitusta kohdistaa selkeästi yhteen teknologiseen ratkaisuun. Euroopassa ennakointia on yleisesti suoritettu yhteiskunnan toimesta yleishyödyllisenä toiminta eroten näin Yhdysvalloissa yritysten tasolla tehtävästä ennakointityöstä. Yhteiskunnan tasolla tehtävä yksittäiseen teknologiseen ratkaisuun keskittyvät valinnat nähdäänkin haasteelliseksi, erityisesti ilman riittävää strategista valintaa mikrotasolla.

Metodologisena havaintona työssä keskityttiin kvantitatiivisen tiedon määrän kasvuun, jonka tunnistettiin olevan merkittävä ennakointitiedon lähde. Bibliometriset ja trendeihin perustuvat mallit ovat kasvattaneet suosiotaan niiden tuottaman selkeän informaation johdosta. Tulevaisuudessa on kuitenkin arvioitava kriittisesti millä tavoin kvantitatiivinen tieto pystyy mallintamaan kompleksista sosioteknistä kehityskulkua.

Asiasanat: ennakointi, teknologiajohtaminen, innovaatiot, tuotekehitys

Foreword

The world works in mysterious ways. If I had to guess 10 years ago, what would be the odds of me becoming a teacher or a researcher, I would have said it to be a slim possibility. However, something seems to be embedded in your DNA. By finalizing this thesis I would like to remember the dissertation of my grandfather Lic. Sc. A. O. Suominen, which remains unpublished.

I would like to thank my supervisors Professor Aulis Tuominen and Associate Professor Jussi Kantola. In addition, I would like to thank the co-workers I had the pleasure of working with in the PortFuCell project. I would also like to thank Dr. Marko Seppänen for co-authoring several papers, one of which added to this dissertation, during the final stages of my dissertation. In addition I thank the three industry members volunteering their time for interview sessions on corporate forecasting. Last, but no least, I would like to thank M. Sc. (Tech) Sami Hyrynsalmi, who has been the most significant influence in me shaping the dissertation in the current form.

I also thank Dr. Markku Salo and Dr. Charalampos Makatsoris on their significant effort during the review process. It is through discussion that science is created.

I would like to express my sincere gratitude for the Finnish Funding Agency for Technology, which funded the research project during which this dissertation was made. I would also like to thank the Turku University Foundation for the several travel grants as well as for the research week made available in Gränö Centre. I also thank Turku Centre of Computer Science for a travel grants received.

Not to forget the most important people in my life, a thank you is in order to my father Tapio and mother Marja for all of the support during different times in my life. Thank you also to my sisters who have had a significant effort in me growing up. I also thank my extended family for their support during my endeavors. In addition, I thank the guys in Jalluklupi for giving me the possibility to focus on something else than my work.

Finally, for the most important, I thank my wife Minna. It is too seldom I have the possibility to thank you for all of the support I have received, so thank you. Not forgetting Rasmus, often the only one listening me for hours on my research.

Turku 11.10.2011

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List of original publications included in the thesis

I. Arho Suominen and Aulis Tuominen. Analyzing the Direct Methanol Fuel Cell Technology in Portable Applications by a Historical and Bibliometric Analysis. *The Journal of Business Chemistry*, Vol. 7, Is 3, September 2010.

II. Arho Suominen, Jussi Kantola and Aulis Tuominen. Analyzing prospects of portable fuel cells with an expert opinion study. *Futures*, Vol. 43, Is 5, June 2011, pp. 513-524

III. Arho Suominen and Aulis Tuominen. Scenarios in technology and research policy: case portable fuel cells, *Journal of Strategic Change Management*, Vol. 3, No. 1/2, 2011

IV. Arho Suominen and Marko Seppänen. Setting the upper bound of growth in trend extrapolations. *In Proceedings of the IAMOT 2011 Conference*, April 2011.

V. Arho Suominen and Aulis Tuominen. The Acquisition of Emerging Direct Methanol Fuel Cell Technology by Industry. *In Technology as the Foundation for Economic Growth - Conference Proceedings*, March 2010.

List of relevant publications excluded from the thesis

I. Marko Seppänen, Heini Järvenpää and Arho Suominen. Order of Appearance of Technology Lifecycle Indicators for Three Case Technologies. *In Proceedings of the XXI ISPIM Conference*, June 2010.

II. Arho Suominen and Aulis Tuominen. Downturn in Regional Electronics Industry Cluster. *In Proceedings of the 2nd ISPIM Innovation Symposium*, December 2009.

III. Arho Suominen, Jussi Kantola and Aulis Tuominen. Reviewing and Defining Productization. *In Proceedings of the XX ISPIM Conference*, July 2009.

IV. Arho Suominen, Jussi Kantola and Aulis Tuominen. Evaluating and Managing R&D Investment under Uncertainty - Case study: Productization of Portable Fuel Cells. *In AHFE Conference, Las Vegas, USA*, July 2008.

V. Arho Suominen, Jong-yun Moon and Aulis Tuominen. Analyzing a Emerging Technology with a Growth Curve: Case Titanium Nanotubes. *In Proceedings of the XXI ISPIM Conference*, June 2010.

Contents

Abbreviations

CTI	Competitive Technological Intelligence
EPO	European Patent Office
FD	Foresight Diamond
FFE	Fuzzy Front End
GPS	Global Positioning System
IPR	Immaterial Property Rights
MOT	Management of Technology, used synonymously with TM
NASA	National Aeronautics and Space Administration
NPD	New Product Development
NRC	National Research Council
OECD	Organisation for Economic Co-operation and Development
R&D	Research and Development
TEKES	The Finnish Funding Agency for Technology and Innovation
TF	Technology Forecasting or Technology Foresight
TLC	Technology Life-Cycle
TM	Technology Management, used synonymously with MOT
USPTO	United States Patent and Trademark Office

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1. Introduction

This dissertation focuses on the challenges in forecasting technological progression. The work, by building a wide theoretical background in technology management and through a large case study, discusses the challenges of technological foresight. This discussion is, in addition to the sections included, based on the included original publication. In order to further elaborate on the overall context of the study, this introductory chapter explains the background, origins and motives, research question, research approach, and the structure of the thesis in individual sub-sections.

1.1. Background

In the 1989 paper, *The Future of Technological Forecasting* Robert U. Ayres called for better methods of forecasting and planning for the future. Focusing especially on quantitative methods of assessing technological development, Ayres thought that more accurate tools for decision making on a macroeconomic and microeconomic scale were needed. Building on previous work on long-range planning and empirical measures of technological development, Ayers sought after decision-making tools that would complement previously used qualitative methods of technological forecasting.

Before and since the mentioned statement, an abundance of technology forecasting literature had been published. In the time *before,* work focused mostly on qualitative tools such as scenarios and long range planning (Gordon and Helmer 1964, H. A. Linstone 1978, Ayres 1969, Dalkey 1967, Dalkey and Helmer 1963) and *since* quantitative tools such as bibliometric, data mining and quantitative approaches have been used (Borgman and Furner 2002, Kajikawa, Yoshikawa, et al. 2008, Huang, Li and Li 2009, Tseng, Lin and Lin 2007, T. U. Daim, G. Rueda, et al. 2006, Kostoff, et al. 2001). Although being a rough categorization, the division into quantitative and qualitative approaches in foresight could be argued to be valid, as seen from significant works on technology forecasting (Ayres 1969, Martino 1993, Porter, et al. 1991).

This thesis, entitled *Notes on Forecasting Emerging Technologies*, draws from the abundance of technology forecasting and long-range planning literature and strives to create new insight on how qualitative and quantitative tools of technology foresight are applied in the context of technology management.

The research question set for the study started from the fact that the rate of technological change has increased. Straining our understanding on what possible, even elementary, development could be feasible within the time frame of 5 years, not to even talk about expanding the horizon to ten or twenty years, has made foresight a necessity. Challenges set by the increased speed of development into industry have made the identification of future development scenarios a question of survival (Day and Schoemaker 2005). In addition to identifying new technological options, the complexity of selecting between technical possibilities, correct or not, will require significant investment from both industry and governments. (Steensma and Fairbank 1999). Studies have shown the challenges of selecting technologies (Torkkeli and Tuominen 2002), however, under turbulent environment survival is dependent on the ability to exploit new technologies through systematic foresight. (Mishra, Deshmukh and Vrat 2002) This has stressed the role of technology foresight in the management of technology (Henriksen 1997). However, while managers are aware of the need to foresight, the methods of conducting a foresight project has remained unclear. (Makridakis, Hodgsdon and Wheelwright 1974)

In addition to the challenges in applying foresight methods, cultural differences in how and to whom the responsibility to organize a foresight work differs significantly. Large national foresight efforts done in Europe (Keenan and Miles 2008, Cuhls 2008) and Japan (Kuwahara, Cuhls and Georghiou 2008) have tried to create a view on the direction of future research and development efforts. Taking a more macroeconomic view on how technological progression is managed, countries with large national foresight efforts strive towards a collective understanding of the future. Selecting technologies of the future *is* based on a somewhat collective understanding on how things will evolve.

In the Finnish context, we have seen efforts such as the FinnSight 2015 foresight project carried out during 2005-2006. Funded and lead by the Academy of Finland and TEKES, the Finnish Funding Agency for Technology and Innovation, the program strived to "lay the foundation for the Strategic Centers for Science, Technology and Innovation. Simultaneously, foresight will reinforce strategy work at the Academy of Finland and Tekes."

Comprising of ten twelve member panels, the Finnish foresight effort went through strategic areas of development and created a collective view on which factors will impact Finnish industry and society. Often going to detailed technological assumptions, the process expanded from creating an overall view of the future to creating market expectations for specific technologies. For example with fuel cells, in the FinnSight report published in 2006 an argument was made that

> *"Within the next ten years, fuel cells will go commercial. In the last two years, significant efforts have been taken in Finland on the application of fuel cells, although the industry base for this has been limited. Core technologies exist in specific areas such as Polymer Exchange Membrane fuel cells and Solid Oxide Fuel Cells. Industry is however getting more and more excited on the technology."*[1] *(Acedemy of Finland and Tekes 2006)*

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[1] Original text in Finnish: Seuraavien kymmenen vuoden aikana polttokennot tulevat markkinoille. Suomessa on parin viime vuoden aikana panostettu varsin paljon polttokennojen sovelluspuoleen, mutta alan yrityskenttä on vielä suppea. Ydinteknologiaa on eräillä alueilla, kuten PEM-teknologiassa (polymeeri-elektrolyyttinen

Elaborating on how a specific technology would mature into a commercially viable technology within a specific timeframe. Clearly also including the assumption that in the near future efforts should be directed to the technologies mentioned.

On the other end, technological foresight in the United States, although having different non-profit foresight organizations working on research policy, is more driven by a microeconomic view on the future. (Porter and Ashton 2008) National roadmaps on the development on, for example, light emitting diode technology can be found, but technology foresight is seen as a corporate level strategic tool, not so much an overall government lead effort. In this, Porter and Newman (2011) refer to Competitive Technological Intelligence (CTI) in explaining the significance of gathering information on the "who" and "what" of research and development outside the organization. Emphasized by the adoption of open innovation (Chesbrough 2003) based development, managing technological trajectories outside the confines of a single organization would seem necessary.

An apparent notion would be that there is a place for both, a macroeconomic foresight effort and a microeconomic effort. However, we often lack in the ability to create well-founded strategic foresight on either level, most significantly in a microeconomics level (Coates 2010).

1.2. Origins and motives

One could argue that in parts due to the Finnish national foresight effort (FinnSight 2015), in 2007 TEKES launched a program to fund research on fuel cell development in Finland. Making a significant national effort, TEKES started several projects on three different focus points: stationary, transport, and portable fuel cells. Launched with the expectation of demonstrating fuel cell technologies, and by these means creating commercial applications and value networks that would facilitate the creation of a fuel cell cluster in Finland, the program commenced as a seven-year effort in 2007. (Felt 2007)

kenno) ja SOFC-systeemeissä (kiinteäoksidipolttokennot). Yrityskiinnostusta löytyy kuitenkin yhä enemmän.

Simultaneously to the national research program being establish decision makers in the City of Salo were awakened by future challenges. For several years, the small region of only 50.000 inhabitants had the good fortune of having one of the world's largest mobile phone companies, Nokia, established there. However, as Nokia had grown to be a global company, the city needed to extend their industrial base from the dependency of the continuation of Nokia´s Salo factory to something else. To this end, different "think tanks" funded by the regional development agency were established. From one of these efforts, the establishment of a portable fuel cell cluster within the regional area of Salo was decided on. Having no prior industry using fuel cell technology, the decision was ultimately based on the significant expectations seen in the fuel cell technology.

Initiated partly by the strong support by the city, the University of Turku had, with Turun ammattikorkeakoulu (a polytechnic school in Turku), a 2 year TEKES funded project focusing on the productization and research of portable fuel cells. The research was carried out in the research organization´s Salo campus and focused on both explaining how this new knowledge created could be applied commercially as well as developing the portable fuel cell technology towards commercialization. The author worked in the project during its planning, funding application and implementation. Thus getting the opportunity to both plan and execute the research.

Summarizing the origins and motives; in this thesis a case technology, portable fuel cells, is analyzed. Being instigated by the strong policy effort from TEKES, a significant amount of publicly funded Research and Development (R&D) was directed towards the fuel cell technology. Interested in this new technological opportunity, several companies sought to apply this new opportunity to their business. Within this large national effort, the city of Salo strived to develop its own cluster of portable fuel cell industry. This resulted in the funding of a project called *Portable fuel cell Research and Productization.* The project focused on applied research and evaluating the commercial possibilities of portable scale fuel cells. This included a significant foresight effort, which was done to ensure the validity of the technology as promising future market for the participating regional companies.

1.3. Research question

Going back to the theoretical background for the foresight effort, we as humans have an innate need, as well as an ability, to forecast and we do so with significant accuracy. Our everyday life includes forecasts made from practical things such as forecasts made on possible congestion on a specific highway within our commute to work. Our day-to-day forecasts are based on experience, word of mouth, or trust in the expertise of others, often relying on historical knowledge. We assume that spring would follow winter, but for an accurate forecast on tomorrow's weather we tend to turn towards professionals using elaborate mathematical models in their predictions.

In a technological context, foresight is approached with different processes and methods than what would be used in our daily lives. Being able to accurately forecast the development of complex technology with an abundance of underlying causal relationships, differs significantly from what is done in a day-to-day basis. This has resulted in the creation of different structured approaches to evaluating technology and even an abundance of methodological options, or even a methodological chaos.

Reviewed in several works (Ayres 1969, Makridakis, Wheelwright and McGee 1983, Makridakis and Wheelwright 1989, 1978, Porter, et al. 1991, Martino 1993, Georghiou, et al. 2008), technological forecasting is done with a variety of methods. Structured in different ways, such as normative and exploratory, or qualitative and quantitative methods, the abundance of forecasting methods should be approached in a systematic way, while maintaining flexibility in selecting suitable methods in a case-by-case way (Makridakis, Hodgsdon and Wheelwright 1974).

Within technological forecasting, we have historically relied on expert opinion and theoretical models of development. Having roots in military planning scenarios, expert opinion studies and mathematical models have been used to elaborate on possible technological futures. In forecasting, selecting methods is most often not a decision of selecting one suitable method, but rather selecting several suitable methods and using them in combination to approach a selected problem (Martino 1993). By using several methods, all of the relevant factors can be taken into consideration (Makridakis, Hodgsdon and Wheelwright 1974), ultimately leading to better forecasts.

Striving for more accurate predictions, the scientific community has developed methods of technological forecasting, some more accurate than others, but still having to deal with the unpredictability of life. This has resulted in an abundance of mistaken forecasts[2], often based in nothing else than an opinion of a single person. This goes to show that forecasting, or foresight, is not an exact science. Forecast can often be seen as confining several foreseeable futures rather than elaborating on one correct future.

However, in an industry context we would have to be able to make an interconnection between technology management, innovation, and product development. Creating a link between the expected futures and company strategy and management, as such, an interconnection between technology management and foresight is more than apparent.

From the background and origins of the study, the following research questions were made:

> *What is the interconnection between technological foresight and technology management?*
>
> *Would a quantitative analysis of bibliometric technological trajectories enable sufficient strategic foresight?*
>
> *Would a combination of a qualitative and quantitative approach add value to the trajectory based analysis?*

The questions proposed an interconnection between the existing culture of national level foresight to a microlevel foresight and between technology management and foresight. In addition the validation of quantitative, computer aided, methods called for by Ayres, for example, is suggested, simultaneously questioning if an analysis

[2] Several authors have made *a posteriori* analysis on forecast made on the development of technology (Ayres 1969, Schnaars, Chia and Maloles 1993, Albright 2002, Armstrong 1978). Elaborating on the successes and mistakes made these studies give us a knowledge base for future work.

of quantitative data could be the sole basis of foresight. Thus accepting the assumption that a mix of relevant methods, suggested for example by Makridakis et al. (1974), leads to better results.

Finally in the context of the case study, the assumption is made that the national foresight effort, fuel cell program, and regional effort in Salo were the result of a well-founded view on technological progression and thus the results of this study would support the continuation of fuel cell development in the region.

1.4. Research approach

The research was approached as a case study on portable fuel cell technology. Using, similarly to Flyvbjerg (2006), the definition in the Dictionary of Sociology, a case study is defined as

> *"The detailed examination of a single example of a class of phenomena, a case study cannot provide reliable information about the broader class, but it may be useful in the preliminary stages of an investigation since it provides hypotheses, which may be tested systematically with a larger number of cases. (Abercrombie, Hill, & Turner, 1984, p. 34 in Flyvbjerg 2006)*

Following the arguments made by Flyvbjerg (2006) the value of a case approach is seen much broader than what would be understood from the definition. It can be argued that a case study is not just a poor surrogate for large scale statistical studies on a specific research question. The value of case studies can be found from its ability to study a specific case extensively such creating value by 1) either by proving that there truly are "black swans", and as such questioning the status-quo or 2) by using the proven force of an example to challenge current knowledge. Arguing that

> *"One can often generalize on the basis of a single case, and the case study may be central to scientific development via generalization as supplement or alternative to other methods. But formal generalization is overvalued as a source of scientific devel-*

> *opment, whereas "the force of example" is underestimated." (Flyvbjerg 2006)*

In the context of this thesis a case study is used, not as a method but as a research strategy. As suggested by Hartley, (2004) a case study can be viewed as a research strategy comprised of several methodologies seen fitting to the case. As such, methodologically the research planned was designed as a four-phased research project: literature review, quantitative phase, expert opinion study, and a concluding scenario phase. The literature review phase was seen as creating the conceptual understanding on the interconnection between technological foresight and management. In addition, the required baseline knowledge on the case study was studied. In the quantitative phase, the case study was approached with computer-assisted tools which were seen as testing if a purely quantitative approach to foresight would give significant insight into the case. This was further complemented by a quantitative study, done in the form of a Delphi study, creating an expert based view on the development. These efforts were concluded in a subsequent scenario phase where the qualitative and quantitative studies done were combined to form a holistic view of developments.

1.5. Structure of the thesis

The dissertation is structured as follows. The following section, Section 2[3], focuses on building the foundation for the study. It elaborates on *managing technology* through innovation, new product development, and management of technology. This could be seen as a different approach from previous literature, which seldom makes a connection between concepts as far apart. In this thesis, the second section is written as it is seen to elaborate on the context to which forecasts are made. Emphasising innovation, managing our technological world and managing uncertainties are often mentioned in New Product Development literature as significant chal-

[3] Section two has been published partly in the authors earlier pre-doctoral degree of Licentiate of Science (Technology). The theses form a continuum in which the earlier thesis focused to understand the conseptualisation focusing on product development. Section two has however been partly rewritten due to the authors furthered understanding in the theoretical background.

lenges. As well, Fuzzy Front Ends call for better insight on the future of our technological surroundings. In addition Technology Management (TM) emphasises the identification and selection of new opportunities as key activities. However, this literature, as seen in section 2, does not make an explicit connection to foresight.

Section 3 elaborates on the theoretical background of T*echnology Foresight (TF)*. Focusing on the rough categorization to quantitative and qualitative tools in foresight, the Section explains the theoretical background of the subject. The section reviews significant literature within the context of TF and creates an understanding of the concepts found to be significant

The concluding Section 4 discusses the theoretical background and draws conclusions from the previously published original publications included in this thesis. The publications are also reviewed in short in Section 4. In the final section the implications and future research possibilities are also introduced.

2. Technology Management

When attempting to analyze the concepts relating to this thesis it is seen as important to limit the work to a specific scope. As Ayers (1969) has noted technology is created, either in response to societal changes or needs or by the second-order effects created by technology itself. It is important to create this context to this thesis as well. The way creating new products or taking advantage of innovations is understood in the confines of this thesis is at the very heart of technological forecasting, as it lays the foundation to what it is that we are attempting to forecast. We have seen that the management of our increasingly technological world is important, but in what context. By creating a background of TM, the author elaborates on the context in with TF is analyzed in. From this analysis, the scientific background has been confined to describe and analyze several terms. These are *innovation*, *Fuzzy Front End* (FFE), *New Product Development* (NPD), and *Management of Technology* (MOT).

This section is divided into four self-containing sub-sections reviewing individual concepts. In the first sub-section, innovation as a term and process is reviewed. This is followed by FFE, which is analyzed in a smaller detail than innovation.

NPD is reviewed in the third sub-section. The analysis, as well as for innovation, hopes to elaborate the definition and process of NPD, but also makes notions on NPD success mostly following the work of Cooper (1994). The analysis on NPD is followed by analysis on MOT, which is seen as a tool for the leadership and management of innovation and NPD.

The chapter is seen as giving a basic understanding on the terms presented. The work is written with the understanding that the work does not cover all of the aspects in the vast scope of the terms presented, but rather lays the foundation to understand the context of the work. The undertone selected, based on the context of the study, is to focus on technology or knowledge-driven development scenarios. This could also be defined, as Rothwell (1994) has done, as technology-push development.

2.1. Innovation

Innovation has been an increasingly researched subject, but not a new concept to humans as such. As (Fagerberg 2006) has pointed out there is something innate in humans need to think of new and improved ways of doing things. As seen from **Figure 2.1** the number of scientific articles relating to innovation has increased in recent years.

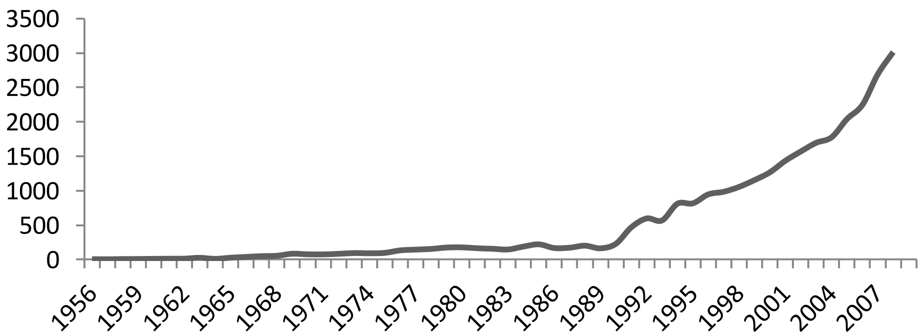


Figure 2.1: Articles analysis from the term innovation by years.[4]

[4] Source: ISI web Of Science Citation Index.

This sub-section focuses on the term innovation. It strives to elaborate the definition of the term as well as what is seen as being an innovation process. The section also includes an elaboration of the sources and types of innovation.

2.1.1. Definition of Innovation

As Fagerberg (2006) noted innovation is innate to humans. Innovations are born from humans working towards new and improved ways of doing things. It can be easily argued that innovation starts from the work of a network or single human working towards depicting the born idea. Earlier innovation was seen as the result of the individual actions of a researcher, but the current understanding emphasizes the role of network of innovators working in a problem-solving process. (Dosi 1992). Innovation is manifested in the interaction of interdependent actors, learning and exchanging information, in a system. (Edquist 2006)

A distinction between idea, invention and innovation can be seen as demonstrating the need for an innovation process. An idea[5] is a change, incremental or revolutionary to the status-quo. It can be a change in thinking, processes or products, but the change has no concrete manifestation. In comparison, invention[6] is the concrete manifestation of an idea. From this, we can see that innovation is the successful application of an invention (Mckeown 2008). Fagerberg (2006) has used the distinction that innovation is seen as the first occurrence of an idea, innovation however is invention carried out in practice. Innovation as such is defined as *"The economic application of a new idea. Product innovation involves a new or modified*

[5] "(Product) idea" An idea for a possible product that the company can see itself offering to the market. If the idea is pursued, the product enters its development stage. - *A Dictionary of Business and Management*. Ed. Jonathan Law. Oxford University Press, 2009. *Oxford Reference Online*. Oxford University Press. Turku University. 30 July 2009 <http://www.oxfordreference.com/views/ENTRY.html?subview=Main&entry=t18.e5052>

[6] "Invention" is the idea of a new product, or a new method of producing an existing product. This is distinguished from an innovation, which is the development of an invention to the stage where its use becomes economically viable. - *A Dictionary of Economics*. John Black, Nigar Hashimzade, and Gareth Myles. Oxford University Press, 2009. *Oxford Reference Online*. Oxford University Press. Turku University. 30 July 2009 <http://www.oxfordreference.com/views/ENTRY.html?subview=Main&entry=t19.e1684>

product; process innovation involves a new or modified way of making a product. Innovation sometimes consists of a new or modified method of business organization."[7] Innovation is similarly defined in scientific literature as *"An innovation is an idea, procedure or object perceived as new by an individual or another unit of adoption, e.g., a firm"* (Rogers 1995), although lacking in the economic component.

A distinction has to also be made between creativity and innovation. These terms, which are also used as synonyms, have a clear distinction. Creativity is by definition used to depict the ability to produce ideas, on the other hand innovation, as seen earlier is tightly linked to the concept of having a concrete and successful application of an idea. (Davila, Epstein and Shelton 2006)

The definition of an innovation is also greatly affected by its context. In arts something innovative means a radical change to the current state, however in economics and innovation is defined by the capability to increase value for customer, product or organization.[8]

In an organizational perspective, innovation can be seen the *"...successful implementation of creative ideas within an organization."* (Amabile, et al. 1996) Innovation is seen as starting from the innovative individuals in the organization. When creative individuals, which can form innovative teams, use their insight on a given subject to create something new that makes a difference and can be successfully implemented an innovation might occur. Innovation is the combination and/or synthesis of knowledge within the organization that creates new processes, products or services. (Luecke and Katz 2003). Studied by several scholars (Bowman and Helfat 2001, Subramaniam and Youndt 2005), the knowledge, or intangible factors owned by the company, are the most significant factors affecting the innovativeness of a company.

[7] "innovation" A Dictionary of Economics. John Black, Nigar Hashimzade, and Gareth Myles. Oxford University Press, 2009. Oxford Reference Online. Oxford University Press. Turku University. 29 July 2009 <http://www.oxfordreference.com/views/ENTRY.html?subview=Main&entry=t19.e1609>

[8] For further discussion on innovation terminology refer to Linton (2009)

Historical discussion on innovation has started as early as 1800´s by Say (Say 1836) and later, purely in an economic context one of the first definitions of innovation is given by Schumpeter (Schumpeter and Backhaus 2003) as:

1. "*The introduction of a new good*"
2. "*The introduction of a new method of production*"
3. "*The opening a new market in which a particular branch has not previously enters.*"
4. "*The conquest of a new source of supply of raw materials*"
5. "*The carrying out of a new organization of any industry*"

Drawing from the work of Kondrantieff (1935), Schumpeter described innovation as the disruption in the regular flow of economics caused by the introduction of novelties. The legacy of Schumpeter has since sprung the birth of Neo-Schumpeterian economics. Neo-Schumpeterian, in addition to basing itself on Schumpeter's work, is based on Evolutionary economics, Complexity economics, Change and Development, and System theory. Evolutionary economics is focused on the emergence and diffusion of novelties based, as well as in the biological evolution, on creation, selection and retention. Complexity economics is based on the interaction between agents in the knowledge creation and diffusion processes. As we can easily see, innovation driven economies, working with novelty are complex systems. Change and development incorporates laws of motion and industry development and finally systems theory introduces the competence building systems, which incorporate several factors such as firms, universities, and regions to the innovation process. (Hanusch and Pyka 2007)

In this thesis, the focus is kept on technological innovation. Making a distinction between social and technological innovations the focus is kept on a micro level technological innovation, although accepting that the role of social innovations in a macro or micro level are significant enablers of technological development (Kuznets 1979, Abernathy and Clark 1985). OECD (1991 in Garcia and Calantone 2002) has defined technological innovation as an iterative process, which is initiated by the possibility of introducing an innovation, or an improvement to an existing innovation, in the context of the industrial arts, engineering, and basic and applied research. As Garcia and Calatone (2002) have pointed out this definition made by the OECD includes two significant points. Firstly, technological innovation is seen as a process, which is iterative in nature. Secondly, the process works through iteration towards an innovation being successful in the market. The iteration can be also seen as including the possibility of reintroducing existing innovation as they evolve in the innovation process. Technological innovation processes are further discussed in the next chapter.

2.1.2. Innovation process

As described earlier innovation is the end product of a process. The starting point, idea and invention, is through a process molded to an innovation as defined earlier. Innovation has by this definition taken place when the original invention has passed successfully through a process of research, production and marketing and been proven on the market place (Mckeown 2008).

Working with innovation, or following with an innovation process, is described as a technological change process where from a novel solution something tangible is developed. The change process follows a path of recognizing needs, creating novel solutions for discovered needs, as well as then developing solutions and implementing them in a wider scale. The process models presented for innovation follow this abstract pathway to some extent, although not following a linear process of R&D to commercial innovation as argued by Freeman & Soete (1997).

Pavitt (2006) has also analyzed the innovation process, partly through the work of Mowery and Rosenberg (1979), and has presented a framework of two aspects:

1. *"Innovation processes involve the exploration and exploitation of opportunities for new or improved products, processes or services, based either on an advance in technical practice ('know-how'), or a change in market demand or a combination of the two."*
2. *Because of the high degree of uncertainty in innovation, innovation processes involves a process of learning through experimentation or theory. The capitalist market is also seen as experimentation through competition.*

From this framework, Pavitt (2006) constructs innovation into three overlapping processes seen in **Figure 2.2**. Pavitt in some sense criticizes the distinction of innovation processes as stages or gates, by this clearly referring to NPD processes.

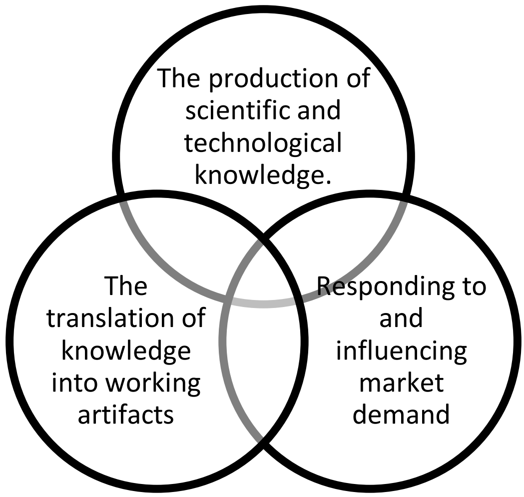


Figure 2.2: Innovation divided into three overlapping processes (Pavitt 2006).

Pavitt (2006) sees the production of scientific and technological knowledge as a major trend. Pushed by the industrial revolution, the increased production of highly focused scientific and technological knowledge is affecting the framework presented by Pavitt. He sees the possibilities of rapid development offering opportunities for commercial exploitation. By coordination of specialization, these opportunities can be taken advantage of. Pavitt also follows in describing three forms of specialization:

3. *Development in R&D departments of large companies producing knowledge for commercial exploitation.*
4. *The small firms improving "producers` goods"*
5. *The "division of labor" in public/private knowledge development*

With the translation of knowledge into working artifacts, Pavitt (2006) troubled with the increased number of scientific knowledge, which theory is insufficient in guiding technological practice. This is underlined by the increased complexity in technological systems. Pavitt (2006) turns the focus of managers working with the endeavor of turning science and technology knowledge into products to take in account possibilities for government funding, system integration, techniques of managing uncertainty and *"technological trajectories and scientific theories"*. By this Pavitt hopes to elaborate that an innovation process is partly a diverse effort of handling vast spectrum of specific knowledge as well as being able to use the specific knowledge on a high abstraction level.

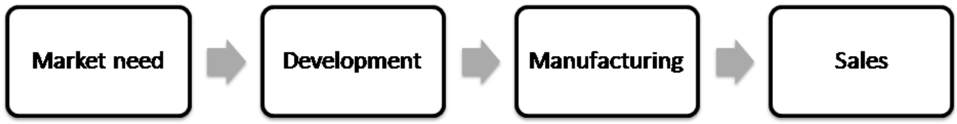
In any case, the process of innovation involves matching the working artifacts with the user's needs. This includes the effort of coping with radical change as well as surviving the "tribal war" with existing technological solutions. Innovation, which is the commercial application of an idea, is significantly linked to the ability to facilitate the exploitation of an invention.

The arguments made by Pavitt (2006) are clearly visible in the publications. In publication I the rapid increase in scientific knowledge on fuel cells is apparent. Keeping in mind that the technology has been invented over 100 years ago, the number of science produced has grown exponentially. Methods of structuring this knowledge are of significant value. As Nonaka and Takeuchi have pointed out, the innovation process can be seen as an intensive knowledge management process (Nonaka and Takeuchi 1995).

In comparison to the overlapping trichotomy process described by Pavitt (2006) a linear representation of the innovation process is given by Rothwell (1994). Rothwell has described the evolution of the innovation process. In the 1950's and 60's the innovation process was seen as a technology push-model seen in **Figure 2.3** (a). The process had as a starting point the production of new scientific knowledge through basic research. This new knowledge produced in universities and other organization doing basic research were then moved through applied research and research and development efforts to the market. This makes the idea of manufacturer innovation and the novelty of end-user innovation, which are discussed in detail in the section 2.1.3, understandable. A technology push, or science push, based innovation can be seen in **Figure 2.3** (b). This easily points out how the voice of the customer was forgotten and ideas or invention developed inside the company was pushed to the marketing department, which then selected the "viable" ideas to be launched. (Rothwell 1994)

To answer the need for more market involvement in the innovation process a market pull type model was increasing in popularity in the 1970's. Market was seen as producing viable ideas or even inventions, which could be in a R&D process turned to products. As such, the market pull process, presented in **Figure 2.3** (b), can be seen as the opposite of technology push. The new market pull innovation process was seen as being in tune with the needs of the market. It made possible by companies' production capabilities, which made it possible to adjust products to customer needs and follow the trends on the market. (Rothwell 1994)

(a) Technology Push



(b) Market pull

Figure 2.3: First (Technology push) and second (Market pull) generation innovation process (Rothwell 1994, Adopted).

The evolution from the linear and static technology-push and market-pull models accounted to the birth of more versatile models. It was seen that either a market driven or a technology driven innovation process by itself would explain how the innovation process works. It was understood that markets and technology was interlinked through the lifecycle of an innovation. By this, the interaction in during the life cycle of the innovation will hold a key on explaining the innovation process. The interaction innovation model, presented in the 1980's took into consideration the interactions between technology development, society and markets as well as the development process. **Figure 2.4** presents the interaction model. (Rothwell 1994)

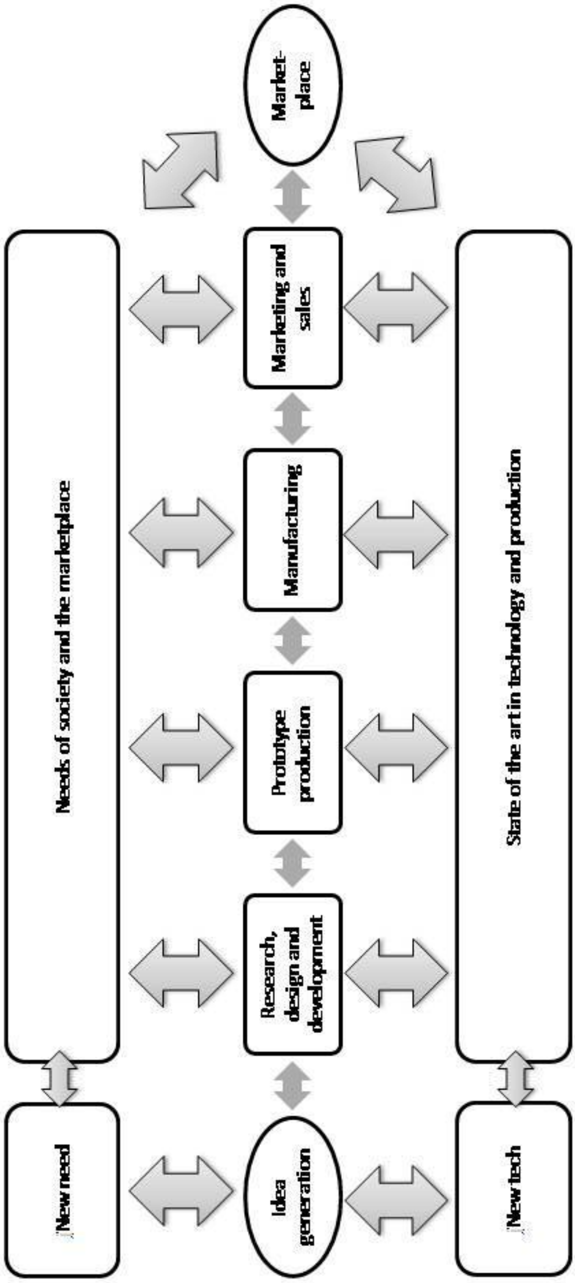


Figure 2.4: The third generation (interaction) innovation model (Rothwell 1994, Adopted).

The evolution of the interaction model was affected by the Japanese orientation to innovation where the voice of the customer was heard as well as where the phased linear processes were changed to parallel processes. The interaction was not limited to one company working with the development efforts by its own. The Japanese model took partners, most significantly sub-contractors, were taken as partners to the innovation process. This adoption of Japanese practices is seen in the evolution of the interaction model in **Figure 2.5**. (Rothwell 1994)

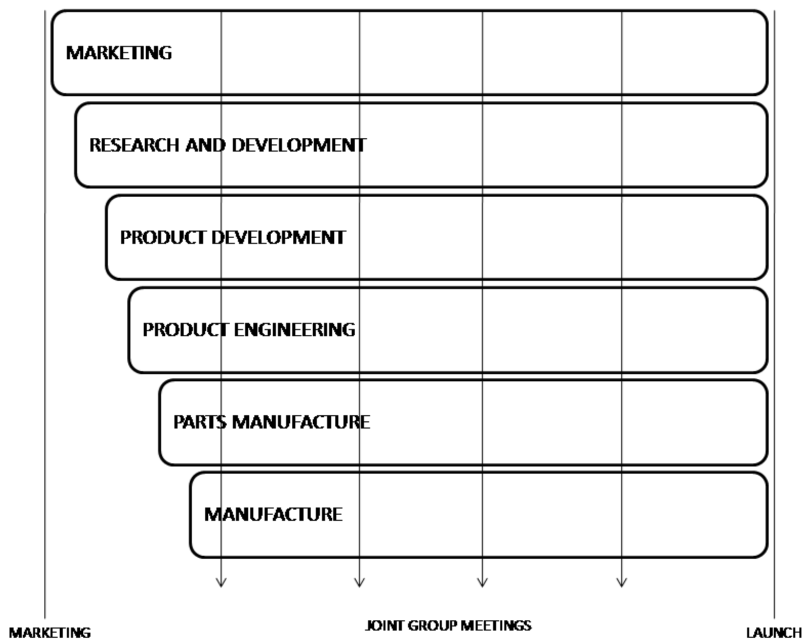


Figure 2.5: Integrated fourth generation innovation process (Rothwell 1994, Adopted).

This effect of Japanese innovation and manufacturing systems is seen in the increased interest shown for Japanese industry processes such as the Toyota manufacturing and R&D process.

Overall, several authors (Day 1994, Srivastava, Fahey and Christensen 2001) have argued the emphasis on market driven aspects in innovation and more over in product innovation. However, it is challenging to make distinctions between different types of innovation, although Linton (2009) has made a significant effort. In the context of this study, the distinction between product innovation processes and its relationship to technological innovation and the processes of technological innovation remain unstructured. An argument could be made that with technological innovation, we focus on an iterative process, which is initiated by the possibility of introducing an innovation, or an improvement to an existing innovation, as defined by OECD (1991 in Garcia and Calantone 2002). Product innovation and its processes are more focused on the commercial result defined as a product. This distinction is significant as, in the context of the study; we focus on identifying and forecasting the possibility of significant technological innovation and its possibility to produce product innovations.

2.1.3. Sources of Innovation

Traditionally we understand the source of innovation to be the manufacturer of a product or a service. However if we look further we can identified several sources of innovation. Erik Von Hippel (1988) has, however, broadent our view on sources of innovation. In his work Sources of Innovation (1988), Von Hippel explains innovation by user, manufacturer and supplier.

The manufacturer innovation is significant innovation source. As Von Hippel (1988) discovered several industries relying on manufacturer innovation. This however relies on the companies having the resources to do a significant amount of research and development to compete by manufacturing innovation (Chesbrough 2003). Supplier innovation was also identified by Von Hippel as one of the sources of innovation. Suppliers are seen to be in a relationship to the innovation by the fact that they supply components to the specific industry to which the innovation is made. The logic of making an innovation, which is not directly used by the supplier, lies in the increased demand produced by the innovation.

One of the most significant results in Von Hippels' work was the identification of end-user innovation. End-user innovation is defined as the innovation process where the person or company using the innovation develops the innovation because the existing product does not meet the users' requirements. Von Hippel demonstrated in the research that in some industry, such as the scientific instruments industry, end-user innovation is by far the most significant source of innovation.

Von Hippel also touched a significant problem, which is ever increasing by seeing marketing research being constrained by user experience. While the life cycle of a product is shortening, the need for a new way to gain accurate user needs should be developed. Von Hippel presented lead user as the solution to the problem. Von Hippel sees lead users to have to characteristics:

1. "*Lead users face needs that will be general in a marketplace, but they face them months or years before the bulk of that marketplace encounters them, and*"
2. "*Lead users are positioned to benefit significantly by obtaining a solution to those needs.*"

The first characteristic of a lead user is specified by them possessing such a real world experience that it represents the experience that the bulk of the consumer base has at a later date. This is possible as we accept that innovations diffuse through society in an uneven pace. To specific user "on the top of the trend" the impact of the innovation happens earlier. The second characteristic is defined by the concept of user innovation. It specifies a situation where the user is significantly impacted by the innovation and by thus pushed to solve the problem at hand. As seen from both of the characteristics given lead users are defined by being a group whose present needs is expected to become the need of the general market in the future. (Von Hippel 1988)

Sources of innovation can also be seen as being closed or open. Closed innovation is a term used to referrer to an innovation model where companies will generate their own ideas, which they would then develop, manufacture, market and sell. This model has been used for decades successfully. Companies, working with large research centers, produce innovations, which are then developed to the market by the companies themselves. Chesbrough (2003) has however seen that an era of open innovation is ending the closed innovation model. Closed innovation is hard to control due to companies possibilities to control knowledge workers. Chesbrough also seen that the increased venture capital has made it easier to commercialize new ideas from start-up companies.

In contrast to closed innovation, in open innovation firms use external as well as internal ideas in the innovation process. Innovations are commercialized by creating pathways for both external as well as internal ideas. Internal innovations can be developed in start-ups outside the companies or outside ideas can be developed inside the company. In open innovation, companies are looking pathways outside its own business. Focus is on using the possibilities produced by the knowledge available outside the company as well as not constricting possibilities produced in internal research projects. This is summed up by Chesborough, Vanhaverbeke & West (2006) as;

> *"Open innovation is the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively. Open innovation is paradigm that assumes that firms can and should use external ideas as well as internal ideas, and internal and external pathways to market, as they look to advance their technology."*

The model is illustrated by **Figure 2.6** and **Figure 2.7**, which represent the difference in open and closed innovation. Chesborough points out that the current society, which is more mobile and produces a significant amount of knowledge, does not support the closed innovation model. The significant down side to closed innovation is that there is only one input to the development process. Research investigations are funneled from the science and technology base to the development cycle where non-viable ideas are dropped and viable are pushed to the market. The developing organization has a strong boundary, which is impenetrable by outside organizations.

In open innovation by definition "opens" the organization to outside influence. As presented in **Figure 2.7**, the organization is embracing the possibility of both internal and external science and technology base. In addition to this, the organization is, at the development phase, open to technology insourcing as well as technology licensing and spin-offs. Technology licensing pushes the results of the innovation process to a market outside the scope of the company. Technology spin-off has been seen as opening all together new markets, and as seen from the funnel the current market is also supplied by the process.

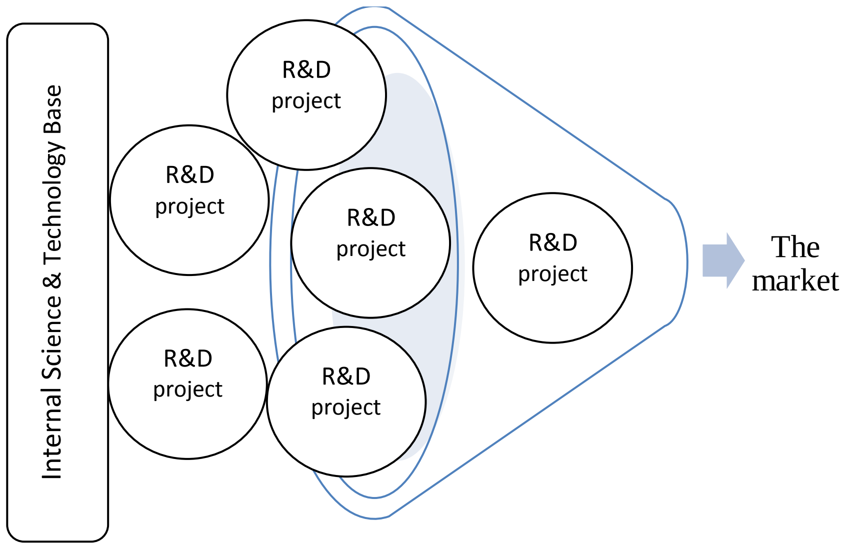


Figure 2.6: Closed Innovation (Chesborough, Vanhaverbeke & West 2006, Adopted).

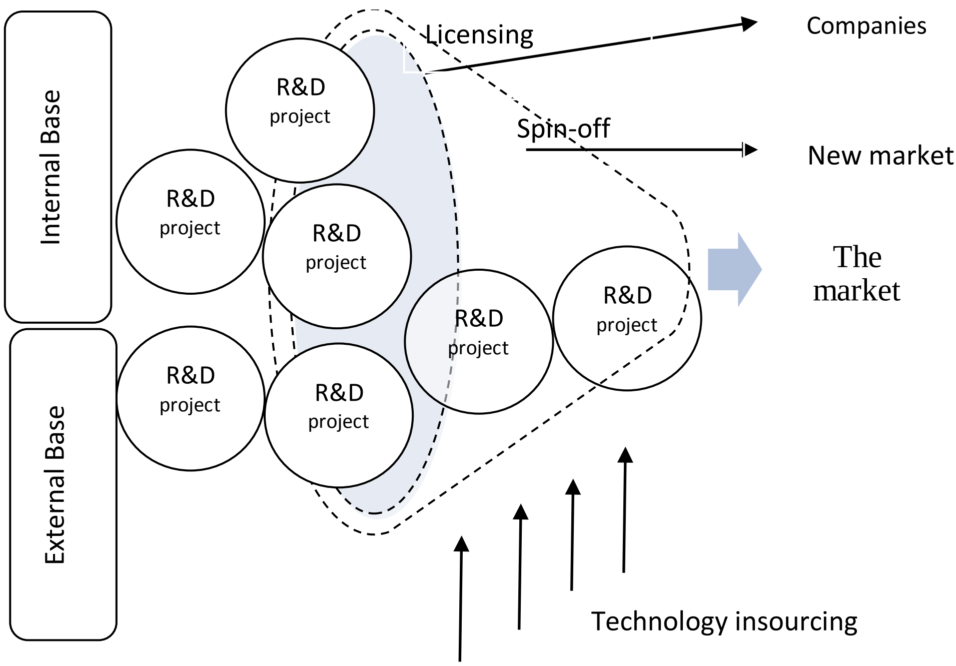


Figure 2.7: Open innovation (Chesborough, Vanhaverbeke & West 2006, Adopted).

Chesborough, Vanhaverbeke & West (2006) have used eight differentiating factors in open innovation in regards to earlier paradigms of innovation. 1) In open innovation external sources of knowledge are regarded as important as the ones internal to the company. 2) From the sources of knowledge is also found the central aspect of the business model, 3) the transformation R&D to commercial value. In open innovation R&D, projects are evaluated against the business model as type one or type two errors.

In regard to knowledge, in open innovation there is a willing and purposed 4) outbound flow of knowledge. This is in parts enables the possibility to have an 5) abundant knowledge base in comparison to the internal knowledge base in closed innovation. The management of this new open flow of knowledge requires 6) a proactive IP management. As a whole open innovation is seen as 7) needing innovation intermediaries to manage the domain. All of the above is analyzed by 8) a metric created to assess innovation capability and performance.

In a fully open innovation model organizations focus on two activities: technology exploitation and technology exploration to create value. (Chesbrough, Crowther and Field 2006, Lichtenthaler 2008). Technology exploitation can be divided into three activities: venturing, outward licensing of intellectual property, and involving other than R&D workers in development efforts (van de Vrande, et al. 2009). Venturing in the open innovation context is seen as the generation of spin-off from internally produced knowledge. Intellectual property rights (IPR) protection is a key factor in both the outflow and inflow of knowledge. The effect of this is in many senses the basis for open innovation existing. The third factor seen as effecting exploitation is the intentional use of person working in other tasks than R&D to facilitate development and growth.

In technology exploration, we see five distinct activities: "customer involvement, external networking, external participation, outsourcing R&D and inward licensing of IP" (van de Vrande, et al. 2009). From these, the interaction with customer interface is the most significant. As seen from Rothwell's (1994) innovation model evolution or von Hippel's (1988) work on sources of innovation, the influence of the market and customer is increasing. External participation is regarded as the usage of capital for the company. This can be seen as alliances with individuals or organizations. (Chesbrough, Vanhaverbeke and West 2006) External participation and outsourcing R&D are seen as "the recovery of innovations that have been abandoned" and the acknowledgement that not all of the R&D required should be done in-house. Capitalization on knowledge outside the organization is at the core of open innovation. Inward licensing activities, as seen from technology exploitation, is a challenging IPR management process in which required technological exploration is done from outside sources for the benefit of the organization.

In the current active discussion on innovation, the role of scientific research, would it be applied or basic, is left out. Although taken into account in the open innovation models presented by Chesbrough (2003). One could easily argue that it currently lack in significant in the current debate. In the context of the study, the focus is set on technology driven innovations and forecasting of such developments and this emphasizes the relationship between research and innovation. Several authors have studied the relationship (Cohen and Levinthal 1990, Mansfield 1981, Rosenberg 1990) and found that there is significant correlation between success and R&D effort done by the company. Technological advancements, the rate of which seems to of be increasing, emphasizes the need for research based innovation. Would this been in the form of corporation creating the capacity to absorb new knowledge from secondary sources such as the universities or by basic research carried out in firms (Lim 2004) remains unclear. However, it would seem practical not to downplay the role of technology-based innovation as a source of innovation.

In conclusion, cooperation between stakeholders, public or private, significantly affect the innovation capability of a company (Lundvall, et al. 2002) Studies in several different contexts have showed the significance of external links and cooperation (Bayona, García-Marco and Huerta 2001, Dittrich and Duysters 2007). This althogether increasing the need to control the technological surroundings of a company (Porter and Newman 2011)

2.1.4. Types of Innovation

Innovation can be seen as a change of some form. Most commonly, innovation can be seen in four dimensions, or the 4P´s of innovation (Bessant and Tidd 2007). These can be described as Product, Process, Position or Paradigm innovation. Although other typologies of innovation has also been expressed, such as Schumpeter division into five types: new products, new methods of production, new sources of supply, the exploitation of new markets and new ways to organize business (Fagerberg 2006). The dimensions given by Tidd & Bessant (2009) are argued to describe the forms of innovation more clearly.

Product innovation is the most self-evident form of innovation. It is regarded as the change in products or services offered by the organization (Tidd and Bessant 2009). Edquist, Hommen & McKelvey (2001) also defines a product innovation as new or improved material goods or intangible services. Clearly, the definitions define product innovation as a concrete change visible to the end-user, such as a new car model or new financial instrument launched by a bank.

Process innovation is the innovation commonly invisible for the end-user. A process innovation is the change in ways in which a product or service is created or delivered, shortly defined as a new way to produce a product or a service (Edquist 2006). As such, it can have an effect to the end user, for example as better quality or faster delivery, but can also remain purely invisible to the end user (Bessant and Tidd 2007). Edquist, Hommen & McKelvey (2001) further define process innovations as technological or organizational innovations.

Position innovation is change to the context of the product or service. This includes the introduction of a product to a context outside its existing context. (Bessant and Tidd 2007) A position innovation could be used to define the strong increase of automotive GPS (Global Positioning System) devices, with precise mapping solutions. This firstly marine device has been introduced to a new domain outside its earlier context with great success.

Paradigm innovation is the most abstract form of innovation, as with paradigms we are working with underlying mental models. Bessant and Tidd (2007) give an example of the airline industry where the introduction of low-cost airlines have significantly change the mental model related to the business.

From the division of specific types of innovation, innovation typology is sometimes also used to referrer to the innovativeness of an innovation. This is most often described as the division into incremental and radical innovations.

Tidd & Bessant (2009) have modeled the 4P's of the innovation domain as seen in **Figure 2.8**. This illustrates the types of innovations and relationship of incremental or radical innovation. Tidd & Bessant (2009) see the circle representing the innovation area an organization can utilize. Although they mention that how much of the area is utilized is decided by the organization itself.

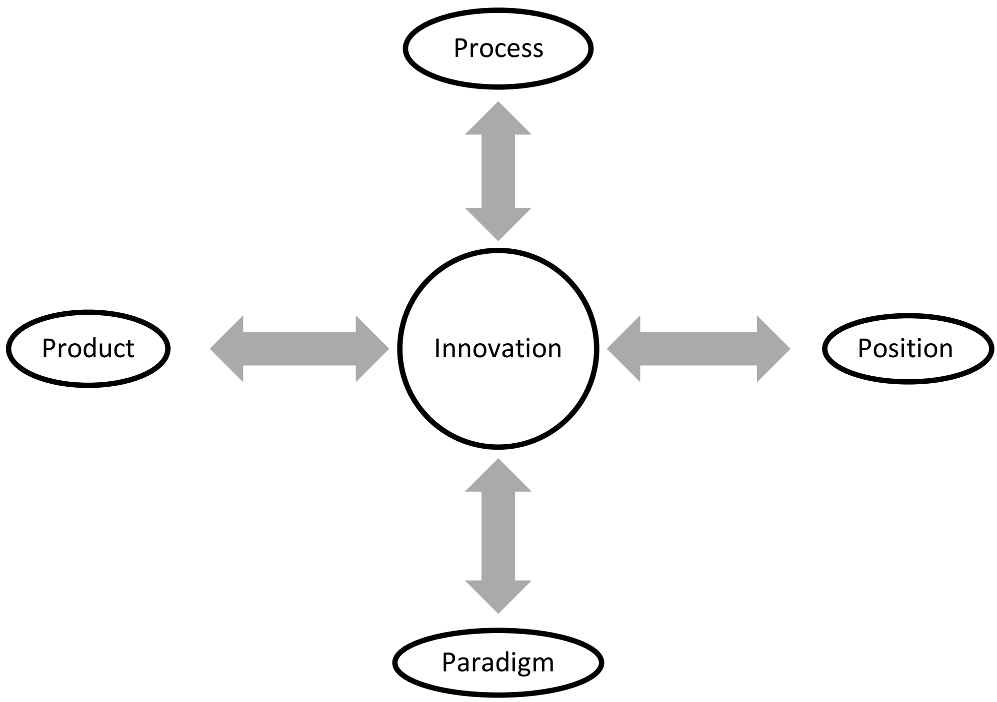


Figure 2.8: The space of Innovation (Tidd & Bessant 2009, Adopted).

While moving in the typologies of innovation it is also significant to recognize that perceived typology or degree of novelty is always subjective. A radical innovation for a small and medium sized company is most likely perceived radical more rapidly as the same innovation in a high-tech multinational company. (Tidd and Bessant 2009)

2.2. Fuzzy Front End

Fuzzy Front End (FFE) is used to describe the early steps of the development or innovation process. Analyzing the possibilities the idea has for success and the uncertainties it presents. FFE is defined by the parts it is made by and these parts are often seen as parts of larger structures. Cooper (1988) described and structures FFE in four parts: idea generation, idea examination, preliminary assessment of the idea and concept definition. Khurana & Rosenthal (1998) argue FFE is developing a product strategy, identification of possibilities and evaluating them, idea generation, product specification, project planning and early acceptance from management. As seen from these two definitions of FFE, which are illustrated in **Figure 2.9**, Khurana & Rosenthal have incorporated several tasks to be included in FFE. However, when Coopers definition is illustrated with the definition by Khurana & Rosenthal, we understand FFE as everything between the idea and the beginning of a funded product development effort. As Murphy & Kumar (1997) have defined, FFE ends when the organization decides to fund the product development efforts of the idea.

The significance of FFE, although it's only a small part of a larger process, is pointed out by several scholars. Cooper & Kleinschmidt (2000) have used the term upfront homework stage to describe FFE. They argue that one of the key factors of having "star" products, or "unique superior products" is project teams using significant time and effort on FFE. In addition to Cooper & Kleinschmidt FFE is seen as a key success factor by several scholars (Booz and Hamilton 1982, Dwyer and Mellor 1991, Atuahene-Gima 1995)

The specific problem with FFE is, however, that it is ambiguous and uncertain in several ways. FFE is seen as having a significant effect in success, if the right decisions are made. The analogy can be made that, if the wrong decisions are made during FFE the negative effects are as great as the positive would be.

The ambiguity of FFE is studied by for example Khurana & Rosenthal (1998). In their work "Towards holistic "Front Ends" In New Product Development" Khurana & Rosenthal (1998) point out from their research a definition of a holistic front end which has several link between parts of NPD process. They see that the key role of FFE is in its ability to reduce uncertainty. This is done efforts such as well-defined executive reviews, clear team roles as well as strict formal processes or in the case of Japanese companies by a culture of organization, which enables interaction.

As seen from **Figure 2.9** Khurana & Rosenthal (1998) divide the FFE model in Pre-phase Zero, Phase Zero, and Phase One activities. They see from the work of Bowen, Clark, Holloway & Wheelwright (1994) that the Phase Zero is forming the link between business strategy and NPD efforts by visions on the business, the product, and the project. These Phase Zero efforts are seen as the most "fuzzy" and linking to underlying efforts of the company.

Phase Zero and Phase One tasks are divided in to customer related actions, such as needs identification and competitor analysis, technical aspects such as technical capabilities and requirement analysis, and risk assessments for the whole product and project planned. Khurana & Rosenthal see that the Phase One concludes in a definition of the product and project plan.

Murphy & Kumar (1997)have defined FFE on the basis of Cooper pointing out that the two factors affecting product success in a significant way are the quality of front end activities and the accurate definition of a product prior to development. They also found that the most significant factor in FFE is the ability to clarify project objectives.

In FFE, the aspect of technological novelty is one of significance. As studied by Tatikonda and Rosenthal (2000) the technological novelty is, while not being associated with overall NPD success, associated with individual success outcomes. Although not being apparent within the models presented in **Figure 2.9** the aspect of technological novelty is apparent when crating new products. Uncertainties relating to the adoption of new technological options are arguable mitigated by consistent technology analysis and foresight. The strugle between user and market driven development and technology driven arguable needs more interaction than separation. (De Moor, et al. 2010)

2.3. New Product Development

NPD has evolved through a significant amount of research from being a linear process to a recursive, iterative or chaotic process. It has been mixed with innovat-

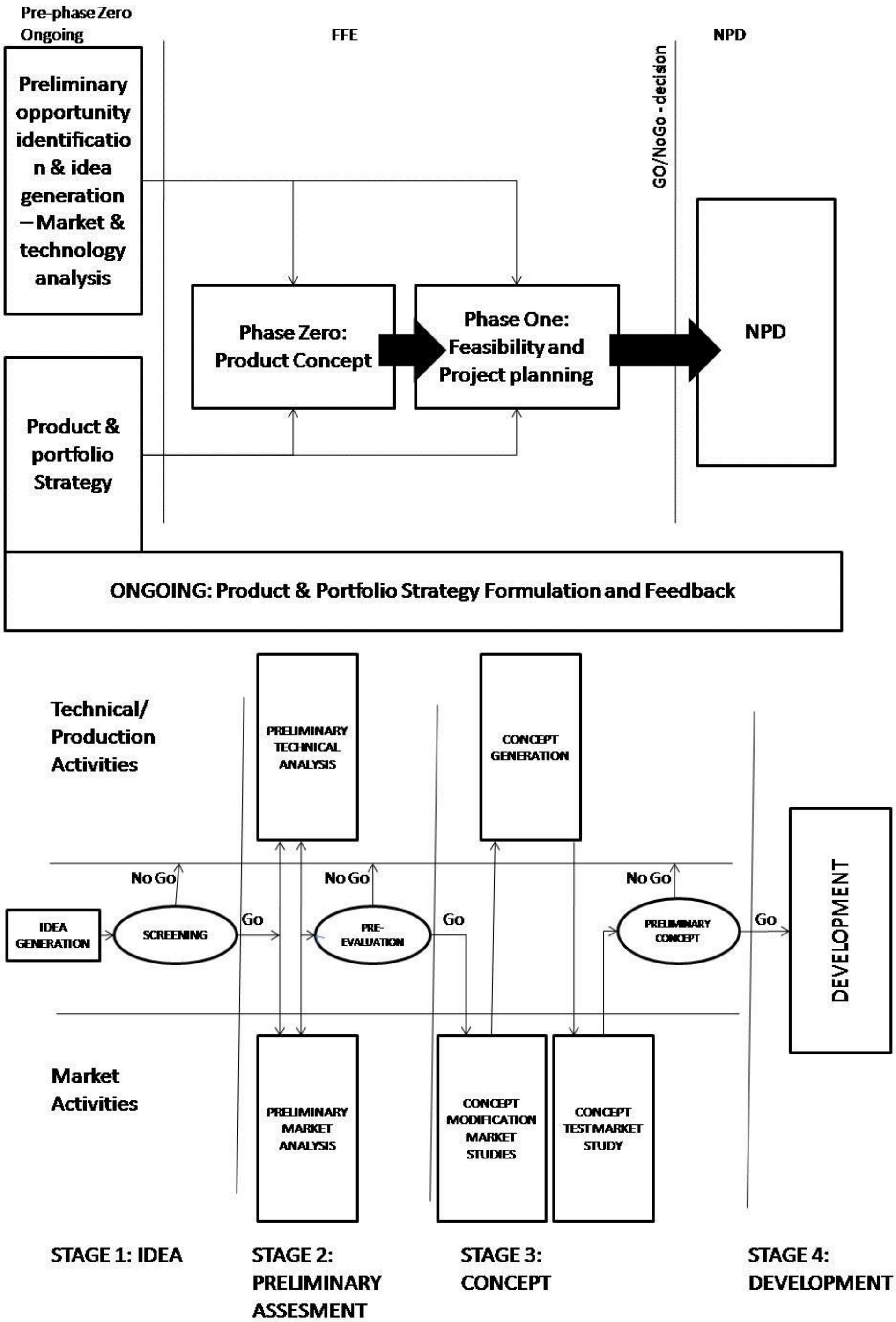


Figure 2.9: FFE process models (Khurana & Rosenthal 1998 above; Cooper 1988 below, Adopted).

ion processes, commercialization, and FFE processes. However, in this section it is hoped to elaborate the definition of NPD. NPD is a process and the requirements of having a successful NPD process.

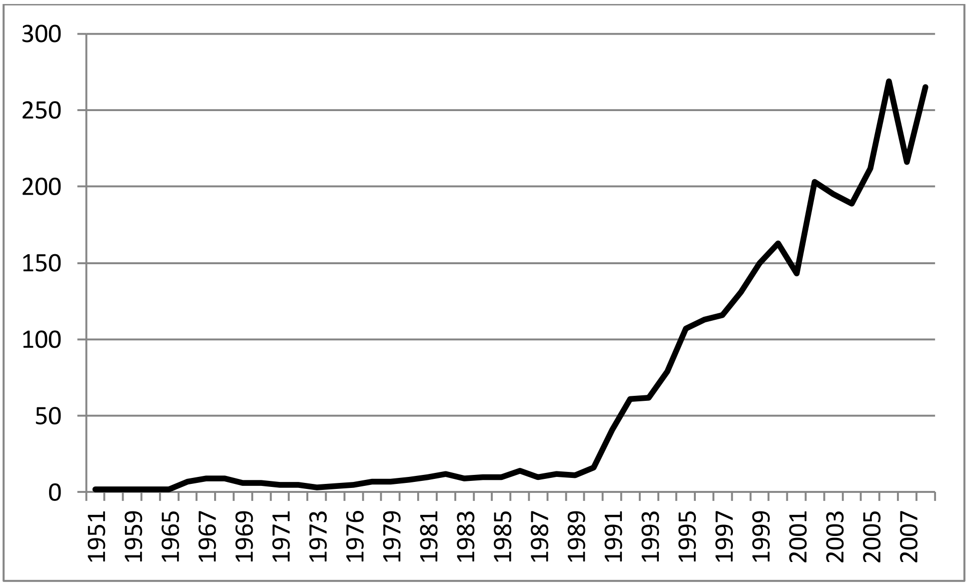


Figure 2.10: Articles analysis from the term New Product Development by years.[4]

The section is limited in that it strives to only elaborate the basic theory of NPD and not go into detail with the current scientific debate on process models and success factors.

2.3.1. Definition of New Product Development

In the Oxford dictionary, a product is defined as "an article or substance that is manufactured or refined for sale". While Parkin (2008) defines goods and services as all the things that we value and are willing to pay for, we can to some degree accept that product is a good or a service. By definition, it is understandable that product development strives to develop a good or service for sale by refining or manufacturing an article or substance.

NPD[9] is defined as "a marketing procedure in which new ideas are developed into viable new products or extensions to existing products or product ranges". In these definitions, commercialization[10] is defined as a part of NPD. When defined as a graphically in **Figure 2.11**, it can be seen that commercialization is defined as the last phase of a NPD process.

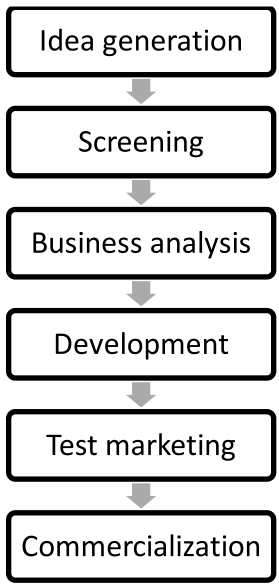


Figure 2.11: New Product Development.

When attempting to define NPD, an acronym broadly used in literature, we understand it to be a process, which starts from ideas and ends on a viable product. This

[9] "new product development" A Dictionary of Business and Management. Ed. Jonathan Law. Oxford University Press, 2006. Oxford Reference Online. Oxford University Press. Turku University. 6 February 2008 <http://www.oxfordreference.com/views/ENTRY.html?subview=Main&entry=t18.e4333>

[10] "commercialization" - The stage in the development of a new product during which a decision is made to embark on its full-scale production and distribution. - *A Dictionary of Business and Management*. Ed. Jonathan Law. Oxford University Press, 2009. *Oxford Reference Online*. Oxford University Press. Turku University.31 July 2009 <http://www.oxfordreference.com/views/ENTRY.html?subview=Main&entry=t18.e1274>

process can be phased differently depending on the process model used. NPD can also be looked as a set of activities that lead to a successful product. Cooper and Kleinschmidt (1987) analyzed a set of activities found to be common in NPD projects. They found that most projects used, even though systematic processes are in use, apply only a fraction of the tasks seen as possible in the process. With this, it can be concluded that reality differs from an academically written “ideal model” substantially. It also suggests that activities and processes are different between companies. While it has been seen that companies use different activities in their processes, the need for a blueprint for NPD is apparent. (Cooper and Kleinschmidt 1987, Kuczmarski, Middlebrooks and Swaddling 2000).

2.3.2. New Product Development Process

NPD discipline has gathered a substantial amount of scholars researching different types of processes. As in all actively researched subject's, there has been different views on and evolution in regard of these processes. From the first-generation linear and static models like Phase Project Planning developed by NASA in the 1960's we have moved towards wider and less functional processes (Cooper 1994) Processes which are recursive or chaotic have been emerging to offer alternatives to the traditional linear processes (McCarthy, et al. 2006). Cooper (1994) has also pointed out that, the stage-gate system, one of the most cited NPD process, is evolving to a third-generation process. Even in the second-generation new emphasis points such as cross-functionality and "Marketing and manufacturing" was pointed out. In the third-generation process, efficiency aspects are added to the mix. (Cooper 1994) When defining today's Stage-Gate Cooper (2008) emphasizes loops, iterations, parallel activities and overlapping activities inside stages. Differing substantially from the historical linear mode of product development.

As understood from the definition NPD process is a sequence of steps that transforms one or several inputs to an output, which is a product, and possibly outputs relating to that product. These steps can be physical, but often the steps relate more to intellectual or organizational activities (Ulrich and Eppinger 2007). As can later be seen in section 2.3.3 the activities and the process of product development is in no way similar between industries and it can vary even inside a company in different development efforts. However, a model or framework of a process can be constructed.

The benefits of a well-defined process are described by Ulrich & Eppinger (2007). They see five factors, which rationalize the use of a defined process: quality assurance, coordination, planning, management, improvement. A development process specifies the process used and makes visible the phases and checkpoints along the way. This assures the quality of the process. Process also facilitates coordination by giving a “master plan” that assures that specific roles are given to specific individuals and that the interrelationships inside the development group are known and visible. A process as a master plan also makes visible the expectations others have on a specific group, individual or organization.

A process also has a natural relationship with planning. By nature a process is an entity that begins and ends and as such is constricted by time, thus a process will naturally have milestones that fix the development to a specific time in space. The above mentioned quality assurance, coordination and planning which are facilitated by the process are beneficial for management. The process can be used as a “benchmark” for performance assessment by the process management. Actual events and the current state of the development can be at any time reflected to the process and thus problem areas can be identified. Finally, the improvement possibilities in the organizations development process can be seen by reflecting backwards through careful documentation. (Ulrich and Eppinger 2007)

As a generic process, development efforts can be seen as a six-phased process. As seen in **Figure 2.12**, a generic process is seen as a straightforward linear process starting from planning and ending at production ramp-up. Ulrich & Eppinger (2007) divide the task and responsibilities in each of the phases to marketing, design, manufacturing and other functions. They have specified key tasks on each of the phases for a specific function, taking actively in account the multidisciplinary effort that is NPD.

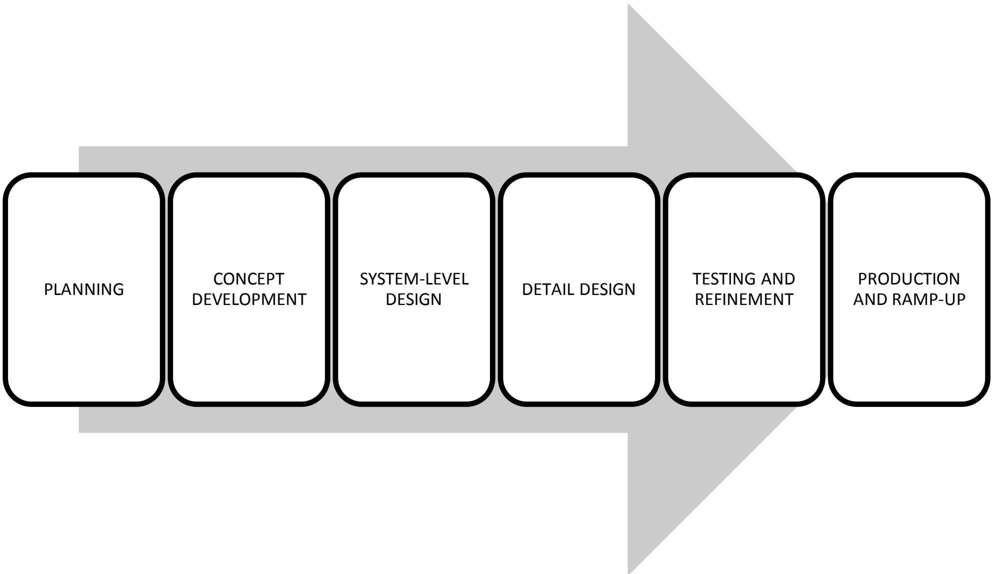


Figure 2.12: The generic product development process (Ulrich & Eppinger 2007, Adopted).

More abstract definition of the NPD process can be seen as containing five distinctive parts. Which are outlined by Crawford & Di Benedetto and Cooper (Crawford and Benedetto 2006, Cooper 2001). These outlines are presented in **Figure 2.13**. These distinctive processes are going through an evolution to the "third generation" processes also described by Cooper (2008).

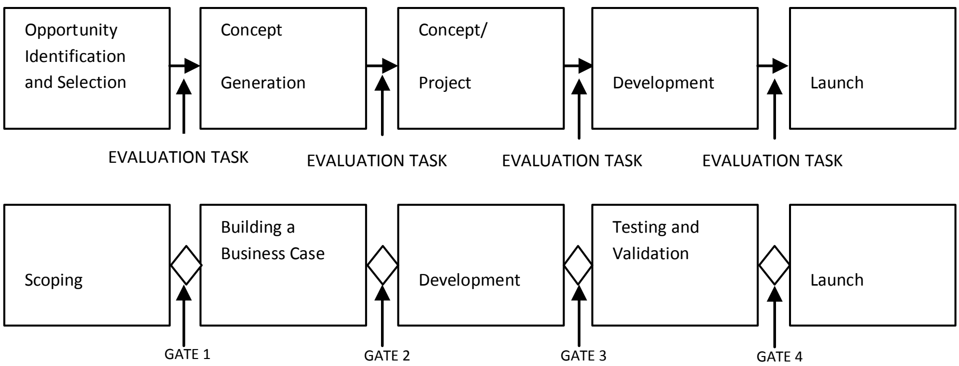


Figure 2.13: New Product Process (Crawford & Di Benedetto 2006; Cooper 2001, Adopted).

As seen from the process described in above, in the scope of the thesis NPD process is regarded as a linear process, although it is seen to include loops and iterations. The form of a linear process is seen as supporting the conceptualization of NPD, and it is argued that this is the reason that these simplifications are made and used. As seen on all of the figures (**Figure 2.11**, **Figure 2.12** and **Figure 2.13**) NPD is seen as a five to six step process and all of the processes include similar concepts, albeit that the terminology used is different between authors.

2.3.3. New Product Development Models

Understanding that NPD is a process that consists of activities that lead to a viable product and that these activities are different between companies, we strive to find the key activities that make or break the project. On several occasions, Cooper and Kleinschmidt (1987, 2000) have demonstrated the key activities separating winners from losers. Cooper and Kleinschmidt demonstrated these as a list of thirteen key activities (1986). Literature regarding the factors found to drive NPD success has been also reviewed and analyzed by Montoya-Weiss and Calatone (1994).

Calatone, Vickery and Dröge (1995) have later pointed out that it is however possible to construct a framework of success that is industry specific. It has been seen that when analyzing a specific industry, top performers put strategic emphasis on eight activities. These are customization, new product introduction, design innovation, product development cycle time, product technological innovation, product improvement, new product development and original product development (Calantone, Vickery and Droge 1995).

In a series of two articles published in 1984, Cooper also points out that NPD success and strategy can be linked (Cooper 1984 a, Cooper 1984 b). From 19 strategy dimensions Cooper formed "clusters of companies that have similar strategies". As a result five distinct strategy types were found: "The Technologically Driven Firm", "The Balanced Strategy Firm", "The Defensive, Focused, Technologically Deficient Firm", "The Low-Budget, Conservative Strategy" and "The High-Budget, Diverse Strategy". Through the concept of these strategy models Cooper showed that companies with a balanced strategy, which combine strong technological capabilities with a strong market orientation, achieved exceptional results in NPD processes. (Cooper 1984 b)

Paladino (2007) has approached the NPD success and strategy through companies' market and resource orientation. Paladino found that companies with a strong resource orientation enable the company to provide the customer with a product that is valuable to the customer. Resource orientation is related significantly and positively, among other factors, to NPD success. On the other hand, strong market orientation enables the development of products that fit the customer better. It is obvious that a strong positive correlation to customer value is found with market orientation. In addition to this, it was found that market orientation was significantly and positively related, among others, to overall performance. (Paladino 2007)

Buijis (2003) pointed out that the concept of developing a new product has two very different aspects, these were the engineer perspective and commercially oriented point of view. As Buijs writes "There was little or no contact between these two worlds - the engineers were talking about the product creation process; the marketeers were talking about new product development." (Buijis 2003) This bipartition can still be seen in the definition of NPD, described earlier in the text. By definition, NPD is a marketing procedure. It should be noted that for example Cooper (2008) points out that Stage-Gate system is not an R&D or a marketing process. The process is strictly a business process. It is however still clear that in many countries, where NPD is engineer driven, a clear bipartition exists.

To understand the NPD process and what makes it successful in context the formation of concrete models of NPD is seen as useful. Brown & Eisenhardt (1995) have reviewed the context of product development in order to articulate the structure of product development and success in it. By presenting models of product development Brown & Eisenhardt (1995) point out differentiating constructs on NPD success. These models, or streams as written by the authors, present the structure of NPD in three clearly defined areas, which are clearly seen from valid and cited studies. The models of Brown & Eisenhardt (1995) can be divided into three: rational plan, communication web, and disciplined problem solving.

Rational plan is view that a successful product development process is driven by careful planning of a superior product to the selected attractive market, and the execution of the structured plan by a cross-functional team working under a facilitating senior management. This model is based on the increased influence of market issues over straightforward technical aspects. The historical development of model have started from the work of Myers & Marquis (1969) who analyzed construction, railroad and computer industry in the United Kingdom by analyzing success factors. They found, as their key result, that market-pull was the product development driver.

The SAPPHO studies published a few years after Myers & Marquis (1969) by Rothwell et al. (1972, 1974) backed up the view by presenting user needs as the product development success factor. This view has later been carried out by several scholars (Cooper 1979, Cooper and Kleinschmidt 1987, Maidique and Zirger 1984) and later by (Cooper and Kleinschmidt 1995, Cooper and Kleinschmidt 2000).

Communication web model works on the premise that NPD is driven by the communication between project group and outside stakeholders. In this model, the focus is not in the overall process, and the focus is purely but on the effects of communication. The work on the model has been started by Allen (1971, 1977) in papers focusing purely on the flow of information in different R&D groups.

One of the key focus points in the communication web model is the flow of external information. From the early papers by Allen (1971, 1977) to several other scholars (Katz and Tushman 1981, Ancona and Caldwell 1990) the effect external communication has on the project is seen as important. In the early papers the effect of a *gatekeeper,* which is seen as an individual with high-performance and ability to communicate often and overall with people outside their specialty, is seen as vital. A *gatekeeper* is seen as bringing new information to the group and by this facilitating development. In the work of Ancona & Caldwell (1990) the model is turned into *boundary-spanning* activities which are seen as an ambassadorial activity of facilitating the work in progress.

The third model of disciplined problem solving evolved from Japanese product development practices (Imai, Nonaka and Takeuchi 1984, Quinn 1985). The model was based on a company having an autonomous project team doing problem solving. This work was facilitated by a strong leader working in between senior management and the project team. This heavyweight manager is seen as making subtle control from the senior management possible. As a significant difference from other model was the strong relation between suppliers and the company. This was seen as one of the key focus points of success.

2.4. Management of Technology

The term *management*[11] is defined as *"the process of dealing with or controlling things or people"* and *technology* can be defined as created capability which is manifested in artifacts that are seen to augment human skills (Rapp 1981). From the definitions we are able to understand the focus of Management of Technology (MOT), which is this thesis used synonymously with Technology Management (TM).

Technology, as defined above, is created. This means that technology is not found in nature and cannot be harvested as such. Technology is created and is a result of a process. This process creates artifacts that are used to augment, by enhancing or replacing, human ability. The MOT can by this understood as dealing with created artifacts that augment human capability. The growing number of technology increases the need to manage to totality of the technological world. (Van Wyk 1988).

In 1987, National Research Council (NRC) in the United States focused on the growing need of technology management. (NRC 1987). NRC defined MOT as *"linking engineering, science, and management disciplines to plan, develop, and implement technological capabilities to shape and accomplish the strategic and operational objectives of an organization"*. This is not the only definition and several authors have since contributed to the definition process (Gaynor 1991, Monger 1988) and to the context of MOT (Van Wyk 1988, Pilkington and Teichert 2006). From these the definition by Badawy (1998) can be seen as further defining MOT. Badawy defines MOT as *"a field of study and practice concerned with exploring and understanding technology as a corporate resource that determines both the strategic and operational capabilities of the firm in designing and developing products and services for maximum customer satisfaction, corporate productivity, profitability, and competitiveness."*

[11] "management *noun*"- the process of dealing with or controlling things or people - *The Oxford Dictionary of English* (revised edition). Ed. Catherine Soanes and Angus Stevenson. Oxford University Press, 2005. *Oxford Reference Online*. Oxford University Press. Turku University. 31 July 2009 <http://www.oxfordreference.com/views/ENTRY.html?subview=Main&entry=t140.e46295>

The history of MOT can be traced to the 1970s. Ulhoi (1996) describes MOT under concepts such as R&D Management, Innovation management, Technology planning (Engineering management) and Strategic management. Described in a simplified fashion R&D management is seen as focusing on providing funding for R&D. Innovation management focused on the radical innovation. Technology planning focuses on the problematic of managing the fast product life cycle, while understanding how the manufacturing process would be designed sustainably. Strategic MOT is describe by Drejer (1997) and seen partly as an evolution from the other concepts described. This evolution is described in detail by Drejer (1997).

Primarily MOT scholars are focusing on eight questions (Van Wyk 1988):

1. "*How to integrate technology into the overall strategic objectives of the firm*"
2. "*How to get into and out of technologies faster and more efficiently*"
3. "*How to assess/evaluate technology more effectively*"
4. "*How to best accomplish technology transfer*"
5. "*How to shorten new product time*"
6. "*How to manage large, complex and interdisciplinary or inter-organizational projects/systems*"
7. "*How to manage the organization's use of technology,*"
8. "*How to leverage the effectiveness of technical professionals.*"

As seen from the questions, MOT has significant contact points with other disciplines such as R&D Management and project management. However, MOT has aspects, which are linked specifically to technology development and not identified in other disciplines. For example, the management of large complex interdisciplinary technological systems can be seen as having a strong link to human factors and as such is linked to social sciences. MOT is seen as connecting these cross-disciplinary actions in the context of technology.

The crosscutting actions of MOT are seen as supporting the activities in the core processes. Phaal, Farrukh & Probert (2004) divide MOT activities into identification, selection, acquisition, exploitation and protection of technology. Similarly, the

NRC has focused, while having a process view on MOT, as identification and evaluation of technology, management of R&D, integration of technology to the overall operations of the company, implementation of new technologies and the management of obsolete/replacement of technology (NRC 1987). In addition to the previously mentioned, MOT has been analyzed by several scholars (Gregory 1995, Levin and Barnard 2008, Rush, Bessant and Hobday 2007). Applying the previously mentioned studies Cetindamar, Phaal & Probert (2009) have suggested technology management seen as a dynamic capability with six activities: identification, selection, acquisition, exploitation, protection and learning. In the structure presented, these activities are also seen as having supporting activities such as project management. The structure of technology management is seen in **Figure 2.14**.

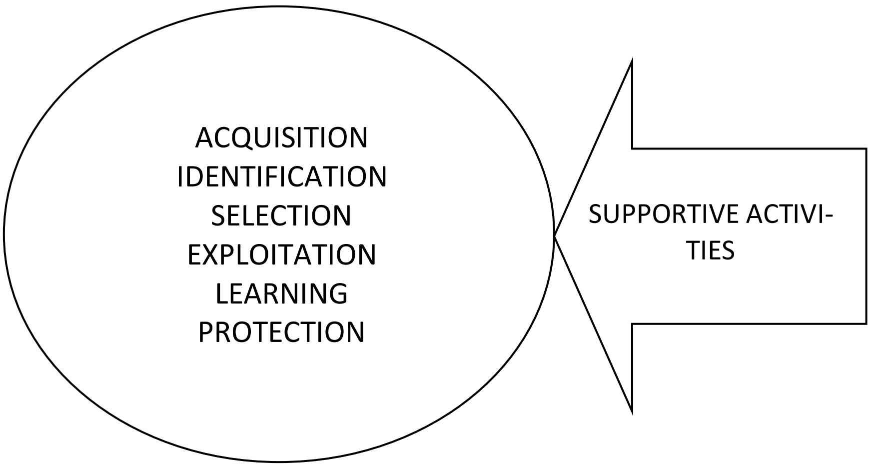


Figure 2.14: Technology management activites (Cetindamar et al. 2009, Adopted).

Although it would see that the premises for having a MOT or TM structure would be valid and needed, as seen from the work of Cetindamar et al. (2009), the structure of technology management can be seen as having two challenges: 1) the need to make distinctions between concepts and practices of innovation, knowledge management and technology management and 2) the need for solid frameworks which would facilitate understanding on practical technology management.

As for the work of for example Cetindamar et al. (2009), which see technology management as a dynamic capability, have in their work presented a technology management system used in Glaxo Wellcome company. The model has similar structuring as the innovation process model by Rothwell seen in **Figure 2.5**. Although understanding that the terminological concepts used differ, as does the abstraction level used, similarities are apparent.

It is however apparent that the dynamic capabilities theory offer viewpoints in understanding technology management. Dynamic capability is defined as the ability to reconfigure, transform and redirect core competencies with external stakeholders, resources and strategy point of view in the rapidly changing market (Teece, Pisano and Shuen 1997). Dynamic capabilities theory structures the understanding of the framework of technology management and makes clear boundaries available. Technology management, or MOT, can be seen as the management of technological capabilities in a rapidly changing market.

3. Technology Foresight

3.1. Review on Technological Foresight

Going back in time to elaborate on the historical background on forecasting we would result in an exhaustive list of prior work and history to describe. This could be argued to have much to do with the innate need for humans to gain insight about the future. We have been, and still are, interested in the prophecies and forecasts, would they be made by Nostradamus or the weather channel. As such, to extend the background too far would be more a confusing and unpractical effort.

Limiting the approach to forecasting in the context of technology, we are still going back in history approximately 100 years. Dependent on the approach[12], we would find the origins of technological forecasting in the works of Wells or Taylor. In 1902 in the newly industrialized world, Wells (1902) argued that by approaching the implications of new technologies in a systematic manner would enable a better society. Similarly, Frederik W. Taylor and his work *The Principles of Scientific Management* (1911) approached the future of management in a systematic fashion.

[12] For more discussion refer to the Special issue Strategic Foresight of *Technological Forecasting and Social Change* Volume 77, Issue 9, November 2010

The significant notion made by Taylor was to move from rules of thumb to a more scientific approach to work. Scientific tools have since been widely applied to work and military applications. The rise in the importance, and later the dominance, of technology in all aspects of life made forecasting a necessity. Would it first be in the military context, in which the complexity of systems developed resulted in long lead times and subsequently made analyzing the future a necessity (Linstone 2011), or in the overall social context, as seen in the work of National Resource Committee report (NRC 1937)

Technological Forecasting (TF) has had a strong policy focus from early on. Moving on from the early works of Taylor and Wells, we see that the methodological background of TF has been created after the Second World War in organizations such as the RAND Corporation. Although other efforts in technological forecasting did occur, the early work of RAND has been cited as the historical background of TF. Works from authors such as Herman Kahn (Kahn 1965, Kahn ja Wiener 1967), later noted as the "father" of scenario analysis, and Dalkey, Helmer and Rescher, on Delphi method (Dalkey 1967, Dalkey ja Helmer 1963, Coates 1975), created the basis for what is known as TF today.[13]

Since the early developments of foresight methods in the US, significant effort has been taken in Japan and Europe. The effort has been focused on a policy aspect of forecasting. Large national effort in the United Kingdom and Japan (Keenan and Miles 2008, Kuwahara, Cuhls and Georghiou 2008), focused on creating a large national level technology plan, has since been taken advantage of in several European countries such as Germany (Cuhls 2008) and France (Barré 2008). This has significant differences to the foresight effort in the US, which does not focus on creating a national level plan, but focuses more on efforts done in individual organizations. (Porter and Ashton 2008), partly showing the cultural differences in the approach towards TF.

Recently, as noted by Martin (2010) we have seen a tremendous increase in studies focusing on the technological forecasting. This is elaborated in detail in **Figure 3.1**, which shows the number of journal papers published about technological forecasting or foresight.

[13] For historical notes on prior work from the authors refer to http://www.rand.org

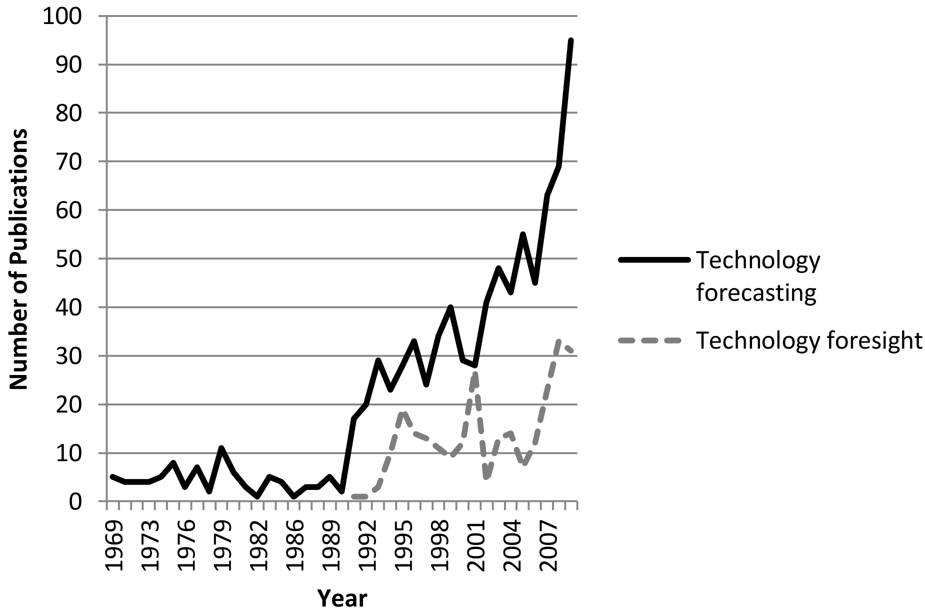


Figure 3.1: Articles analysis of the terms Technology forecasting and Technology foresight by years.[14]

To avoid confusion, the terminological difference between forecasting[15] and foresight should be defined. In the work of Martin (2010), a review on the differences of the concepts is made explicit. Technology forecasting, which has been applied most prominently from the 1950´s in organizations such as the RAND Corporation and the Hudson Institute, is defined as making a probabilistic statement of the future. While, as Martin and Irvine (1989) explain, foresight involving "…the explicit recognition that the choices made today can shape or create the future and that there is little point in making deterministic predictions in spheres (including science and technology) where social and political processes exercise a major

[14] Source: ISI web Of Science Citation Index. Searched by terms appearing in the Topic-field.

[15] "The art of estimating future demand for goods or services by anticipating how buyers are likely to react under given sets of conditions." "forecasting" *A Dictionary of Business and Management*. Ed. Jonathan Law. Oxford University Press, 2009. *Oxford Reference Online*. Oxford University Press. Turku University. 27 January 2011 <http://www.oxfordreference.com/views/ENTRY.html?subview=Main&entry=t18.e2646>

influence." Martin (2010) further elaborates through the work of Godet (Godet 1986), Martin and Irvine, and Coates[16], that while forecasting takes a passive role towards the future, foresight rests on the firm belief that the future is created.

From the above mentioned, foresight, in this thesis is seen as aiming to conceptualize the future. By a conceptual framework as well as using foresight as a process, the long- and mid-term future is processed to likely, plausible or thinkable visions of possible futures. Foresight is a contribution of multiple stakeholders generating a vision of the future and giving tools to shape the future into a desired direction. Foresight can be seen as communication where a deeper understanding of the foreseeable futures is gained. Foresight enables understanding of the system, which is analyzed. Factors, drivers, and their interaction are made visible. This creates a holistic view of the system analyzed and enables the stakeholders to affect the system.

Although trying to use terminology consistently throughout the thesis, it should be noted that the discussion on forecasting or foresight is to some extent trivial. As Linstone has described "contrast between key factors that distinguish forecast from foresight is, in my view, quite arbitrary." (Linstone 2010). Taking a practical point of view, we should be more interested in why than how we define the methods and tools used. However, for consistency foresight is used to describe the approach taken in this thesis.

Moving from terminological discussion towards practice, the outcomes of foresight work can be derived from the objectives of the foresight study. Ranging from scenarios, roadmaps, Delphi studies, and trend extrapolations to more informal outcomes, foresight processes are carried out in different shapes and forms. Foresight is, in some form, innate to organizations in a dynamic system. Decisions regarding the future of an organization require an opinion on the future towards which the decisions are then directed. This view of the future state of the system can be the result of a formal process or the opinion of a specific decision maker.

In a more formal approach, foresight methods can be categorized in several ways. Popper categorizes foresight methods based on their nature and capabilities. Based on nature, which refers to the type of method used, Popper argues that methods can

[16] Refer to (Martin 2010) for an explicit review on terminology

be divided into *Qualitative, Quantitative, and Semi-Quantitative methods.* By their capabilities, which are defined as the methods in which information is gathered or processed, Popper (2008a) defines four categories based on 1) expertise, 2) interaction, 3) evidence, and 4) creativity. Kostoff & Schaller (2001) have categorized, specifically when analyzing science and technology roadmaps, foresight into two distinctive categories; expert approach and computer based approach. The most elaborate definition of technology foresight methods has been done by Vanston (1995). From the work by Vanston, we can divide TF methods to highly quantitative and semi-quantitative methods. The methods seen in **Table 3.1** are structured based on the work of Vanston and Watts & Porter (1997)

Table 3.1: Forecasting Methods based on Vanston (1995) and Watts and Porter (1997), adopted.

Semi-quantitative	**Highly quantitative**
Delphi Surveys	Technical trend analysis
Nominal group conference	Substitution analysis
Structured/unstructured interviews	Precursor Trends
Analogies	Growth limit analysis
Content analysis	Learning curves
Comprehensive opportunity analysis	Feedback Models
Alternate scenario planning	Monte Carlo models
Monitoring	
Content analysis	
Patent analysis	

Further defining the methodical options available in foresight efforts Popper (2008a) has made the conceptualization of the Foresight Diamond. Taking advantage of earlier work by Cameron et al. (1996), who defined a triangular structure of methodologies, Popper (2008a) defined a diamond with four types of knowledge source expertise, interaction, evidence and creativity. Seen in **Figure**

3.2 this also takes into account the aspect of method being a quantitative, semi-quantitative or qualitative, as seen before.

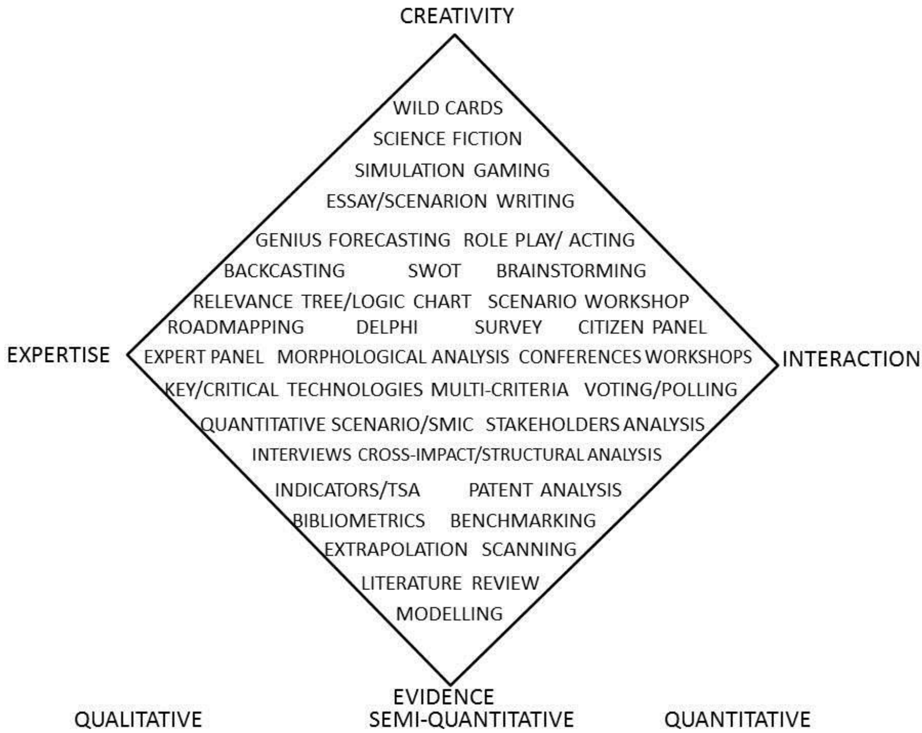


Figure 3.2: The Foresight Diamond of methodological options.

Methods, although seen in the diamond as individual methods, are used as complementary activities by their type of knowledge. In a comprehensive study, a set of methodological options should be taken advantage of.

However, regardless of the methodological options, the methods of technology foresight rely heavily on the notion of orderliness in innovation (Balconi, Brusoni and Orsenigo 2009). As Fagerberg (2006) has noted, the creation of new knowledge and innovation is a basic function to humans. The transformation towards a more knowledge driven society has ever increased the speed of innovation. However, the methods of technology analysis rely on this orderly process of creating new knowledge and turning that into the benefit of humans.

We would tend to model development with a naïve form where new ideas form innovations in a linear process from research laboratory to industry. This linear process of development, which has a clear starting point and a result, is an easy to grasp approach to modeling the complex socio-technical change occurring. One could easily argue that a cyclical model of idea generation and thereafter exploitation would be valid. This would be the result of a cyclical process where new exploitable knowledge creates an opening for new ideas.

The above mentioned focuses the discussion back to technological change and economic growth. Explaining the interactions in detail, Dosi (1982) goes to describe that economic growth and technological development is not as easily explained by causal relationship. Technological change being categorized only by technology-push or demand-pull, as seen in 2.1.1, could be argued to lack validity. Either expecting that innovative activity would be based on a prime mover or an autonomous increase in demand or technical development would be a simplification.

3.2. Foresight as a tool for technology management

In the work of Porter et al. (1991) foresight or forecasting is described as a tool for MOT. Making the notion that in MOT is ultimately linked to a time constraint. To make an almost naïve argument, more explicit, one could argue that everything surrounding us is linked to four dimension, one of which is time. Technology does not make an exception in this.

However, when focusing on a more practical aspect, we could ask if this notion of our four dimensional lives translates to corporate planning and if it does, what is the period we need to make explicit. We are aware of our past, but might not be willing to learn from it. We are living in the now, but might not be aware of it. We are faced with our future, but might not expect it more than a quarter at a time.

Going back to the previous Section 0, several notions were made. Firstly on the creation of new knowledge, elaborated in section 2.1.2. The abundance of new knowledge created and distributed has increased. One could argue that we are not troubled with the creation of new knowledge, although it is not insignificant, but our ability to take advantage and synthetize what we have already invented is the factor of significance. As noted earlier

> *With the translation of knowledge into working artifacts Pavitt (2006) troubled with the increased number of scientific knowledge which theory is insufficient in guiding technological practice. This is underlined by the increased complexity in technological systems. Pavitt (2006) turns the focus of managers working with the endeavor of turning science and technology knowledge into products to take in account possibilities for government funding, system integration, techniques of managing uncertainty and "technological trajectories and scientific theories". By this Pavitt hopes to elaborate that a innovation process is partly a diverse effort of handling vast spectrum of specific knowledge as well as being able to use the specific knowledge on a high abstraction level.*

We have to also be aware that what we endeavor to accomplish by technology is and will be the result of human activity. Referring back to the section 2.4

> *Technology, as defined above, is created. This means that technology is not found in nature and cannot be harvested as such. Technology is created and is a result of a process. This process creates artifacts that are used to augment, by enhancing or replacing, human ability. The MOT can by this understood as dealing with created artifacts that augment human capability. The growing number of technology increases the need to manage to totality of the technological world. (Van Wyk 1988).*

One could easily make the argument that by managing Van Wyk is not referring to hindsight and current state analysis, but to the continuous process of learning from experience, managing our current reality and expecting the future. Expanding even more, from the pure notion of innovation and creation of new scientific knowledge, one could take a leap to New Product Development. For decades, scholars have focused on the Fuzzy Front End of product development, taking the focus of the practical process of developing a new good or a service, and focusing on the more uncertain future of consumer needs. As elaborated previously in sub-section

> *The significance of FFE, although it is only a small part of a larger process, is pointed out by several scholars. Cooper & Kleinschimdt (2000) have used the term upfront homework stage to describe FFE. They argue that one of the key factors of having "star" products, or "unique superior products" is project teams using significant time and effort on FFE. In addition to Cooper & Kleinschmidt FFE is seen as a key success factor by several scholars (Booz, Allen & Hamilton, 1982; Dwyer & Mellor, 1991; Atuahene-Gima 1995; Shenhar et al. 2002).*

Would it be that we have not made it explicit or that we are aware of it but not implementing in our practices, the significance of foresight is implicit even when it is not made explicit.

Translating the before mentioned to practical managerial implications is more of a challenge that we would want to accept. Not to turn into oracles or expecting for a time machine, one would seek for practical methods of foresight. Explaining how and in what manner we would expect the process of socio-technical-change to happen.

To some extent scholarly journals such as the Journal of Technology Forecasting and Social Change, have been publishing research on the topic for decades. Focusing on technology foresight, one would argue that we are more interested in the identification and selection parts of TM. As explained by Cetindamar et al. (2009) identification of technologies focuses on discovering prominent technologies which are important to business. Selection on the other hand is the decision-making process that takes into account relevant strategic focuses of the company.

Technology selection is seen as one of the most challenging decisions that a technology-based company has to deal with (Torkkeli and Tuominen 2002). The increased complexity of technologies combined with the abundance of alternative options increase the difficulty, offer opportunities for differentiation and new business, but also makes processes of foresight even more important. Ability to identify significant future technologies, quantify and measure the development of the identified technologies and finally select technologies based on a valid metric is an exhaustive process.

Studies on technology forecasting have identified the importance of creating tools for making methodological selections in between different forecasting tools (Mishra, Deshmukh and Vrat 2002, Makridakis, Hodgsdon and Wheelwright 1974)

3.3. Methods used in this dissertation

As several authors have noted (Watts and Porter 1997, Martino 1993, Popper 2008b), a selection of methods should be used to design a practical foresight effort. The methodological selection made in this dissertation is seen in **Figure 3.3** in the context of the Forecasting Diamond (FD) seen in **Figure 3.2**.

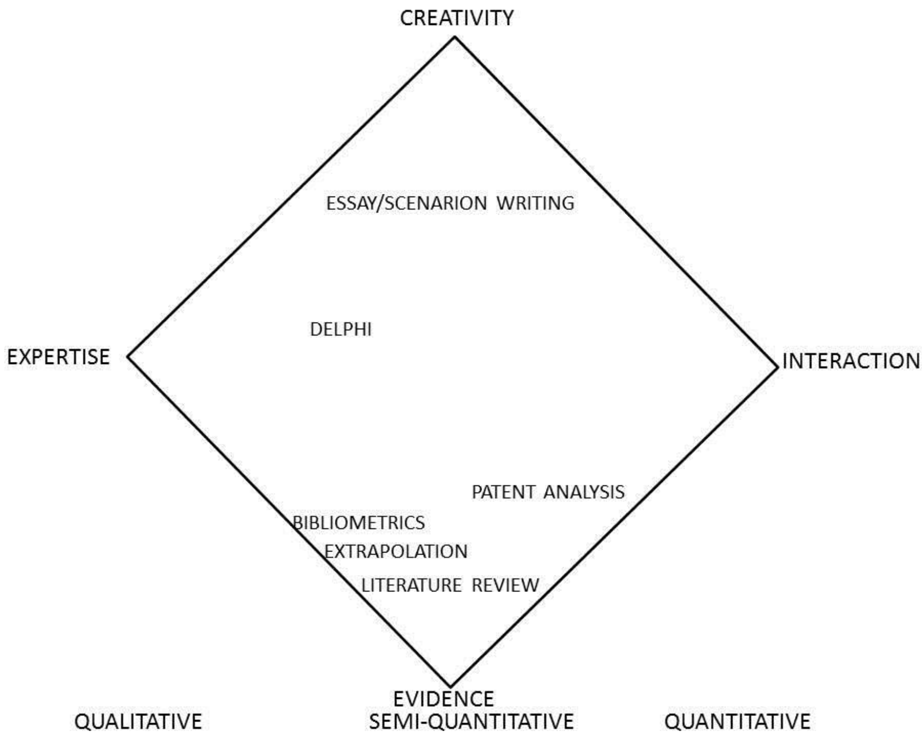


Figure 3.3: Methodological options made within the context of the Forecasting Diamond.

The methods selected rely on different types of knowledge, ranging from evidence based to creative methods. The methodological options available for a researcher are defined by the difference, in addition to the type of knowledge, by their quantitative and qualitative nature of the approach.

Oxford Dictionary of Business and Management define qualitative methods of forecasting as "Techniques used to forecast future trends, e.g. the demand for a product, when there is little meaningful data to use as the basis of statistical techniques, or when it is considered necessary to triangulate the results of statistically based projections. Typical techniques include making use of sales-force estimates, juries of executives, and surveys of user expectations."[17] To further elaborate, qualitative research is by nature interested in the why and how of the problem, this as a distinction on asking what, when and where, which often fall in the context of a quantitative approach.

On the other hand, the Oxford Dictionary of Business and Management define quantitative methods of forecasting as "Techniques used to forecast future trends, e.g. the demand for a product, based on manipulation of historical data."[18] Relying on historical data when creating insight into the future was seen in the 1980's as creating a more precise view on the future than what would be available if we would just rely on qualitative methods. In the paper *The Future of Technological Forecasting* Ayres (1989) argued this by stating that

> *"Better methods of forecasting and planning are needed now as never before… -clearer more* ***quantitative*** *answers to a number of generic questions pertaining to technological progress. (Ayres 1989, emphasis added)*

[17] "qualitative forecasting techniques" *A Dictionary of Business and Management*. Ed. Jonathan Law. Oxford University Press, 2009. *Oxford Reference Online*. Oxford University Press. Turku University. 27 January 2011 <http://www.oxfordreference.com/views/ENTRY.html?subview=Main&entry=t18.e5244>

[18] "quantitative forecasting techniques" *A Dictionary of Business and Management*. Ed. Jonathan Law. Oxford University Press, 2009. *Oxford Reference Online*. Oxford University Press. Turku University. 27 January 2011 <http://www.oxfordreference.com/views/ENTRY.html?subview=Main&entry=t18.e5254>

A quantitative approach to forecasting future development is based either on a time series based analysis of future or on a more causal relationship of several variables which are used as the basis for foresight.

Causal relationships of two or more variables, such as the number of basic and applied research journals articles, can be used to predict future development, in for example the number of patents. However, using causal relationships is dependent on the variables used being identified correctly.

Time series, on the other hand, forecast future trends based on existing historical data plotted against time. With time series, we would also expect that an underlying element, such as seasonal variation or cyclical economic variation, would to some extent, explain the trend of development. The accuracy of time series analysis often relies on the identification of these underlying elements. Time series analysis would, in a practical example, be used to model the number of scientific publications in the future. As seen from example in the **Figure 2.1** the time series of articles related to innovation could be used to forecast future number of articles. In this we would first search for a possible trend or seasonality and in this case end up in using a non-linear regression model to anticipate future development.

In causal relationships we would, most likely, result in either linear or multiple regression in analyzing future development. Linear regression in the situation that we have one independent variable (X) being used to predict a dependent variable (Y) and multiple regression where two or more independent variables are used to predict the future values of a specific dependent variable. In a form of an equation the above-mentioned relationship is described as:

$$Y = a + bX$$

for linear regression where a is intercept and b is slope. For multiple regression where there are p independent variables we define

$$Y=b_0+b_1X_1+b_2X_2+\ldots+b_pX_p.$$

However, in technological development a linear model of development is regarded as highly unlikely. Often in technological development, we would rather make an analogy to biological systems where development, or growth to be more exact, is often modeled with an S-shaped growth curve.

The use of S-shaped growth curves stems from the notion, clarified by Ayres (1969), that modeling technological development is basically a process of “fitting unruly data into a mathematical straightjacket”. In this process it is not relevant to seek a perfect function which would fit a specific historical data, “but to find a function which fits reasonably well and which is believable!” This process is most often referred to as curve fitting.

The “curve fitting” of different growth curves resulted in “a Competition of Forecasting Models” in which growth curve would be able to model a specific set of data with the best accuracy, (Young 1993) which would then be extrapolated into the future resulting in a “trend extrapolation”. The process of trend extrapolation is often referred to as the “workhorse of technological forecasting” (Lenz and Lanford Jr 1973) However, as seen from Publication IV, the models used are often based on the evolutionary limit of known technology. Explained in a different context by Mann (2003), there are significant challenges in attaining the “ideal final result” or in other words “evolutionary limit” of a technology.

The abundance of models developed has been applied to a variety of different data sets, which are seen as modeling technological development[19]. As described by Porter et al. (1991) data such as the adoption of a specific technology to the social system could be used to model technological development. However, technological development has also been modeled through sales data, industrial capacity, technology substitution (such as color vs. monochrome televisions) and materials consumption etc. (Young 1993). All of the above mentioned implicitly or explicitly accept the underlying fact that the data used represents concrete technological development. Compared to highly concrete development data such as for example Moore’s law[20] or Haitz’s law[21], which are both based on a measurable attributes, limitations in using more abstract data sets are apparent. Although it should be noted that growth models, such as the Fisher-Pry model (Fisher and Pry 1971) or

[19] For discussion on empirical models of technological forecasting (Fisher and Pry 1971, Gompertz 1825)

[20] Moore's law describes the long-term trend of the number of transistors in computing hardware. The law states that the number of transistors which can be placed inexpensively in an integrated circuit would double approximately every two years.

[21] Haitz’s law refers to the lumen/watt efficiency development of LEDs, which is claimed, similarly to Moore’s law, being exponential. (Haitz's law 2007)

Gompertz model (Gompertz 1825), are validated by an abundance of empirical evaluations.

Not going into detail in specific methods of quantitative analysis, the significant factor in basing foresight on historical data is the ability of the data used to capture future development. The increase in available data has, however, opened new possibilities for acquiring historical data. Most significantly this is seen in the ability to quantify bibliometric data. This often refers to analyzing textual databases with quantitative methods, referred to as bibliometrics (Borgman and Furner 2002). Bibliometrics has been applied to forecasting emerging technologies in several studies (Huang, Li and Li 2009, Huang, Guo and Porter 2010, Bengisu and Nekhili 2006, Chao, Yang and Jen 2007), most notably in (Daim, Rueda and Martin 2005, T. U. Daim, G. Rueda, et al. 2006, Kostoff, et al. 2001). A bibliometric evaluation of portable fuel cell technology is also included into this thesis as Publication I.

Being used for decades it has been argued that extrapolative methods have matured several decades ago; however contradicting arguments have also been made (Ayres 1989). It could be argued that the contradiction noted by Ayres (1989) has significant insight. The future of quantitative analysis is not driven by methodological development as much as it is driven by the availability of data to be analyzed. Currently, the abundance of data has extended to having databases for basic and applied science, patents to news articles and the number of possibilities is ever increasing. However, one might argue, the future relies on validating different datasets in their ability to model technological change. This is ventured in the original Publications I and IV, which all analyze the possibilities of using quantitative data in modeling of specific case studies.

This turns the discussion to what is seen as being the relevant Technology Life Cycle Indicators (TLC), or the databases in which a specific advancement could and should be seen in. This has been described in the work of Martino (1993, 2003) and Watts and Porter (1997) seen in **Table 3.2**.

Table 3.2: Technology Life Cycle (TLC) indicators based on Martino (1993, 2003) and Watts and Porter (1997) **,** adopted.

Factor	Indicator		
R&D profile	**Stages of Technology Growth**	**R&D stages**	**Typical sources of TLC data**
	Scientific Findings and Demonstration of laboratory feasibility	Basic Research	Science citation Index
	Operating full-scale prototype or field trial	Applied Research	Engineering Index
	Commercial introduction and/or operational use	Development	Patent databases
	Widespread adoption / Proliferation and diffusion to other uses	Application	Newspaper Abstracts
	Societal effect and/or significant economical involvement	Social Impacts	Business and Popular press
Growth rate	Trends over time in the number of items		
Technological issues	Technological needs noted		
Maturation	Types of topics receiving attention		
Offshoots	Spin-off technologies linked		

Quantitative analysis of technology and foresight based on the historical data is however limited by the dataset´s ability to emulate technical development. Even though empirically proven studies with different databases have been seen in literature, we might still argue that further analysis on the validity of different databases is needed. As noted by Watts and Porter (1997) bibliometrics is for example limited by secrecy related to publishing R&D results.

4. Conclusions

This section draws from the theoretical background presented in the previous sections as well as from the publications included to this thesis. The section will, through several sub-sections, give an overview on both the case study used and on the overall context. It will also draw conclusions of the case as well as argue several conceptual findings.

The section is sub-sectioned as follows. Section 4.1 Summary of the publications elaborates on the original publication included in the thesis. The publications are gone through individually and insight to the origins of the publications is given. Section 4.2 Contribution elaborates on the overall finding on the publications. Developing from the summary the publications are analyzed as a set of interconnected publications. This is then analyzed further in the section 4.3 Discussion where the overall summary of the work is given. The concluding section draws from the previous section analyzing the limitations of the work simultaneously suggesting future research efforts.

4.1. Summary of the publications

The first three papers (Publication I, Publication II, and Publication III) form an interconnected continuum of work. Seen in **Figure 4.1** the dissertation structure is defined as a process where quantitative approaches are taken advantage of in Publication I, and followed by two more qualitative approaches done using the Delphi method and the Scenario method.

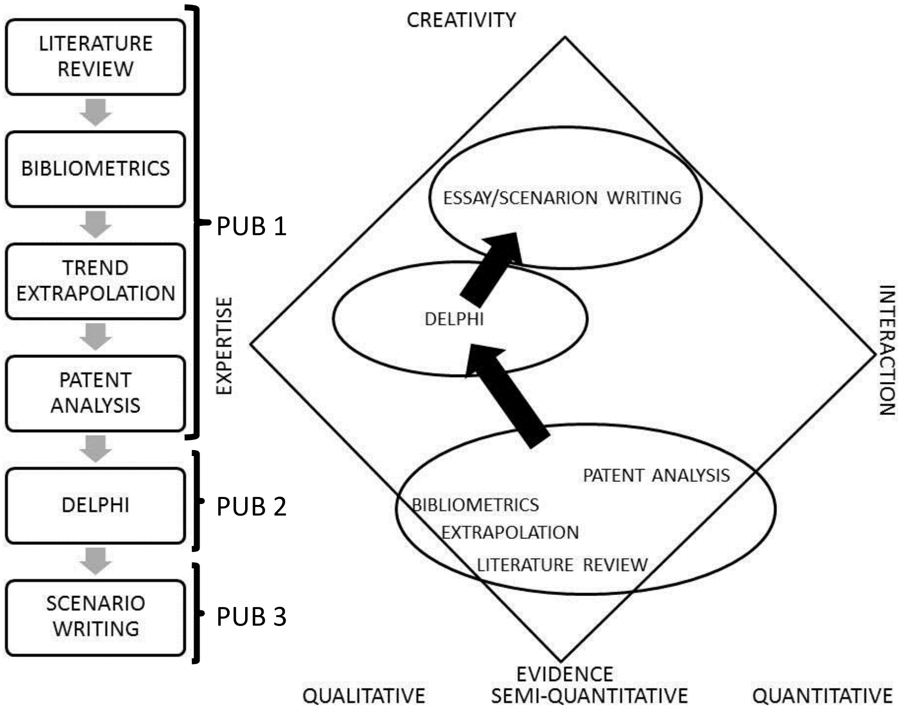


Figure 4.1: Dissertation structure

The idea behind the structure was based on creating a baseline in Publication I. This was further studied with an expert opinion based on a Delphi study, the results of which are presented in Publication II. The dissertation was concluded in a scenario study based on the body of knowledge created during the work for Publications I and II.

Publication I focuses on using a qualitative approach analyzing bibliometric data relating to the case study. This data was then modeled to form a cohesive view on developments. Broadening the body of knowledge created for Publication I, experts with significant knowledge on the plausible futures were consulted for Publication II. This was done in the period of two years, with two iterative rounds. Combining existing historical baseline with the significant knowledge provided by industry experts, a valuable setting for the final stage of the study was enabled. In the final phase, the scenario phase, the previous studies were discussed and concluded by a significant scenario effort. Focusing on creating plausible futures, a creativity based scenario study was conducted. The study structure is seen in Figure 4.1.

In addition to Publications I, II, and III, the original publications include two methodological papers. In Publication IV the challenges of bibliometric and trend extrapolation based studies are shown by reviewing the challenges of trend extrapolations with a larger technology base. In Publication V the linkages with trend extrapolations and expert opinion, moreover the perceptions of human thinking is studied. In the Publication V, it is argued that development scenarios, such as the Hype Cycle (Fenn and Linden 2005, Linden and Fenn 2003) where developments are based on inflated expectations and not on concrete future developments, are producing errors in judgment.

In addition to the original publications directly connected to this study, there are several publications from the author given as a *List of relevant publications excluded from the thesis*. These selected papers from the author have a strong connection to the dissertation, but for the publications and the background to form a coherent thesis, they were excluded.

The thesis was planned to, in addition to being a self-contained work, have significant interconnections with the more conceptual knowledge base of innovation, product development, and management of technology. In the following subsections, the author connects the theoretical background to several conceptual notions made during and after the study.

4.1.1. Publication I

In Publication I the authors analyze the developments of research and patent landscapes on portable direct methanol fuel cell technology and review these against historical data on commercial adoption. The work was based on modeling quantitative data to the extent that it would show emerging research trends, identify organizations, and immaterial property right owners. The study also applied a growth curve to model future developments of research intensity, which was measured by the number of research articles and patents published.

The theoretical background of the publication focused on describing the characteristics of portable fuel cell technology, showing that prior work had described in significant detail the challenges of adopting fuel cell technology in commercial devices. However, as the review on commercial adoption done in the publication showed, there was a widespread enthusiasm towards the technology.

As described in the publication, the quantitative analysis showed a highly concentrated effort by a relatively small number of industry members, a near exponential growth of publications and patents, and an almost identical patent portfolio among different immaterial patent portfolio owners. Commercial efforts, on the other hand, showed an abundance of prototype studies and expectations of commercialization with little or no evidence of commercially sustainable market offerings.

As a conclusion the study revealed that portable fuel cells are very much in a fluid phase. Developers are looking for the application for sustainable growth by developing an abundance of prototype solutions, while creating a patent portfolio focusing specifically, not on fuel cells as such, but to auxiliary arrangements needed to embed fuel cells to applications. A significant disruption in “the natural progression” of technology has been, however, the significant governmental substitution towards fuel cells. The study discussed the possibility that this, to some extent, hinders the creation of a market driven eco-system to portable fuel cells.

4.1.2. Publication II

In Publication II the authors represent the results of an extensive Delphi study on the development of portable fuel cells. The study, done in the period of two years, leveraged the knowledge of experts in assessing the future prospects of fuel cells.

The method strived to take advantage of moderated non-verbal method of communication through a set of questionnaires. As seen during the work on Publication I, the fuel cell industry is relatively small and highly focused on a few corporations and research organizations. As such, being able to gather opinions without the challenges of face-to-face interaction enabled a variety of different viewpoints coming across from the participants. Through iterations, the 23 experts participating in the effort focused on significant development trends affecting the future of the industry.

The Delphi study findings analyzed the fuel cell industry as a value system, as defined by M. Porter (1991). Describing through suppliers, "the firms", channels and end-users, the study described the foreseeable future of development.

The study found that in many cases the experts were greatly divided into optimistic and pessimistic evaluations of future development. For example. seen in Figure 3 in Publication II, the expectations on Net loss development of the fuel cell industry varied greatly between the upper and lower quartiles. However, as a summary, the experts produced a chain of developments leading to increased demand through the ability to produce a practical application that would enable customer value. Expectations, driven by public policy and technological strategies in a number of companies, had however created inflated expectations, which to some extent fell short.

4.1.3. Publication III

Publication III is the concluding study of the process seen in **Figure 4.1**. The Publication focuses on a scenario study, within the context of the case study, from two underlying assumptions. First, we see that all too often has technology and research policy been based on inadequate assumptions (Ayres 1969) and, second, we could argue that human nature drives us to hype about interesting (technological) futures. As a result of these we often see a pattern of over enthusiasm and disillusionment (Linden and Fenn 2003) prior to sustainable growth.

Technology strategies in several companies were directed towards the probable future of a large-scale adoption and commercialization of the technology (Fuel Cells Bulletin 2002 a, 2003 b, 2007 d), although there was no concrete evidence of the technology having been adopted even by lead users, as defined by Von Hippel (Von Hippel 1988).

Using scenarios, the authors sought after a coherent combination of the qualitative and quantitative studies (Publication I and Publication II) done prior to the scenario effort. Scenarios, by definition[22], enabled the conceptualization of an alternate

[22] A scenario in the technological foresight context is defined "as focused descriptions of fundamentally different futures presented in coherent script-like or narra-

plausible view of the future. Largely accepting that by creating multiple visions of the future, we are creating an outlook from which we can select a suitable future and impact it becoming a reality.

With this basic understanding, Publication III represents results from a scenario study, based on the scenario workflows by Porter et al. (1991) and Schaars (1987), and describes three plausible scenarios of portable fuel cell technology development: a crisis of confidence, continuing trend of development, and niche applications. Arguing that the technology will have three practical development trajectories;

1. Through a crisis of confidence, scaling down research and venture capital ultimately slowing down public research, industrial R&D, and immaterial property rights acquisition, ultimately slowing down development or;
2. by continuation of development through a disruptive player being able to create value through the technology. This would also suggest a highly clustered industry with a few large successful players complemented by a few imitators.
3. Finally, through the creation of sustainable growth in a few niche applications, a portable fuel cell industry, although small, would emerge.

In the Publication III the above mentioned conclusions, in the context of the case, are connected to management implications by the understanding that we can shape or even create our future. Elaborating to decision-makers that identifying plausible futures and then taking action to shape technology and foresight policy to a direction suitable for a specific company. Thus, creating an organization where the notion that

> *"…technical experts tend to be too optimistic in the short-term, failing to appreciate implementation problems, and too pessimistic in the long-term, failing in their imagination in regard to major impacts and new solutions" (Linstone 2011)*

would be incorrect.

tive fashion" (Schoemaker 1993) or as "a hypothetical sequence of events constructed for the purpose of focusing attention on causal processes and decision points" (Kahn ja Wiener 1967). However, scenarios should not be mistaken as a forecast, but rather a method illuminating plausible and multiple future situations. (Ayres 1969)

4.1.4. Publication IV

Publication IV is a methodological paper assessing the practicality of using bibliometric data in technological forecasting and trend extrapolations. The study was based on assessing the assumption that bibliometric data would have a correlation with actual development.

Trend extrapolations have been long since used to forecast development trends into the future. Development in this should be understood widely, as similar growth curves are used to forecast population growth, cell growth, and technological growth, often assuming an "evolutionary" S-shaped growth. In a technological context, actual technological development data, such as the lumen per watt efficiency of light emitting diodes, market shape of color television, or speed of airplanes, have been modeled with significant accuracy through S-shapes growth curves (refer to Ayres 1969, Porter, et al. 1991, Martino 1993). The conceptual leap made in recent literature has been to extend this modeling method to bibliometric data (Daim, Rueda and Martin 2005), which stems from the increased number of databases available. In addition to arguing correlation between actual development and a specific bibliometric data set, we have also seen arguments that stages of technological development could be identified through different databases. This assumes that linearity in technological development, from basic research to market, would hold true. The Publication IV focuses, based on the challenges in Publication I, on studying the challenges of modeling bibliometric data through S-shaped growth curves. This is argued to be the first premise in further studying correlation and ultimately causality of bibliometric data to technological development. If we are unable to make a valid model, proving that the data could represent the linear development of technology into the future, further studies are irrelevant.

Challenged with the case study extending beyond the range of current bibliometric data, the case used in this publication was white light emitting diodes. With this case technology, data was gathered form Science Citation Index, Compendex, US Patent and Trademark Organization and News Services, which are argued to show linearity. The data was there after model through to S-shaped growth curves, Fisher-Pry (Fisher and Pry 1971) and Gompertz (Gompertz 1825), thus creating a statistically valid fit.

The study concluded two challenges in applying S-shaped growth to bibliometric data. First, although the models could explain a significant portion of the variance in each of the datasets, the forecast based on the different databases had significant challenges in showing the linear stages of technological development. Second, the possibility of the research to affect the results, through the selection of an upper bound for the bibliometric data, is extensive.

4.1.5. Publication V

Publication V analyses the adoption of fuel cell technology by industry, analyzing if and who is acquiring immaterial property rights in the context of fuel cells. Publication V adds to the analysis in Publication I by creating more insight to the patent landscape within the technology. The study also suggested that to some extent we would be able to see a correlation with the developments of immaterial property rights acquisition with the theory of Hype Cycles suggested by Linden and Fenn (2003) seen in Publication V Figure 2.

As noted in the Publication V, the core of Technology Management is the acquisition and protection of identified technological opportunities (Phaal, Farrukh and Probert 2004, Cetindamar, Phaal and Probert 2009). Analyzing the patent landscape of a specific technology enables the identification of emerging trends within an industry and technological selections made by competitors supporting strategy formulation in a company.

Through a quantitative analysis of databases, the study showed a similar trend of development in patent applications than in journal publications. This showed a strong growth in both of the before mentioned databases. Focusing on the patent application, the study showed significant differences in both what was searched (abstraction level) and where was searched (database). In a high abstraction level (fuel cells) the overall focus of the fuel cell development was clearly focused on automotive industry. Searching at a lower abstraction level (direct methanol fuel cells) a number of electronics manufacturing companies emerges as the dominant companies. In the more specific level, significant differences were made concerning the source of data used.

When making the interconnection with immaterial property right owners to advancements reported in professional literature, as made in the publication by a text mining application, several time dependent scenarios were evident. The immaterial property rights holders were eagerly presenting demonstrations on viable technological trajectories, however lacking in the ability to produce a commercial solution enabling sustainable growth. The commercial solutions launched have had a hard time proving that there would not be a need for disappointment. Databases are however unable to show anything other than the current state and trajectory of growth. To which extent a hype cycle is plausible, remains for further study.

4.2. Contribution

This section strives to create a cohesive view on the contribution of the original publications (in sub-section 4.2.1) and on the managerial implications derived from the overall work (in sub-section 4.2.2).

4.2.1. Analysing technological progression

In the first sentence of this dissertation, a reference was made to the argument by Ayres (1989) that

> *"better methods of forecasting and planning for the future were needed. Focusing especially on quantitative methods of assessing technological development, Ayres thought that more accurate tools for decision making on a macroeconomic and microeconomic scale were needed."*

Trying to introduce categorizations of industry life cycles and creating a metrics for evaluating developments, Ayres (1987) worked on these quantitative methods. Trend extrapolations, as used in this dissertation, have been found to be an accurate measure and forecasting tool on technological development. However, only creating a development model on one specific historical data being analyzed.

Extending the prior modeling of actual development to databases, bibliometrics were thought to enable a further outlook on the specific stages of development, creating a tool for the creation of strategic foresight through understanding the stages of development of a specific technology. As seen in **Table 3.2**, the TLC of a technology is argued to be embedded into the knowledge within databases. As such, a research question was set to evaluate,

> *If a quantitative analysis of bibliometric based technological trajectories enable sufficient strategic foresight?*

As seen in Publication I and Publication V an elementary trajectory and patent landscape of a specific technology, based on bibliometric data, is easy to make and easily modeled to the future. However, to which extent, this models actual technological progression is questionable.

Several challenges and limitations were noted that support this argument. First, as seen in Publication I, the rate of change and division of publications can imply several factors. The strong increase in publications can either be a result of rapid technological progression or due to the increased funding directed to the technology. In addition, the fact that Asian research organizations have produced a significant quantity of the publications analyzed for the study could be argued to be based on the overall increase in research effort in the Asian countries, most notably in China, not so much on the advancements of a technology per se. This creates a bias, where publication activity is increased due to the increase in research efforts overall, which is again based on several socioeconomic factors.

Second, the databases used have limitations that create a significant bias. Bibliometric databases are only accurate for a few decades and remain in a dynamic mode. Database can add new entries to the historical data, most notably in scientific databases where new journal archives can be added and excluded from the database. In addition, currently there are no saturated technological trajectories of bibliometric data available, which could validate the accuracy of bibliometric data in modeling technological progression. The overall causality of bibliometric data against technological progression or TLC is unproven and even questionable (Publication IV)

Third, bibliometric trending does not support discontinuities. As an example, the discovery of a new type of light emitting diode, although being revolutionary in producing usable white light, would have been challenging to identify in between bibliometric data. As seen in **Figure 4.2** the advancements of a single, although discontinuous change in the technological trajectory is submerged within the overall data produced.

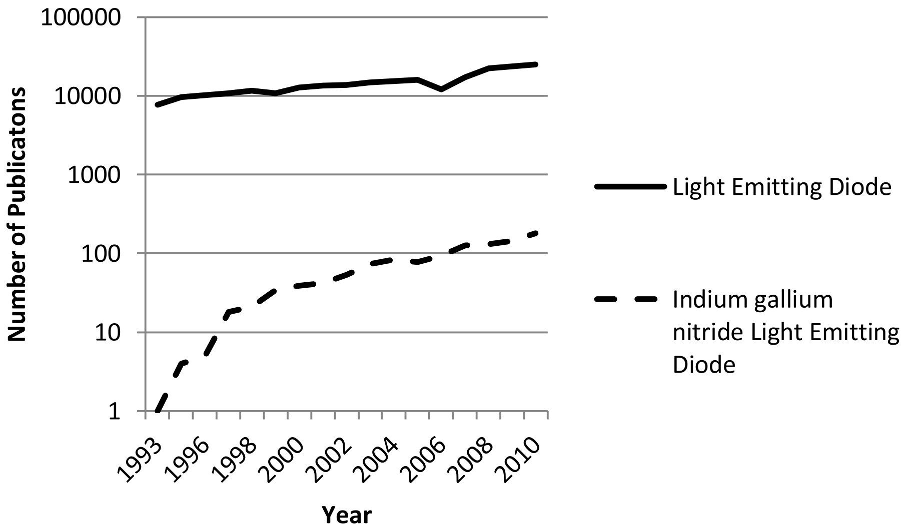


Figure 4.2: Bibliometric data on the development of light emitting diode publications and more specifically on Indium Gallium Nitride based light emitting diodes. (Source: ISI Web of Science)

In the example, the invention of Indium Gallium Nitride based light emitting diodes, published by Shuji Nakamura in 1993, is compared against overall light emitting diode publications. As seen from the figure, although revolutionary, the change in the overall trend remained modest.

Quantitative approaches are bounded by the researchers' ability to ask the right question and transform the produced quantitative data into knowledge. Due to this, quantitative tools only enable the foundation of knowledge on which to build a more profound profile. In this, the use of qualitative approaches would be practical. As such, it is apparent that

a combination of a qualitative and quantitative approach will add value to the trajectory based analysis?

The quantitative approach enables the creation of an objective baseline for further evaluations, which is then integrated to the context of the individual organization through a subjective qualitative evaluation.

Several restrictions should, however, be noted. As the Delphi method used in Publication II, several of the more qualitative methods mentioned in the FD (**Figure 3.2**) are time consuming. In addition, selecting participants and appropriate work methods to further structure a continuous foresight effort is challenging.

In addition to the restrictions, several overall notions are apparent. In an industrial setting, one should focus on deciding to carry out efforts either as an in-house effort or by taking advantage of a more open approach. Within an in-house context sessions are easily arranged, privacy issues, and the participants are easily arranged. However, the result can have significant amount limitations due to subjectivity and organizational structures. In a more open approach, the structure of work, committing outside stakeholders, and mode of work is more challenging, but the results are arguably more objective. For example, Deutsche Telekom has adopted an open approach to foresight by creating a process seen in **Figure 4.3**. (Thom, Rohrbeck and Dunaj 2010)

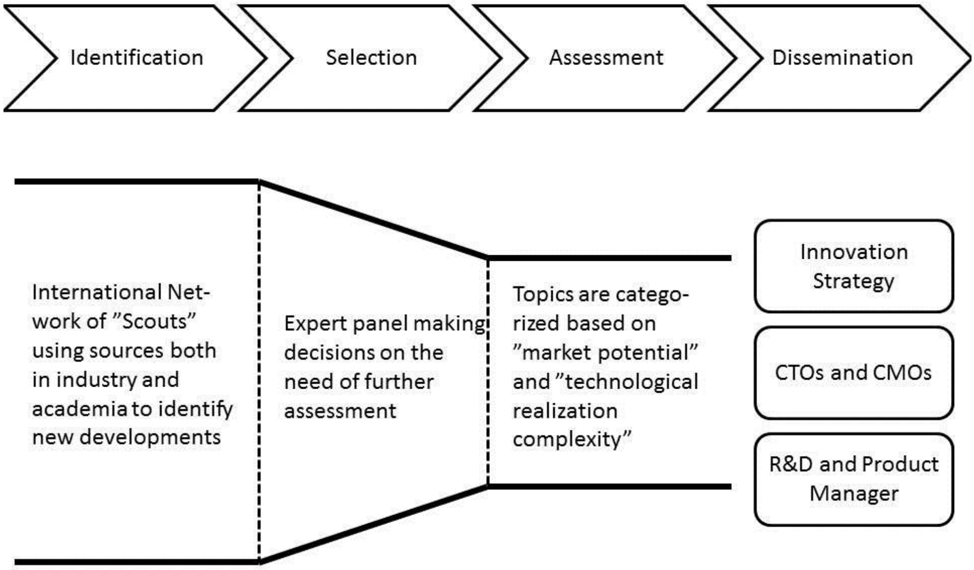


Figure 4.3: Deutsche Telekom Technology Radar process (Thom, Rohrbeck and Dunaj 2010, Adopted)

In the process, a qualitative approach taken to derive knowledge from a network of contributors after which an in-house assessment in the specific technological development scenario is made. This process has significant interconnections with the theory and challenges of open innovation described in Section 2.1

It should be also noted that it is likely that humans tend to go through a cycle of optimism turning into pessimism prior to finding a sustainable solution. Although there is little concrete evidence of this cycle, also known as the *hype cycle* (Linden and Fenn 2003), based on this case study the effect of such a cycle is clearly visible. In the context of the case study, one could argue the emergence of two distinct groups; *the believers* and *the non-believers*. *The believers* are the ones that enable the hype to take place. Increasing in numbers, they push a technology into a development phase where the technology is seen as an all-powerful solution. *The non-believers* are the ones being pessimistic towards the technology. Few in numbers at first, the number of *non-believers* increases as the technology fails to meet expectations. The balance of these two *congregations* seems to have an effect on the *hype cycle.* In Publications II and III the division into two groups, with significantly altering views on the progression of a technology, was apparent.

In conclusion, a holistic view on technological progression can be created by using quantitative and qualitative methods of technological forecasting. In this, the abundance of information embedded in databases creates a valid source for insight, but is limited by the organizations ability to transform it into knowledge.

4.2.2. Managerial implications

The success of a company correlates significantly with its ability to be innovative (Brown and Eisenhardt 1995, Rothwell 1992). Being innovative, as defined in Section 2, is seen as having two dimensions; the exploration and exploitation of opportunities based either on an advancement in technical practice ('know-how'), or a change in market demand or a combination of the two (Mowery and Rosenberg 1979). Focusing on the advancements in technical practice, as noted by Pavitt (2006), is increasing, and thus several managerial implications are apparent.

First, as the rate of change in technology increases, the effort needed to monitor it increases. In addition, as Pavitt (2006) noted, companies should be aware of not only the body of knowledge related to existing technologies but possible disruptions. Maintaining competitiveness in this ever-dynamic field of technological development, and being able to exploit new promising technologies in the company requires the integration of foresight activities into corporate functions. (Costanzo 2004, Day and Schoemaker 2005, Andriopoulos and Gotsi 2006) This notion is arguably embedded also in the definition of MOT (Van Wyk 1988, Cetindamar, Phaal and Probert 2009), which in turn answers the research question,

> *what is the interconnection between technological foresight and technology management?*

Foresight, although not often mentioned explicitly, is implied to be the core function in managing companies' technological surroundings. One could even argue that the fast pace of technological progression increases the emphasis of *technology-push* development. This not to argue that development should return to the technology-push model described by Rothwell (1994), but more to the fact that the rapid pace of technological development stabilizes the relationship between the "overemphasized" market-pull (Day 1994, Srivastava, Fahey and Christensen 2001) and technology-push.

This implies that industry, in contrast to active market research activities, should take up technology research activities, which would enable the creation of CTI (Porter and Newman 2011). This has been an active function in larger companies in the USA for decades (Porter and Ashton 2008), while for example in Europe technological foresight has been a governmental function. However, in a corporate level, large focused public foresight efforts are often misdirected, as we see public policy makers identifying and selecting technologies that industry should exploit. Later referred to as policy-push this is further discussed in Section 4.3.1.

Accepting that a technological research function should analyze the technological progression in a company, the focus turns to processes enabling technological foresight. Processes such as the one used in Deutsche Telekom (Thom, Rohrbeck and Dunaj 2010) and for example Glaxo Wellcome (Cetindamar, Phaal and Probert 2009) are built on the activities of TM (Cetindamar, Phaal and Probert 2009, Gregory 1995). This implies the need to set up procedures supporting the active management of current and future technological surroundings within an organization. This should be done with the understanding of the context of technological foresight seen in **Figure 4.4**.

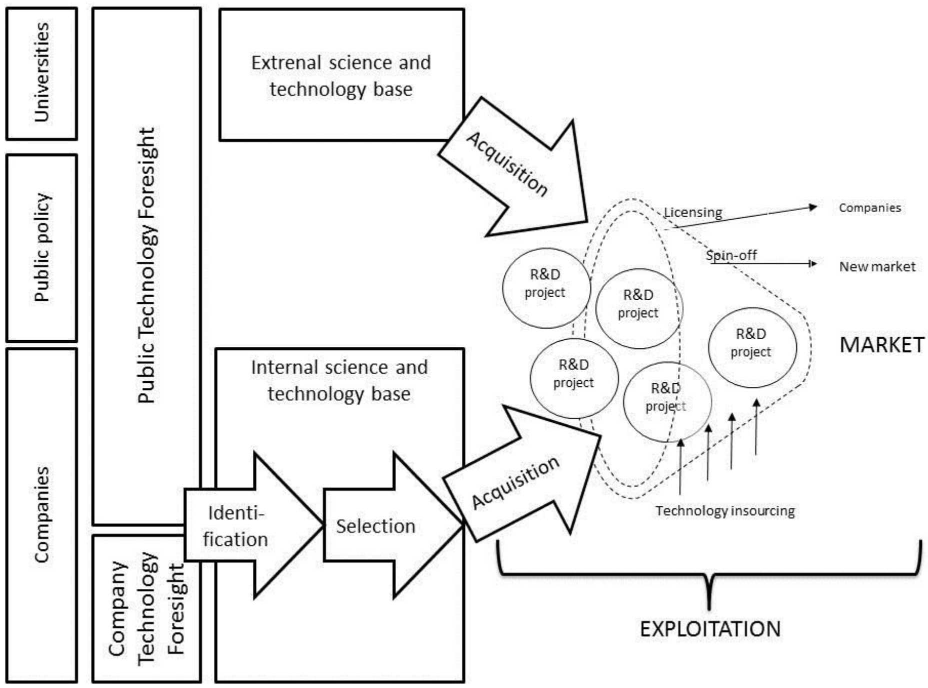


Figure 4.4: The context of Technological Foresight.

4.3. Discussion

Based on the work done, several implications have been drawn. Although aware that the empirical work done for a single dissertation, based on a case study, could not model technology overall, several conceptual notions are argued. These are done aware of the fact that several of these will require future research to be validated. Possible approaches to endeavor solving these are described in the Section 4.4 Future work and limitations.

4.3.1. Policy-push[23]

What came across as painfully obvious during the scenario work in Publication III is that in the context of research policy we are to some extent forced on subjects. In hindsight, it could be argued that the national program on fuel cell development was, to some extent, mistaken in their foresight on the future prospects of portable fuel cells and how Finnish industry would adopt this technology. Mentioned as the early market application of fuel cell technology, portable application was seen as having a rapid adoption curve. However, to date, it seems unclear if even a small group of early adopters would see this technology as being an interesting opportunity.

The argument made, not to go into detail in explaining the shortcomings of portable fuel cells in the Fuel Cell program, that a *policy-push* process would have a significant impact to the more familiar technology-push and market-pull (see **Figure 2.3:** First (Technology push) and second (Market pull) generation innovation process (Rothwell 1994, Adopted).) *Policy-push* is defined as the involuntary, policy-driven, adoption of a technology to research organizations and industry.

In comparison to technology push or market pull, policy push is a seldom researched topic. In the context of innovation economics and eco-innovations, the existing traditional innovation economics discussion on technology push and market pull has been extended to include a regulatory aspect (e.g. regulatory push/pull or policy push/pull) (Cleff and Rennings 1999, Jaffe, Newell and Stavins 2002, Green, McMeekin and Irwin 1994)

The technological trajectories of policy driven technologies, eco or not, have several underlying challenges which should be further studied. Ayres (1969) described in the early work, how research moves in a process of a new invention gathering significant research interest as there is an abundance of new knowledge creation opportunities created by the new idea. However, as new scholars tackle the new challenge, the pace of knowledge creation increases as long as the creation of new knowledge is “easy” to some extent. Due to increased effort needed to produce new

[23] In this thesis the focus is on the impact to technology management and such research policy, such as governmental policy decisions, are left out of the discussion.

scientific insight, scholars will lose interest towards the idea and move towards new more fruitful topics.

We could argue, as an extension on the notion by Ayres (1969) that research funding, in a sense, is this "new idea". The abundance of research funding focused towards a topic focuses research, not for the easy of producing knowledge, but to serve a more primal need, survival.

This could result in misdirection, as results are produced in a significant quantity, but to which extent they are moving development forward, or most significantly to commercialization, is questionable. Applying an analogy by Senge (2006) we should ask if we see the development of, for example fuel cells as a linear process where increased funding provides a catalyst for a more rapid approach towards commercialization or by doing this prime function are we creating a secondary effect that in a sense is more significant.

In this notion from Senge, the author would make a notion on the findings of Schnaars et.al. (1993) on technological foresight guidelines:

> 1. *"avoid over optimism in when forecasting the timing of market success for new technologies;*
>
> 2. *The uses of new technologies work their way into practical products in different often unforeseen ways;*
>
> 3. *Minimize the attempts to predict the social implications of technologies;*
>
> 4. *Include logical, economic, and historical analysis for each innovation;*
>
> 5. *Careful, studied approach to assessing the future technologies can yield valuable insights and reasonable accurate prediction"*

As seen from the arguments made in Publication I, fuel cells have fallen to most of the shortcomings noted by Schaanrs et.al. (1993). Numerous references to expected market success, using old technology to demonstrate a new one and overestimating the social implications embedded to fuel cells were all done while expecting a rapid commercialization of the technology.

The policy implications tried to make explicit by several references and the extensive work argue firstly, that the natural selection of basic research should be to an extent supported. In second, the underlying causal relationships between technology policy options should be made explicit. Thirdly, the expectance that policy cannot precede basic research should be self-evident.

4.3.2. Growth of data

In comparison to what was available only a few decades ago (Nutt, et al. 1976), the abundance of data readily available has exploded. To some extent made freely available in services such as Google Scholar, UPSTO database, and EPO Espacenet database and in addition, the wealth of data embedded in commercially available service such as ISI Web of Science, Gompendex, Reuters, and Lexis Nexis, create a never-ending source of new data. When added to the beforementioned, the data embedded in databases of companies such as Google, Facebook and other social networks or online services unavailable even by commercial means, we can go back to the argument made by Ayres (1989). In the work decades ago, Ayres called for better quantitative methods of technology foresight. The databases made available have increased the opportunities for quantitative analysis.

We should however be more interested in what the information in these databases truly tells us. Selecting different growth curves or to which extent different models produce a statistically valid extrapolation is irrelevant if the data source does not have a causal relationship with the actual development process. Touched on in Publication IV, we question if the technological life cycle of light emitting diodes could be modeled through extrapolation from science, patent and news databases as suggested in several works (Martino 1993, Martino 2003, Watts and Porter 1997). The ability of bibliometric methods, such as used in Publication I, to capture the concrete development remains uncertain.

However, recent studies have drawn conclusions on technological trajectories based on different quantitative approaches (Hörslesberger and Klerx 2011, Huang, Li and Li 2009, Huang, Guo and Porter 2010, Chao, Yang and Jen 2007, T. U. Daim, G. Rueda, et al. 2006, Schiebel 2011), done also in parts by the author in

Publication I. The publications make different assumptions based on whatever has been captured from a specific database, most going on to make managerial implications, directing research policy or company strategy. Studies analyzing the interconnections between data sources and actual development are however scarce. The early studies by Ayers, Porter, and Martino (Ayres 1969, Martino 1993, Porter, et al. 1991) have been confined to a narrower data scope, often modeling adoption more concretely through actual adoption data. Since, as the number of quantifiable data has increased, analysis on the correlations and interconnection between data and reality need to be more closely analyzed.

In conclusion, by quantifying the number of publications, using TF based on quantitative approaches, we see that there is a significant number of qualitative or semi-qualitative approaches used. This represented clearly in **Figure 4.5**. Arguing that while scholars have readily adopted the method as something that would be practical, methodological development is still ongoing. Practical measures and guidelines that would somehow standardize the metrics used are argued to be useful.

4.4. Future work and limitations

The work carried out for this dissertation has been done with the clear understanding that it is not possible to answer all of the questions in the world with a single study. As such, several limitations are apparent. First, the study is made in a specific context in which foresight is mostly a macro-level task. The context in, for example, the US could have had a significant effect on the results. Second, the work done is based on a single case study and as such several aspects would require further study in order to be generalized.

However, the work done for this dissertation has led to several possibilities for further research, most significantly to the further study of technological forecasting in the context of strategic management. Technological forecasting in Europe and Japan has been predominantly policy driven (Cuhls 2008, Kuwahara, Cuhls and Georghiou 2008), in comparison to the US effort where the significance of CTI and

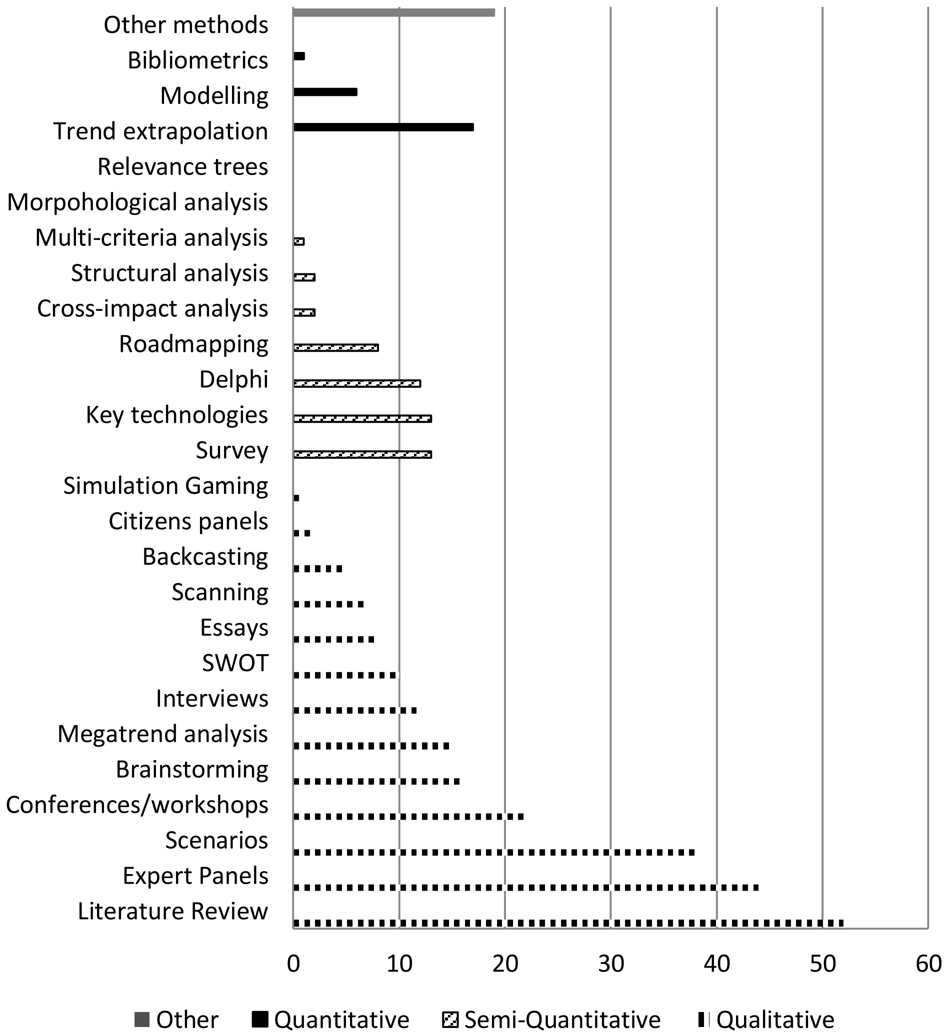


Figure 4.5: Common foresight methods, adopted (Popper 2008a)

researching future technological trajectories has long been valued (Porter and Ashton 2008, Porter and Newman 2011). Not to diminish the value of policy efforts, such as the ones done by the Finnish government, the role of technical intelligence in industry is rising. Due to innovation models such as open innovation (refer to Section 2.1.3), the boundaries of internal and external knowledge are being blurred. Unclear boundaries require a wider view on the technical intelligence within the framework relevant for an individual company. In addition to open innovation, we accept that industry works in a ever-dynamic environment. As Drucker (2008) noted, a company can only exist in a dynamic system, but as the dynamic system is becoming increasingly dynamic, with shortening product life cycle, increased number of scientific findings, and increasingly commoditialising market, the early detection and front end activities (refer to Section 2.2) are becoming increasingly valuable.

It is apparent that within the Finnish context[24], technological forecasting in micro-level is an unfamiliar effort. Different innovation models and traditional new product development processes are used in companies, but managing technical intelligence in larger scale, such as suggested by several scholars (Watts and Porter 1997, Porter and Newman 2011, Porter, et al. 1991, Martino 1993), is still new to companies. This dialogue with industry members opened the avenues for forming several future research questions.

What are the strategic management implications of foresight in the Finnish context? In the discussion with industry members methods such as open innovation (refer to Section 2.1.3 Sources of Innovation) and New Product Development processes (refer to Section 2.3.2 New Product Development Process) are familiar, but the application of foresight methods has been restricted to patent portfolios. Although limited by the low number of interviews, the lack of foresight activities found in the companies warrant further study.

In addition, research on the methodological options that make practical use of the abundance of quantitative data available, is seen as a possible further avenue of study. Going back to the notion of Ayres

> *"Better methods of forecasting and planning are needed now as never before… -clearer more* ***quantitative*** *answers to a number*

[24] During the finalizing stage of the dissertation work, in depth interviews were conducted with three "technology managers" of large companies with significant operations in Finland. The interview focused on the companies' technology forecasting processes or the lack of these in a semi-structured fashion. The limitation of the study was the low number of interviews conducted. The interviews however elaborate on the need of further study of technological forecasting within Finnish and European companies.

> *of generic questions pertaining to technological progress. (Ayres 1989, emphasis added)*

a more current research question would arguable be

> *"Better methods of forecasting and planning are needed now as never before... -clearer more coherent answers, merging causal relationships between qualitative and quantitative information, to a number of generic questions pertaining to technological progress are needed.*

To achieve this, a number of methodological studies explaining the interconnection and causal relationships between data sources and technological trajectories, suggested in parts in the work of Ayers (1987), are needed.

In conclusion, the above mentioned has opened several future research questions.

1. What are the causal relationships between quantitative foresight data and actual developments?
2. How could strategic management take advantage of micro-level foresight?
3. How could the large-scale macroeconomic foresight effort better serve industry?

These questions are however only answered through extensive research with a significant amount of underlying sub-questions.

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Original publications

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Publication I

Arho Suominen and Aulis Tuominen. Analyzing the Direct Methanol Fuel Cell Technology in Portable Applications by a Historical and Bibliometric Analysis. *The Journal of Business Chemistry*, Vol 7, Is 3, Sep 2010.

Journal of Business Chemistry

Research Paper

Analyzing the Direct Methanol Fuel Cell technology in portable applications by a historical and bibliometric analysis

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The development of direct methanol fuel cell (DMFC) technology through an analysis of research, patenting and commercial adoption is studied in this paper. The analysis uses a dataset gathered from both publication and patent databases. This data is complemented with a review on commercial efforts on portable fuel cells. Bibliometric methods are used to identify research networks and research trends. The Fisher-Pry growth model is used to estimate future research activity. The patent landscape is also analyzed by exploring patenting activity. The bibliometric and patent database analysis results were then reflected against a review on commercial adoption. The research indicated increased research activity from the early 90's and expectations of significant growth in the future. Strong emphasis is seen in Asian organizations producing research results and gathering Immaterial Property Rights. However the early expectations on rapid commercialization of the technology have not been met. The commercially viable application of the technology is still lacking.

1. Introduction

The growing environmental awareness has made new energy solutions, such as solar, wind, and fuel cells promising alternatives for existing technologies. In the search for an environmentally friendly and efficient energy source Fuel Cell (FC) technology is one promising choice. FC is an electrochemical device that produces electricity through a reaction between a fuel and an oxidant.

The most significant difference to existing electricity production methods is the possibility to produce electricity without moving parts in a single process (Barbir, 2005). The principle of FCs was invented already in 1838 by German scientist Schönbein and proven by Sir William Robert Grove one year later (Kurzveil, 2009). Since then the technology had for decades been only of mediocre interest, only to increase in interest due to the space programs in the 1950s.

Only in the last twenty years has FC technology taken leaps forward in technology maturity. Due to their versatility, FCs can be adopted to a variety of applications from large stationary solutions to small milliwatt scale systems (Cropper, et al., 2004). The possibilities of using FCs in portable devices have been driven by the high power and lifetime requirements of portable devices. These requirements are proving hard to meet with conventional rechargeable battery systems, due to their limited specific energy and operational lifespan. (Broussely and Archdale, 2004; Eckfeld et al., 2003; Dillon et al., 2004). To meet this market need FCs and specifically Direct Methanol Fuel Cells (DMFCs) are seen as a viable option.

The development of FC technology has taken several leaps forward since the technology was first applied. In the 1970s the development focused on large solutions. Partly due to the oil crisis, possible future energy sources received a significant amount of attention. Only more recently, since the 1990s, has the focus turned towards smaller solutions (Cropper et al., 2004). In the 2000s there has been an increased amount of attention to FCs as a whole. This development can be awarded to several companies which have put significant effort into the development of portable fuel cells (Kamarudin et al., 2009).

In addition to being used in different applications ranging from large stationary power plants to micro watt solutions, FC technology can be divided into several sub-groups such as Solid Oxide (SOFC), Molten Carbonate (MCFC), Alkaline (AFC), Phosphoric Acid Fuel Cell (PAFC) and Polymer Electrolyte Membrane (PEM) Fuel Cells. DMFC is a sub-category of PEM fuel cells. It uses methanol as a fuel in a direct process. DMFC is seen as an energy storage and production device for portable applications (Goodenough et al., 1990), although higher output transport and stationary solutions have also been suggested. DMFCs can be seen as one of the most prominent fuel cell technology to be used in small portable application, this largely due its high energy storage density fuel, fast refueling and capability to refuel during operation. DMFC can also be viewed as a "comparatively simple system" (Cremers et al., 2005).

The paper focuses on the application of DMFC technology in portable applications. A portable application, in the scope of the study, is seen as movable fuel cells with the purpose of producing usable energy. These applications range from power systems in consumer electronics to larger back-up power systems. DMFCs, in portable devices, are entering a highly matured market of providing an energy service. DMFC based power systems are restricted by similar expectations of reliability, cost, noise, efficiency and regulations as conventional systems. Even though the requirements for new electronic devices have increased, the power consumption a specific application has decreased. Nevertheless systems, such as mobile phones, offer several other services than the primary function. This has increased the demands for an energy source. Battery technology has been able to follow the increased requirements of new portable devices. As an example, the newest mobile phones even with cameras and other services have an operational time that exceeds that of the first mobile phones produced. As Agnolucci (2007) has noted, battery manufacturers see that secondary batteries are not facing an urgent crisis.

Despite this, in several geographical areas, governments, research organizations and industry are putting increased effort into developing FC systems. As an example the European Union's 7th framework program has allocated significant resources on the development of fuel cell and hydrogen technology (Fuel Cells Bulletin, 2008 a). Similar efforts can be found in the USA and Japan (Fuel Cells Bulletin, 2008 b). Although these programs focus on FCs widely, there is a significant portion of the effort put to the development of portable devices. In the industry sector we can also see increased efforts as we have seen a steady increase in units shipped in the portable FC sector for several years. In 2008 approximately 9,000 portable units were shipped (Butler, 2009).

By analyzing the developments of research and patent landscapes, while reviewing this data against commercial adoption, scholars and practitioners can gain insight to emerging possibilities. DMFC technology has been developed for decades, often with a clear expectation of commercial possibilities. The research questions set for the study strived to 1) identify research trends, 2) identify significant research organizations, and 3) identify the patent landscape, while reflecting these against commercial adoption. This is done by a bibliometric and historical analysis on research trends and patent landscape.

The paper is structured as follows. The following chapter will explain the characteristics of portable fuel cell technology. It will also review the background on technology lifecycle analysis. The third chapter will describe the methodology and dataset. Fourth chapter will give the results of the study. These are later discussed in the final chapter.

2. Background

2.1 Characteristics of commercializing Portable Direct Methanol Fuel Cell Technology

The challenges of portable DMFC technology can be divided into several barriers, most significantly to lifetime, cost and commercialization. Technological barriers still have a significant effect on portable FCs being seen as a viable option for existing power sources. Technological barriers are analyzed in detail by Kamarudin et al. (2009). Cost as a factor is also analyzed by several authors. In the work of Wee (2007) DMFC based fuel cells were seen as more expensive than conventional lithium-ion batteries in both manufacturing cost and operational cost. Dyer (2002) however found contradictory results. However, the low application rate of FCs would argue against Dyer's results. For detailed analysis on the lifetime and cost barriers refer to e.g. Kamarudin et al. (2009) and Wee (2007).

In analyzing commercialization, Smith (1996) has studied how emerging technologies, such as FCs, can substitute existing technological solutions. Smith described the methods as relating to functionality, and product or asset substitution. Hellman and van den Hoed (2007) have used Smith's work in the context of FCs and presented several significant factors seen as relating to the technological characteristics of FCs. These are 1) immaturity, 2) application diversity, 3) replacement technology, 4) subsystem product and 5) complexity.

1) FC technology immaturity is seen most easily in the rapid technological progress seen in several measurable attributes such as power densities. Significant development has happened in a short timeframe, which has enabled several demonstrations of portable FCs. 2) Application diversity is derived from FCs being energy sources. The abundance of devices requiring a power source has grown significantly. In this the distinctive aspects of portable devices are even more significant. Even thought scholars might disagree on the applicability of fuel cells in mobile phones, we are able to demonstrate the overall increase in of portable devices needing an energy source. The number of mobile phones has from its invention in the 1980's risen to over 4 billion. A similar trend can be found from several different types of portable devices from PDAs to laptops. These all require a power source to which FC is one possibility among others.

3) It is however important to point out, as Hellman and van den Hoed (2007) have done, that FCs are a replacement technology. Competing technologies, some of which are extremely mature, are seen as setting the bar in the customer's expectation on cost and performance. If we for example analyze the cost structure of a mobile phone, we see end-user products being offered to the customer with ever lower prices. This will drive the price of components ever lower, and if we see FCs as a viable solution for portable solutions we are faced with a strong need for price reductions and technological development. We can even question if the assumptions, made by Dyer (2002), that the allowable cost of fuel cells in portable devices is in the range of $3-5/W would be sufficient in the future?

In comparison to cost, FC and DMFC technology has a clear advantage in system energy densities. Currently the portable electronics industry mainly uses lithium based battery technology. This technology enables energy densities of 475 Wh/l and 220 Wh/kg-1 with the expected growth path of 5 to 10 percents yearly (Ryynänen and Tasa, 2005, cited in van der Voorta and Flipsena, 2006). This development phase is however expected to diminish due to the physical constraints related to the technology (Broussely and Archdale, 2006). The theoretical energy density of FCs is near 5000 Wh/l from which the practical energy density with current technology is in the range of 250 – 1000 Wh/l (Dyer, 2002; Flipsen, 2005).

4) The characteristics of FCs also include the notion that FCs are subsystems of product. Although different structures of fuel cells have been researched (Qian, et al., 2006), FCs will most likely have some BoP (Balance of Plant). In the current demonstrational status we see FCs being integrated as such to existing products. These products, for examples mobile phones, are designed to use batteries as a power source. Through a high degree of interdependence current devices are optimized to work with existing power sources. FCs that are integrated to a product are also heavily interdependent on the application and as such will set design constraints.

5) FC is a system which is constructed from the actual FC as well as from the BoP connected to the FC. This structure is in no way a simple one. We can see it requiring specific knowledge on several aspects from materials science, chemistry, electronics to mechanics. Complexity and the sub-system nature of FCs have a significant effect on the convenience and perceived safety of FC based systems. Concerns on the storage of fuel, such as methanol, and the technical limitations of materials can reduce the practical advantages of using DMFC in portable applications (Dyer, 2002).

2.2 Emerging Technology lifecycle indicators

Pavitt (2006) describes innovation into three overlapping processes: 1) The production of scientific and technological knowledge, 2) responding to and influencing market demand,

and 3) the translation of knowledge into working artifacts. Pavitt sees the production of scientific and technological knowledge as a major trend. Pushed by the industrial revolution, the increased production of highly focused scientific and technological knowledge will be seen as offering opportunities for commercial exploitation.

There have been several notable scholarly presentations on the process of Research and Development (R&D) diffusing to the market. Abernathy and Utterback (1978) have presented the model of innovation which presents the dynamic process of industry over time. The model shows innovation going through three specific phases in its lifetime: fluid, transitional and a steady state. The fluid stage is characterized as the uncertainty phase where technological and market related uncertainties prevail. In the transitional phase producers are becoming more aware of true customer needs as technological application. This is seen also as an increased need for standardization. This stage can be presented as a "dominant design", which can be seen as a standardized product design with little or no variation between applications. In the steady state the focus moves from differentiation through product design to cost and performance enhancements.

The evolution of technology and its market applications is also presented by Balachandra et al., (2004). They see the evolution as a co-evolution with three specific stages: exploratory, transitional, and technology variation and refinement. The model is coherent with the work of Abernathy and Utterback (1978) as it sees the first phase as an exploratory phase lacking the knowledge of widespread application. The first stage is seen as evolving to a transitional stage where the industry is more aware on the external inputs from the market. The last phase focuses on variation and refinement.

An S-curve is often used to demonstrate the evolution of a technology. Presented in the work Diffusion of Innovation, Rogers (1962) presents the diffusion of innovation through a social system as an S-shape curve. Rogers presents the rate of adoption, which is defined as the relative speed in which the members of a social system adopt a specific innovation. This work divided adopters to specific categories such as innovators, early adopters and majority. With this categorization a technology can be seen as diffusing into the social system.

While the work of Abernathy and Utterback, and Rogers present the model of which a specific technology can diffuse to the market, Watts and Porter (1997) have presented methods to understand the evolutionary status of a technology. In their work Watts and Porter elaborate on the possibilities of bibliometric methods in assessing the lifecycle status of a technology. Borgman and Furner (2002) define bibliometrics as methods of analyzing text databases quantitatively. Daim et al. (2006) elaborate that bibliometric methods enable the analysis of large databases in order to understand the underlying structures in technological development. These structures can then be modeled through analysis to understand the evolution of a technology. One of the most known concepts in analyzing a specific technology is the Technology Life Cycle (TLC) indicators presented by Porter et al. (1991). Watts and Porter argue that technological development has five stages which could be identified by bibliometric methods. The stages, basic research, applied research, development, application, and social impact, can be identified for example by the number of instances counted in a stage specific databases. The stages should, in an ideal situation, form a continuum where each stage reaches its most active phase after the previous stage has started to diminish in activity. This linear model of development has however been criticized (Rosenberg, 1994). It however gives a simplified representation of technological life-cycle (Balconi, Brusoni and Orsenigo, 2010).

Bibliometric methods are seen as giving a direction, but one should avoid making too straightforward assumptions on the specifics. As mentioned by Watts and Porter, bibliometrics are limited by the secrecy related to R&D as well as it is limited on the queries made to databases. Databases also include a significant portion of mistaken information which confuses the data analysis. Technological forecasting can however give an understanding on the direction and rate of development of a specific technology.

3. Methodology and dataset

There are several studies on the bibliometrics and patents analysis on a specific technology (Chao, Yang and Jen, 2007; Kajikawa et al., 2008; Kajikawa and Takeda, 2009; Huang et al. 2010). These are used to analyze the future trends, research co-operation, and Immaterial Property Rights (IPR) owners. The study presented in this paper uses bibliometric methods to assess the developments of portable DMFC technology.

In this paper a time series analysis is done by applying an S-shaped growth curve to research and patent trend analysis. Several different growth models have been used to forecast technological development, such as the exponential growth model. The S-shaped growth curve has been, however, seen as fitting well to the modeling of technological growth processes. Scholars are seen as using two distinct S-shaped growth models, the Fisher-Pry model or the Gompertz model to forecast growth (Porter et al., 1991; Watts & Porter 1997; Bengisu & Nekhili 2005; Huang et al. 2010). In this paper the Fisher-Pry model is used to forecast the trend of DMFC related articles. The Fisher-Pry model, named after Fisher and Pry, was described by its authors as "a substitution model of technological change". Fisher and Pry (1971) explained that the model would be powerful in for example forecasting technological opportunities. The basis for the Fisher-Pry Curve is described by Porter et al. (1991). The Fisher-Pry curve is defined as $f = 1 / (1 + c \exp(-bt))$.

In the equation, the analysis is constricted by the analyst being able to determine the values of b and c which fit the data used. This is done by assessing the upper bound for the growth. For detailed analysis refer to Porter et al. (1991) and Chung and Park (2009). Analyzing the Fisher-Pry curve is however seen as giving the trend for future research efforts.

In addition to the Fisher-Pry trend extrapolation the publishing organizations were identified by the regions, countries and research organizations. The ten most frequent countries and research organization publishing research results were identified to form a picture of the research landscape.

Patent landscape has also been analyzed by several authors. A wide view on the feasibility of patent analysis has been given by Bretizman and Mogee (2002). They see patent analysis been used from IPR management to stock market evaluation. A policy view on the use of patent analysis is given Hicks et al. (2001). Strategic analysis is also seen as one of the applications of patent analysis (Liu and Shyu, 1997). Combining bibliometric analysis and patent analysis has been presented for example by Daim et al. (2006). By studying both research and patent data, the authors hope to describe the transformation of knowledge to industry. The patent data was analyzed by the trend of development (frequency) and a forecast with the Fisher-Pry growth model. Patent data was also categorized by applicants to gain insight on the companies developing the technology. The International Patent Classification (IPC) was used to find possible underlying structures in the applications. Applicants and IPC classes with a high frequency were then structured to a bar chart by the co-occurrences that applicants and IPC classes have. This was seen as showing the focus of patenting within the most frequent patent applicants.

The data for the study is based on evaluation of bibliometric and historical data gathered from several sources. The main section of data, the journal data, is based on data gathered from the Science Citation Index (SCI) database. Patent data has been analyzed from the European Patent Office (EPO) Espacenet database, which is openly available. In regard to the query design, there were no studies published which could of explain the keywords needed to cover all of the bibliographical and patent data related to Direct Methanol Fuel Cells. By a trial and error-phase the authors found a suitable search algorithm. The analysis was done by a query of "fuel cell" AND ("Direct Methanol Fuel Cell" OR "DMFC") being mentioned in the title or topic in the SCI database and by using the same query for the Espacenet database "Keyword(s) in title or abstract" field. With industry development, the data refers to PriceWaterhouseCoopers (PWC) series of FC industry surveys as well as to the Fuel Cell Bulletin journal for textual analysis on industry development.

4. Results

4.1 Development trends

Fuel cell technology has been an extensively researched topic in recent years. The last 20 years seems to be a period of increased activity in research publications as a whole. In figure 1, the historical trend of portable fuel cell research is depicted. An increase of publications can be seen yearly from 1990's, this is also the starting point for DMFC related articles.

As significant notion is that among the various FC technologies DMFCs are a relatively young technology. Although similar to other FC technologies, DMFCs have their own challenges.

From figure 1 we can easily argue that FC technology research has grown significantly

Figure 1 Cumulative journal and conference publications in fuel cell and direct methanol fuel fell technology

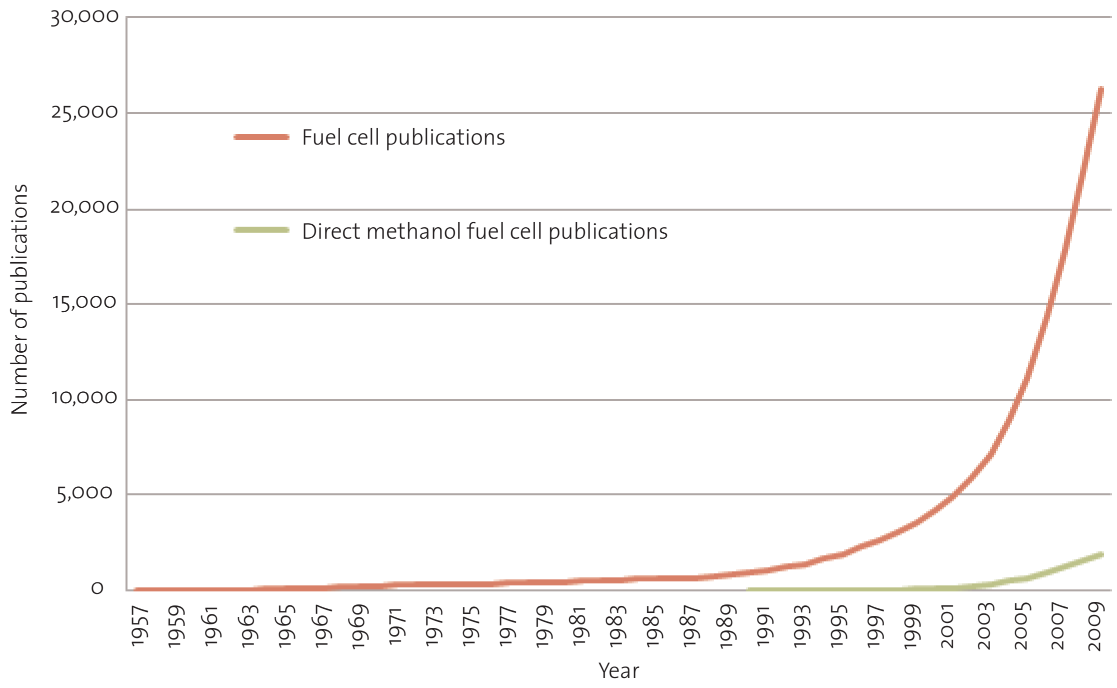
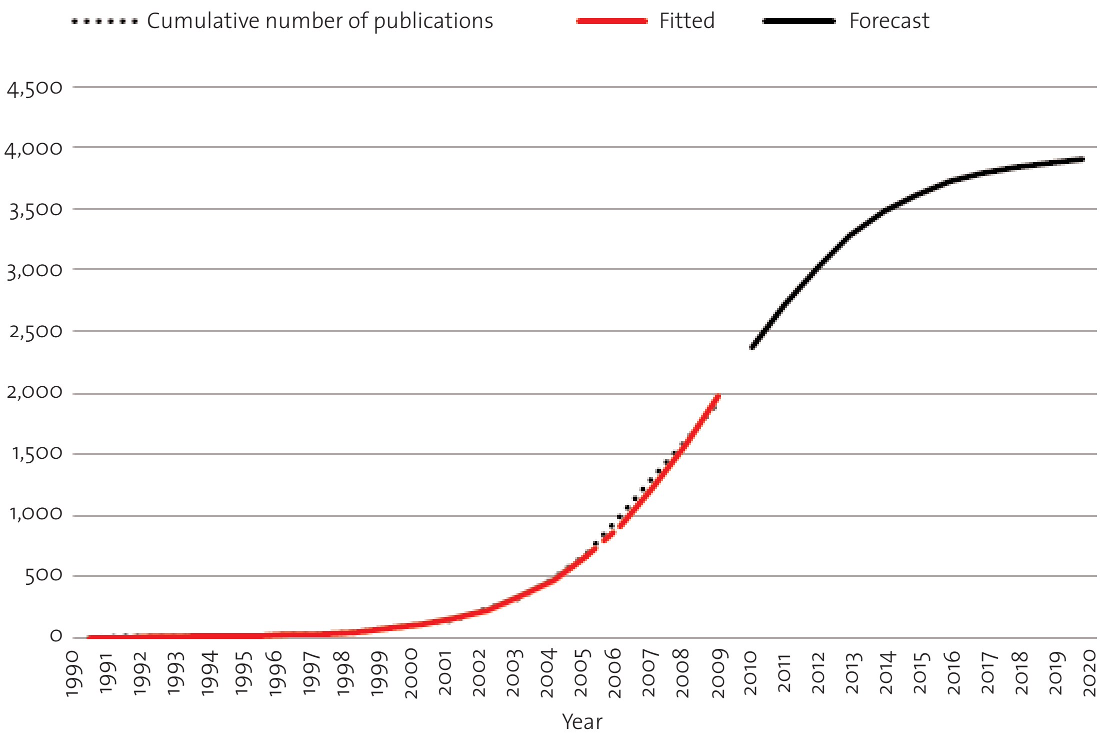


Figure 2 Cumulative journal and conference publications and trend extrapolation of Direct Methanol Fuel Cell technology



in the recent years. DMFC technology has however had a significantly shorter research period. To gain perspective on the technology life cycle of DMFCs, we extrapolate the research trend of DMFCs. In figure 2 the trend analysis of journal and conference publications in the Science Citation Index (SCI). The bibliometric data was modeled using the Fisher-Pry model that fits the data with a high R^2 coefficient of 0,99.

The growth model suggest that the growth period of basic research would continue for a few years, but by 2014 we would see the phase of rapid growth as ending. This would suggest

Table 1 The document frequency of the ten most frequent Countries and Organizations of DMFC research. Percentages are counted from the overall number of records 2128. [Based on the SCI database]

Region	Country	Organization	Document Frequency	Percentage (in %)
Asia			1411	66.3
	China		491	23.1
		The Chinese Academy of Science	123	5.8
		The Hong Kong Ubniversity of Science and Technology	60	2.8
		Tsinghua University	46	2.2
		The Harbin Institute Technology	45	2.1
	South Korea		346	16.3
		KAIST	57	2.7
		Seoul National University	57	2.7
		Korea Institute of Science and Technology	42	2.0
		Hanyang University	34	1.6
	Japan		213	10.0
	Taiwan		161	7.6
	India		80	3.8
Europe			566	26.6
	England		81	3.8
		Newcastle University	63	3.0
	Germany		201	9.4
		Forschungszentrum Jülich	41	1.9
	Italy		89	4.2
North America			381	17.9
	USA		340	16.0
	Canada		60	2.8
South America			58	2.7
Australia			12	0.6
Africa			6	0.3

that within the following year's research would move more towards application and not towards basic research. Current status would indicate that the research is at a half-way point. Several technological barriers, such as analyzed by Kamarudin et al. (2009), are unanswered but within the following few years we should expect significant advancements in DMFCs

The gathered database entries were analyzed by the research organization and region of research. From the dataset 876 individual terms that refer to an organization were indentified. The terms were checked for possible duplicate organizations caused by misspelling of names. Organizations were only analyzed at the university, research organization or company level. Possible sub-organizations, such as research labs, were not identified. In addition to organizations, the text mining tool was used to identify nationalities of the research organizations. Regions of research were identified as continents and countries of research and shown by their document frequency. Document frequency being defined as the number of record in which a country or research organization appears.

As seen from table 1 a significant portion of DMFC research is done in Asia, China and South Korea being the most significant research countries when counted by the pure number of publications. It is significant to note that in addition to Asian organizations being involved in 66,3 percent of the research, there are several focused research organizations in the region which contribute significantly to the number of papers being published. The effort done in Europe and North America shouldn't however be forgotten.

The increase in patent data can be seen in the Figure 3. The increase in patents has had a similar trend in comparison to the research journals plotted in Figure 2. Modeled with the Fisher-Pry equation, the patent trend has a lower R^2 value of 0,94. It is however visible that patent data has had a simultaneous increase with the increase of research trend frequency. When looking at the forecasts in Figure 2 and Figure 3 the trend extrapolation seems similar to both datasets.

It is significant to note that the patent applications have increased in numbers simultaneously with the increase of basic research results. The forecast suggested that basic research would reach the end of the growth phase by 2014, this is the half-way point for patent data. This suggests a lag between basic research and patents, which is coherent with the linear model of TLC indicators. By the end of the decade we would see the patenting frequency in DMFCs slowing significantly.

When clustering the patents by applicants, we see a strong emphasis on a few companies in gathering immaterial property rights rela-

Figure 3 Cumulative patent applications and trend extrapolation of Direct Methanol Fuel Cell technology

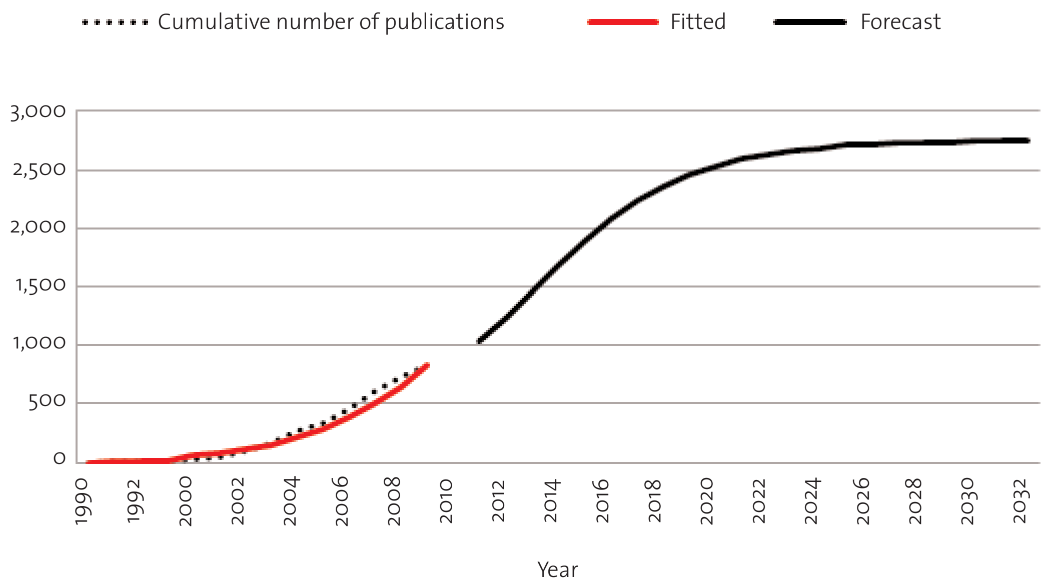
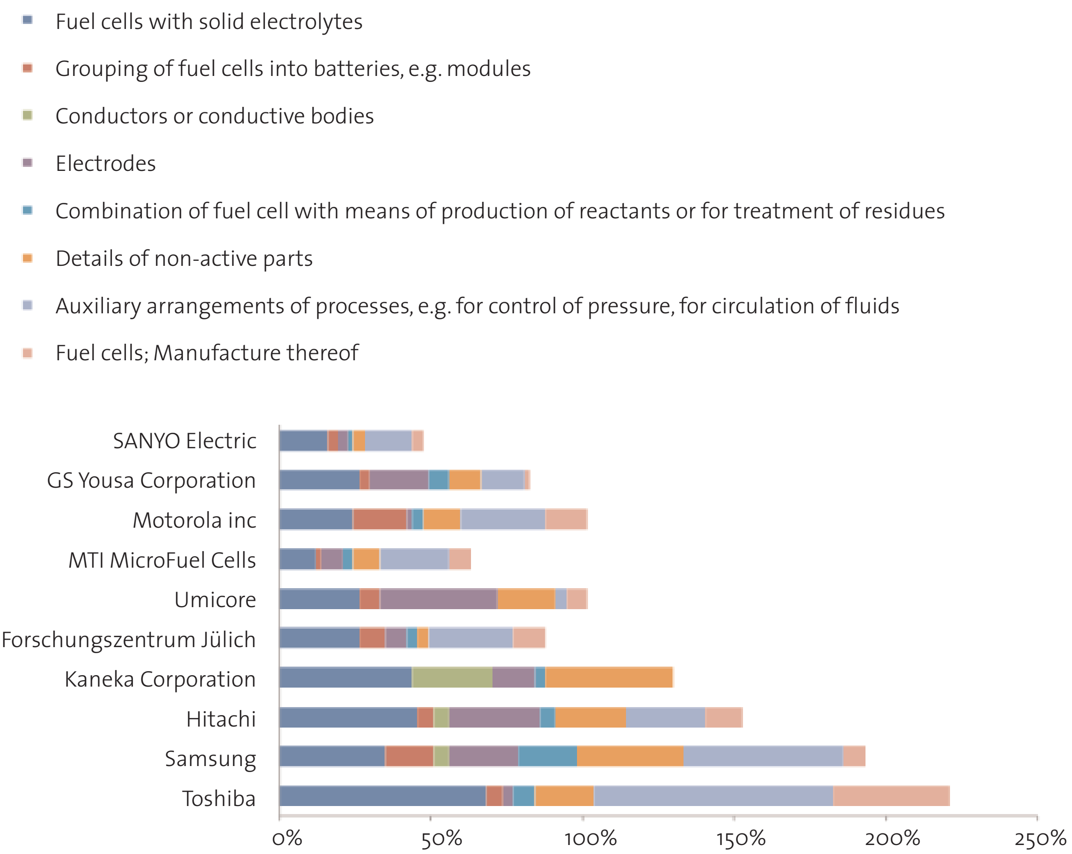


Table 2 Ten most frequent Direct Methanol Fuel Cell patent applicants. (Based on the Espacenet database)

	Applicant	Count	Percentage
1	Toshiba	57	6,9%
2	Samsung	52	6,3%
3	Hitachi	31	3,8%
4	Kaneka Corporation	25	3,0%
5	Forschungszentrum Jülich	21	2,5%
6	Umicore	20	2,4%
7	MTI MicroFuel Cells	16	1,9%
8	Motorola inc	16	1,9%
9	GC Yuasa corp	15	1,8%
10	SANYO Electric	13	1,6%

Figure 4 The patents of the ten most frequent applicants by the IPC classes of the patents. Figure contains the eight classification most frequently used in DMFC patents.



ted to DMFCs. As seen in Table 2, only 10 companies sum up to 32,2 percent of the patents applied. This shows a high concentration of patents, which is argued by Ayers (1987) to be one of the indicators of an infant technology.

The applicants were clustered by the IPC classes the patents have been classified. In Figure 4 the ten most frequent patent applicants seen in Table 2 have been classified by the IPC classification. Classification "Electrodes" is a collection of sub-categories under the Electrodes category. All other categories consist of a single classification. Patents can and often are classified to several classifications. As seen from the Figure 4 all of the companies with the exception of Kaneka Corporation and Umicore have a similar profile in patents. What can be seen as significant is the strong emphasis on patents relating auxiliary systems seen in the patent portfolios of several companies. These could indicate a focus on concrete fuel cell systems. This would support the finding made by Verspagen (2007). Verspagen found that the patent development in FCs development trend in patents have moved from components to systems. As the patents taken into this study are from the last 20 years, we see the focus turning to "Auxiliary Systems" and "Grouping of fuel cells into batteries".

4.2 Commercial adoption

As seen from the article and patent data analysis, portable FC development efforts are focused to a few companies focusing on this emerging technology. PWC (2008) has divided the worldwide FC industry to five market focus areas: stationary, portable, fuelling infrastructure, vehicle drive and auxiliary power units for vehicles. PWC data elaborates that 20 percent of the industry is focused on the portable market, geographically dividing most significantly to organizations in the EU, US, Japan or Canada. Over 50 percent of the companies with a market scope on portable fuel cells are in the US, and if North America is seen as an entity, we see that over 70 percent of companies with focus on portable are based in the US or also Canada. The PWC analysis is however based on surveying public companies with the primary goal of fuel cell production, integration or related fueling infrastructure. The survey does not take into consideration subsidiaries and private companies. This leaves out a significant portion of the industry.

The survey can however give an overview on the commercial development the industry. The growth indicators for the industry are presented in consequent years by PWC (2005; 2006; 2007). We have seen during the period of 2003 to 2006 a growth of 14 percent to the whole industry. This, while R&D expenditures have risen by 26 percent and employment numbers by the industry have risen by 36 percent, can be seen as challenging. By this we see the increased usage of corporate research funding by large corporations and venture capital funding by new ventures. The increased corporate R&D expenditure and employment cost can be seen as draining the resources of the industry.

In the portable FC industry we see a near four time increase in portable units shipped from 2005 to 2008. This however, still amounts to only little over 9,000 units shipped worldwide. These units are mostly used for toys and other demonstration by Chinese and Taiwanese companies. European and USA based companies focus mainly on military solutions (Butler, 2009.)

Similarly to the increase of journal and patent data, industry activity can be seen as increasing in the 2000s. Companies such as MTI Micro Fuel Cell (MTI), seen also in Table 2, have started FC technology development in the early 2000 (Fuel Cells Bulletin, 2001). MTI is an example of technology transfer as MTIs work is based significantly on the technology of Los Alamos National Lab (Fuel Cells Bulletin, 2002a), MTI has been a significant developer of small portable solutions. Development has been partly driven by large military contract with US Marines and Army, which have focused on the development of handheld power devices based on FC technology (Fuel Cells Bulletin, 2004a; Fuel Cells Bulletin, 2004b). MTI has since gone to develop its own FC based systems as well as manufacturing prototypes for Samsung (Fuel Cells Bulletin, 2007a). MTI has also demonstrated a GPS system with a FC system integrated to the product. This has resulted up to 60 hours of continuous operation (Fuel Cells Bulletin, 2008c).

In larger portable systems, early enthusiasm on finding the suitable application to take advantage of the technology can be seen for example in the Japanese based Yuasa Corporation, which published its FC technology based power production system in 2002 (Fuel Cells Bulletin, 2002b). Yuasa also had the ambitious goal of commercializing its technology by 2003. At the same time a US based Lynntech delivered a self contained FC power production system to the US Army (Fuel Cells Bulletin, 2002c). Presenting a similar prototype as Yuasa demonstrated in Japan. Both of these systems were designed for larger applications, Yuasa's system weighing from 25 to 60 kg. The applications were clearly targeted to independent power production in a small scale. In this application range the German based Smart Fuel Cell (SFC) has been able to commercially manufacture its EFOY system. Offering products to a small market, SFC has been able to market its product successfully. SFC manufactures a portable energy source for military systems and recreational vehicles (Fuel Cells Bulletin, 2003a; Fuel Cells Bulletin, 2007b). SFC has been successful in a specific market attending to a large consumer base in recreational vehicles (Fuel Cells Bulletin, 2007c; Fuel Cells Bulletin, 2008d).

Early R&D has also been done at Samsung, which has carried out research in both applied as well as the fundamental technology. (Fuel Cells Bulletin, 2002a). Similarly to Samsung, Japanese industry has also focused on small FCs and consumer electronics applications. NEC co-operated with Japanese research organizations in 2001 in the development of micro fuel cells. (Fuel Cells Bulletin, 2002a) Similarly to NEC and Samsung several other large companies have focused on FCs at an early stage. This has resulted in several consumer electronics demonstrators, such as FCs in laptop computers. The competitive advantage seen in the laptop application was the extended operating time a fuel cell system could offer. For example Samsung demonstrated a laptop working with a FC power system with the operational time of 10 hours (Fuel Cells Bulletin, 2004c). Similar demonstrations have been made by companies such as Fujitsu, IBM, LG, Motorola, NTT, Sanyo, Sony, Casio, Polyfuel and Toshiba, which have all presented a FC powered laptop prototypes (Wee, 2006, Fuel Cells Bulletin, 2002a, Fuel Cells Bulletin, 2003b).

Many of the companies also, similarly to Yuasa, had high expectations on commercialization. Companies such as Toshiba, suggested that it would commercialize FC systems in 2005 (Fuel Cells Bulletin, 2003c). Samsung claimed to be ready for commercialization with a laptop docking station by the end of 2007 (Fuel Cells Bulletin, 2007d). These efforts did not deliver wanted results even though several scholars (Rashidi, et al., 2009; Wee, 2006) have analyzed the cost of using a fuel cell powered device in comparison to battery based systems, and found that a FC power source would be more cost-efficient after one year. However as Agnolucci (2007) has pointed out that consumers are more interested in the physical size and weight of the system than its cost-efficiency. Subsequently the market is still waiting for the competitive portable FC application.

Mobile phones, and several other small portable devices (Flipsen, 2005; van der Voorta and Flipsena, 2006), have been suggested to be the competitive application. This possibility has been presented for example by Toshiba and at an early stage by start-ups such as Manhattan Scientifics. (Fuel Cells Bulletin, 2004d; Fuel Cells Bulletin, 2002a) Similar to laptops the cost-efficiency of FC systems isn't a problem (Rashidi et al., 2009). More significantly, the development of the FC products in mobile devices is dictated by the development of lithium batteries and innovations making devices more energy efficient, smaller in size and weight, and the ease of use of the systems (Agnolucci, 2007). Subsequently integrated commercial FC systems have not been available.

It seems more likely that a portable device charger would be the application enabling sustainable growth. As a product, this would be similar to the larger scale products presented by e.g. SFC, which have all been based on independent power production. Several companies have demonstrated future portable FC products in this product range. Sony has been for several years developing its system. Trying to meet the growing power need of a mobile phone, Sony claims that its system enables a state-of-the-art cell phone to be used for watching a TV broadcast for 14 hours with only 10 ml of methanol. (Fuel Cells Bulletin, 2008e). However, also in this niche market, high expectations have led to several promised market launches, such as Hitachi's small FC system. Hitachi was expected to commercialize a small FC by the end of 2007 with the manufacturing capability 2,000-3,000 units yearly (Fuel Cells Bulletin, 2007e). However, Toshiba was the first to present a commercial FC based mobile charger (Fuel Cells Bulletin, 2009).

5. Discussion

To gain an insight on the future possibilities of the portable FC technology, a historical and bibliometric analysis was performed. The study revealed the increase of journal publications since the early 90s as well as the increase in patenting frequency. The growth models suggested that the rapid development phase in both research and patents would continue for the next few years. In this the patent trend was seen as lagging, which would be coherent with the "linear model of change" (Porter et al., 1991).

The identification of research regions, countries and organizations brought forward the leading DMFC research areas. Complementing this with patent data has shown the significant effort made in Asia to develop DMFC technology. It could be argued that the research and development of DMFC is concentrated to a group of organizations. The argument made by Ayers (1987) that this would suggest an infant technology could be argued to be accurate in the case of DMFCs. However, as in the findings of Verspagen (2007), the patent classifications would suggest that the patent applicants would be focusing towards FC systems in addition to basic research. This could be seen as encouraging to the industry hoping to take advantage of this emerging technology. In addition the several years of widespread technological demonstrations by several large corporations has laid the ground work for actual DMFC products being offered to customers.

The authors would however argue that DMFC technology is having a hard time in integrating to the mature energy production market. The existing extremely mature technologies are still offering more value to most existing solutions. As Agnolucci (2007) has pointed out, consumers will not adopt DMFC technology only to use new technology. Cost, convenience, and physical size are more significant factors impacting consumers. R&D managers should also notice the increased public funding towards FC technology. Programs such as the 7th framework program in the European Union (Fuel Cells Bulletin, 2008a), while funding R&D efforts, can be seen as building up a hype towards the technology. In addition the high expectations of commercialization promoted by several companies can be building excitement towards the technology.

As a conclusion, DMFC technology is in a fluid phase, where technological and market related uncertainties prevail. Consumers have not adopted DMFC technology in a large scale. This can be seen from the fact the number of DMFC systems delivered, although there has been significant increase, is small. DMFC technology is still looking for the application that would enable sustainable growth. It can be argued that the development efforts are still highly subsidized governmental projects and this, while creating a market, disrupts the “natural creation” of a demand based market. Viable market applications, such as the one created by SFC, have been unable to show that a DMFC solution would be viable outside the niche that it occupies. However, as the power demand of small portable devices continues to increase in the future, existing systems can be unable to meet the demand. This situation would arguably create the needed competitive edge for portable DMFC systems.

Acknowledgements

The research was funded by the Finnish Funding Agency for Technology and Innovation

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Publication II

Arho Suominen, Jussi Kantola and Aulis Tuominen. Analyzing prospects of portable fuel cells with an expert opinion study. *Futures*, Vol 43, Is 5, June 2011, pp 513-524

Futures 43 (2011) 513–524

Contents lists available at ScienceDirect

Futures

journal homepage: www.elsevier.com/locate/futures

Analyzing prospects of portable fuel cells with an expert opinion study

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ARTICLE INFO

Article history:
Available online 2 March 2011

Keywords:
Delphi
Expert opinion
Fuel cells
Portable fuel cells

ABSTRACT

Fuel cell technology is becoming a significant option as an energy technology. Attracting significant research funding, industry research and development (R&D), and commercial anticipation different fuel cell technologies are indicating potential as viable products. One of the anticipated applications of the technology is portable fuel cells. Ranging from small back-up power systems to small micro watt solutions portable fuel cells have been widely demonstrated but lacking widespread commercial exploitation. This paper presents the prospects of portable fuel cells which resulted from a Delphi study.

1. Introduction

In the recent decades, significant effort has been directed towards new energy technologies. Photovoltaic, wind, and fuel cell technologies have been of interest in both research and industry. When looking for non-polluting and efficient energy technologies these new technologies are indicating potential. Among the emerging energy technologies, fuel cell (FC) technology is one viable technology. FC is an electrochemical device that produces electricity through a reaction between a fuel and an oxidant. Different from existing electrochemical cell batteries FCs consume reactant from an external source which can be replenished. The principle of FCs was already invented in 1838 by a German scientist Schönbein and proven by a Sir William Robert Grove a year later [1]. Since its invention FCs have attracted mediocre attention which has increased during the last 20 years. Driven by their versatility FCs have been applied to a variety of solutions from large stationary solutions to small milliwatt scale systems [2]. Larger FC systems have been of interest since the first commercial FCs in the 1950s. Only more recently, in the 1990s, have smaller portable fuel cells (PFC) been of interest [2]. This can be awarded to several companies which have put significant effort at the development of PFCs [3]. The possibilities of using FCs in portable devices have been driven by the high power and lifetime requirements of portable devices. These requirements are proving hard to meet with conventional rechargeable battery systems, due to their limited specific energy and operational lifespan [4–6]. To this market need, PFCs are seen as a viable option.

In several studies, scholars have analyzed PFCs [3,7–11]. The commercial possibilities of PFCs overall have been also studied in several papers [2,12,13]. Many of these studies review the technology and its application from a qualitative aspect or relying on the expertise of some experts. The aim of this paper is to use the expertise of several experts by a Delphi study to create an outlook on the commercial expectations of PFCs. PFCs have been expected to be a commercially viable technology several times within the last decade [14–16]. This study hopes to provoke discussion on what are reasonable expectations on the commercialization of PFCs.

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doi:10.1016/j.futures.2011.01.010

2. Delphi overview

The Delphi method was first taken into active use in the Rand Corporation in the 1960s. The first paper on the use of the Delphi method was published by Dalkey and Helmer [17] in 1963. After which, several papers continued to explain the use of the Delphi method. In 1964, Gordon and Helmer [18] published a study describing the possibilities of using Delphi for long-term forecasting. In 1967, Dalkey [19] published a paper explaining to the principals of the Delphi study. Gupta and Clarke have reviewed the theory and application of the method in a review paper [20].

In the 1967 Delphi paper, Dalkey describes the method and the need for such a method. As Dalkey explains, usually in a situation of making forecasts there are several in-house experts, outside consultants and other to choose from. A decision can be made that we select only one and rely on his/her knowledge and opinion of the future. It is, however stated that the statistical aggregate of several individuals is more accurate than a judgment of just one person. When we add the disadvantages of using a group with direct interaction, such as the problem of a dominant individual, we can understand the benefits of Delphi [21]. Dalkey also points out that in a group with direct interaction there is a lot of useless material produced that clouds the key facts and that in direct interaction there is always a "pressure" towards a compromise [19].

Delphi exercises are described to be conducted in several different ways. Dalkey [19] described the procedure as consisting of a first round and several following iterations. The idea is that with the first questionnaire the respondents are requested to assess a set of numerical quantities such as dates for future events. The results from the first questionnaire are then summarised, with the analysis of median, upper and lower quartiles and given as feedback to the respondents. The respondents are then asked, in the second round, to assess their earlier answers in the light of the new information. Respondents whose answers had deviated significantly from the median are also asked to justify their answer. In the third round, the counter arguments written by respondents with "deviating" answers are also given to the respondents, in addition to the statistical feedback [19]. More recently there have been several developments and variations to the classical Delphi method [22,23].

There has also been some criticism towards the Delphi. One of the best known is Sackman's [24] critique. Sackmans argued that the value of "experts" would be questionable. Scientific debate on the value of "experts" and who should be regarded as an expert has since been active [25–28]. The critique has resulted in several attempts to re-evaluate the validity and reliability of the method [21,22,29].

3. Delphi design

The Delphi experiment was designed to be a three round survey. Emphasis was taken on participant selection, first round design, result presentation for the participants and pointing out disagreeing comments. These emphasis points have been

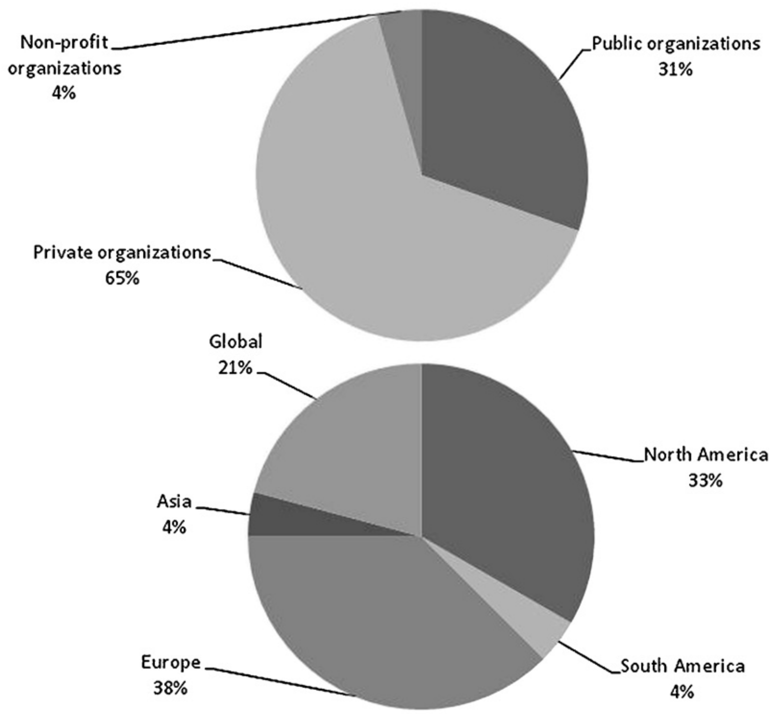

Fig. 1. Delphi Group structure.

found to be important also by Linstone and Turoff [30]. Participant selection was made by collecting addresses from publicly accessible sources. The analyses of the participants were done by gathering names from FC technology developers, relevant non-profit organizations and legislative and standardization organizations. There was also a substantial amount of researchers, actively publishing scientific results, gathered for the list of invited participants. As a result, the Delphi panel comprised of 23 participants. This would be in the range of suggested panel sizes for a Delphi study [31,32]. Fig. 1 presents the backgrounds of the experts.

Fig. 1 also elaborates on the background of the participants. The participants were asked to categorize themselves according to the geographical interest of their affiliation. This was done to point out any restrictions set by the focus of the experts' interest. Noteworthy is the lack of Asian participants. This should also be taken as a consideration when analyzing the results.

The first round questionnaire included an accompanying letter inviting the recipient to participate in the study. The letter included a brief description of the study. It also referred to the book of Linstone and Turoff [30] additional information. The

Table 1
Delphi round 2 questions.

Round 2 questions			
1	QUESTION: In what time (years) will we see 2–5 large[a] FC component suppliers, with efficient and high volume production, emerging?	10	QUESTION: What would be the cost target (kW/$, please use US dollars) for portable fuel cell solutions.
2	QUESTION: In what time (years) will we see 2–5 large[a] companies mass producing portable Fuel Cells?	11	QUESTION: In your opinion, how much of the energy will be produced with Fuel Cells in the year 2030 (estimate a percentage)? You can take into account all types and sizes of fuel cells.
3	QUESTION: In what time (years) will we see a "black box" power source for portable devices, working with FC technology, which will work as well the existing battery technology? An example is given for clarification. We can switch a power source, from existing technology "black box" to FC technology "black box", to a person's mobile device with out the person knowing the difference until he/she loads the power source.	12	Distributed power generation has received significant market and policy attention. Areas in which transmission and distribution costs are high, decentralized production with Fuel Cells have been seen as one option. It has been argued that in this case Fuel Cells may offer superior efficiency, reliability and availability. QUESTION: Estimate the percentage of Fuel Cell electricity generation capacity from the total electricity generation capacity (excluding transport sector) in the year 2030. Do you think the energy produced with Fuel Cells will be mainly decentralized or centralized?
4	QUESTION: In what time (years) will we see a 2–5 large[a] companies offering FC component or system assembly machinery and/or processes?	13	QUESTION: In what time (years) will we see a large commercial infrastructure, where 2–5 large[a] companies have a large infrastructure, supplying fuel for fuel cells.
5	QUESTION: If thinking about portable solutions, that normally uses conventional batteries, with what kind of lifetime (hours) you would see Fuel Cells as a viable solution?	14	QUESTION: n what time (years) will we see 2–5 large[a] portable fuel cell end product manufacturers, with efficient and high volume production, emerging?
6	QUESTION: Please estimate the amount percentage of mobile devices (such as PDA's, mobile phones, MP3-players, etc.) using Fuel Cell technology in 2020.	15	QUESTION: When (years), in your opinion, will we see the first commercially viable hydrogen production plants which use all renewable sources for their production?
7	QUESTION: The IEC (International Electrotechnical Commission) is preparing standards relating to Fuel Cell technology as well as the IATA (International Air Transport Association) is preparing to add directives for fuel cell transportation. In your opinion, in what time (years) will we see the positive impact of common codes and standards effecting the Fuel Cell industry?	16	QUESTION: In your opinion, what are the High-Priority Research Directions which have to be emphasized in Fuel Cell Research and in what kind of a time span (years) can these key issues be solved.
8	QUESTION: In your opinion in what time (years) will developing small portable FC solutions be fully commercial in selected applications.	17	QUESTION: What application do you see the best possibility for the first commercial portable fuel cell product (please select one that you see as the most prominent) and when do see this product in being commercial?
9	QUESTION: Do you think that the deployment of a fuel infrastructure for Fuel Cells would be premature, as some of the key technical issues are still being worked on. In what time frame (years) should there be a large scale infrastructure build.		

[a] Large company is defined as a company that has over 250 employees, revenue is over 50 million euros and has a total balance of over 43 million euros.

book was selected for its easy access on the Internet. In the first round questionnaire detailed instructions about answering and the objectives of each section were given.

The first round questionnaire was designed to facilitate a possibility for unstructured communication. The round was designed so that it would give the participants the possibility to point out issues and forecasts important to them, while still using selected questions to draw opinions from the participants.

In the first round 47 different arguments were made to the participants. There were also four graphs that were given to the participants. The arguments were gathered from different studies, in which there were arguments made in regard to PFCs or matters relating to it. The arguments collected were taken out of material concerning PFCs directly [33–35] and other related to areas thought to be of interest [36], such as energy infrastructure [37]. In addition to this, there were some arguments generated by the organizers. This was done to draw out arguments on specific interest points. The first round questions are available from the authors.

The arguments were presented in the questionnaire in the form of ‘‘a potential development or occurrence’’. The participants were asked to assess the ‘‘probability’’ and ‘‘impact on the development and commercialization of portable fuel cells’’. Probability was analyzed with a 6-point scale ranging from ‘‘Very probable’’ to ‘‘Very Improbable’’ and impact was analyzed with a range from ‘‘Strong’’ to ‘‘Slight or none’’ In addition to these, participants were asked to describe the nature of the impact they expected in respect to its probability. Participants were also encouraged to write comments to the question in general.

The graphs given in the first round of the Delphi were taken from PriceWaterhouseCoopers (PWC) Fuel Cell surveys [38–40]. The graphs indicated the financial development of publicly listed FC companies. Even though these graphs represented only a fraction of the whole effort taken to develop FCs, it was argued by the organizers that this would give a realistic picture of the economic aspects of PFC development. The participants were asked to continue drawing the lines given, so that they would fit their opinion on future developments, to the year 2013. Participants were asked to draw the line in figures presenting net loss, revenue, R&D expenditures, market size between FC technologies, and technological maturity.

The second round questionnaire was formulated from the first round answers. The results of the first round's 47 arguments were analyzed. The arguments that had the largest probability and effect were selected for further analysis. It was seen that these were the areas of interest selected by the participants. The graphs presented in the first round were analyzed by calculating the median and upper and lower quartiles from the participant's answers. These values gave the possibility of formulating the second round of questions. The second round was formed from 17 questions in Table 1 and from the graphs to which the median and upper and lower quartiles were added from round one. The participants were asked to make corrections to the graphs if their opinion has changed or if the results from the first round had changed their perception. Participants were also given a summary of the comments made to a specific question in round one.

The questions in round 2 also formed the structure of representing the Delphi discussion results. The seventeen questions focused on different areas of the value system of PFCs. For the third Delphi round, the answers were structured to follow a value system from component supplies to end users. As such the third round was designed partly as a traditional iteration round, but mostly as an overall comment round. Participants were given the same list of questions and graphs presented in the second round. They were also given the overall answers written by the organizers from the textual and numeric answers given in the second round. The textual answers were presented to the experts in the structure presented in Section 4. The experts as such had the opportunity to review the Delphi study findings presented in this paper. The participants were asked to review the answers and make notes on differing views.

4. Delphi study findings

The FC industry has been working towards its full commercial potential for several years. From a market ‘‘bubble’’ to a downturn, investors have been once interested in this emerging technology and at other times turning down viable ventures. The future of the technology for some seems near and for some it's always five years away. This difference in views can be accounted to youthful enthusiasm and experience from several decades of work with FCs.

By discussion, a picture of the future and the proactive vision between pessimistic and optimistic visions can be established. A value system for the future of PFCs was assessed in the Delphi study by visioning the maturity of different steps in the value system (Fig. 2), presented by Porter [41], from the component supplier to manufacturers until the end user. These steps in the value system of PFCs, formed on the basis of questionnaire two seen in Table 1, have been used to categories the expert opinions. The sub-sections used summarise the answers of the participating experts.

The answers focus on the context of PFCs, however the comments made can be applicable to larger FC systems as well. When referring to larger systems, it is made apparent in the text.

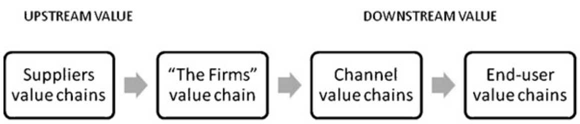

Fig. 2. Value system by Porter [41].

4.1. Component suppliers

As we see the number of component suppliers increasing we can assume a market pull from the manufacturing industry. The increased demand for components will attract a larger base of component suppliers to develop, modify and offer products to the FC industry. Technology developers, companies that are working towards commercialization, are testing the component manufacturing industry on their ability to produce good quality products. However the integration of PFC power sources to devices has been seen as a hurdle that will still take time to be overcome. This will push back the possibility of mass market volume being reached in component manufacturing. Companies that produce a generic product can, however, be seen as profiting from the increase in business from PFCs. However in the timeframe of five years we can see 2–3 large component suppliers emerging which focus purely on PFCs as a market.

4.2. Fuel cell manufacturers

As we assume an increase in the number of component suppliers we should also assume an increase in companies that mass produce PFCs as their business. Large PFC manufacturing companies are needed to set up the infrastructure and processes to manufacture cheap PFCs. Low cost manufacturing techniques, such as the reel-to-reel process, are at the core of this development. Currently marketed prototypes and small series releases are paving the way for mass production. If for any reason mass production would not start in a large scale within ten years, the experts argue that, it would be unlikely that it would happen in the foreseeable future. FCs are also seen as being a business of choice for small start-up firms. The lack of large players inhibits the development of a large scale manufacturing industry.

When analyzed if and when the industry would reach an efficient and high volume production stage, clear distinctions are harder to make. Efficient and high volume production implies that the technology would be mature. This sets a different scale for analyzing companies. High volume implies a strong demand. Efficient production implies that PFCs, which are in many cases at concept level, would be designed for mass manufacturing. Pioneering companies, with the possibility to test high volume production and thus have the possibility to make the process an efficient one, are companies with a high degree of different types of government subsidies. These can be given to end users as an incentive or directly to the companies as R&D funding. With these subsidies a number of companies will have the possibility to test manufacturing processes even though there is no real market demand.

In addition to the companies' capability to develop working PFCs, the ability to develop the skill to manufacture such a device is important. The experts argue that specialization will be one possibility to survive and grow to become a significant company in a specific PFC application area. However, the idea that the PFC would be a "game changing" technology that would greatly change the company structure in any technology area is unlikely to happen.

4.3. Integrators

A significant effort in addition to establishing component and PFC manufacturers is to establish companies willing to serve as the end user or integrator for PFCs. This can be seen as the third section in the value system. In regard to portable devices, we can hope to replace current power sources such as batteries or we can design PFCs as auxiliary power sources which would extend the expected life time of the device. In any case PFCs will always be designed to be a hybrid system including secondary energy storage.

From an end user point of view, PFCs are seen as one solution among a mix of other technologies. PFCs have taken significant leaps in development, but this is also true among competing technologies. For example battery technologies such as lithium-air batteries are showing promising development. This could make PFCs an unlikely solution to be integrated into products.

4.4. Machinery

To facilitate the formation of a value system from materials and components to system integrators the evolving industry requires system assembly machinery. Currently there are companies offering machinery for PFC production. These are, however, companies that have PFC manufacturing devices as an extension of their existing product portfolio or as new ventures which are small in size.

The manufacturing equipment market is directly linked with the PFC manufacturing volume. Currently, the volume of the business is not attracting companies. It is however worth noticing that if the machinery comes from existing industry, the transition to mass volume production is not as challenging. The machinery industry will be ready for the mass production of PFCs.

4.5. Infrastructure

Infrastructure is more important for larger FC solutions, mostly the automotive industry. However an infrastructure of some kind is needed for portable solutions as well. At the initial stage, when consumption is low, fuels are produced by companies which produce suitable fuels as a part of their current product portfolio or as a process by-product. However in a fully commercialized market, large energy giants will more than likely take over the production.

The timeframe of this development is questionable. A high confidence can be put on an infrastructure forming in the timeframe of five years. Arguments on it happening in the timeframe of 20 have also been made. Such arguments are mostly based on experience in companies like Shell that have made development efforts towards hydrogen economy from the 60s, but can be seen as being no more near commercial hydrogen economy now than they were when they started.

As a policy need, the experts noted that the infrastructure for FCs should be built according to a national level plan. At the first stage, this could mean taking advantage of existing complementary infrastructure. This for example has been done in Denmark where existing gas industry has been deployed to hydrogen production. Using this existing infrastructure the investment cost for fuel infrastructure will be significantly smaller.

On the other hand, no infrastructure will form without a compelling reason for its development. No-one will invest in establishing an infrastructure for a product that might not even become commercial. We have to also accept that the infrastructure solution is highly dependent on the fuel used.

These arguments point out the problem of creating an infrastructure. Small and inexpensive fuel cartridges for portable solutions can be sold at gasoline stations and convenience stores worldwide. This supply chain can be formed with existing logistical pathways. The problem for stationary and transport solutions is however a completely different problem which has to be based on existing industry. In all of the development scenarios, the development of an infrastructure is driven by the commercialization of the technology, which is of course inhibited by the lack of infrastructure. This problem is however solved by developing commercially available applications. Infrastructure can, to some extent be seen as being ready, when a customer is willing to pay for the product.

Overall, the value chain is affected by the ongoing economic downturn. Lack of funding for investments and shrinking markets are slowing down the industry. The future developments are also affected by several factors such as government bodies, environmental regulations, and the supply and production of petroleum.

4.6. Standards and research

Although funding is limited, additional efforts in research and standardization are needed to enable commercial applications. Critical technological hurdles are worked on and solved during the process of standardizing FCs. With this process, we see an increasing amount of correctly focused research and commercial interest in FCs overall.

The significant impact of work done within the codes and standard work is lessening uncertainty. This process, if the technology matures at the level indicated earlier, should be done within five years. This means that the impact on development and investment could be almost immediate. The experts stated that, significant commercial exploitation can only follow this process, but significant safety and security aspects cannot be solved just by having codes and standards.

Standardization can also be seen as directing research to important focus areas. FC research and development has been funded in the area of FCs. An argument can, however, be made, that the development in the past 50 years has not been that encouraging. Although small development steps have been taken, breakthroughs are missing. Table 2 presents the high-priority research directions seen to affect FCs.

In addition to the solutions mentioned above, new ideas which could be breakthroughs are welcome. One possible solution can come from nanotechnology.

4.7. Competitive advantage

In any case, a PFC in an integrated product would require a product being designed to be a PFC powered device. PFCs have several design constraints that need to be taken care of and, the experts noted that, it is unlikely that a battery replacing PFC is produced in the foreseeable future.

Integrators are however interested in what the product actually adds in value to their customer. Specific solutions which serve a narrow niche market would be possible. However the end user, which often is a consumer, is interested in price, reliability and convenience. The question remains if we can show that device, even if designed specifically to use PFCs, would have a competitive advantage.

From a technology point of view we see that in a timeframe of ten years, as the mass production of PFCs has begun, a battery replacement, to some extent would be viable. The feasibility of such a product is tested in specific consumers or B-to-B applications, most significantly in areas with a shortage of electricity infrastructure.

PFCs are replacing an existing, often mature, technology. Experts noted that PFCs should be seen as offering substantial benefits for the user to validate them as a solution. This requires the lifetime and recharging span to be similar or better to

Table 2
Research Direction and estimates on time needed to solve key problems.

Research direction	Timespan when solved (years)
Cost – non valuable catalyst development	5–10
Durability – membrane development	5–7
System packing – integration and miniaturization for commercial success	3–5
Low cost manufacturing – design for manufacturing	10
Fuel – energy density of fuel	5

rechargeable batteries and other existing solutions. This is a race between different developing technologies. In either case, we have to accept that the utility will depend on cost, operating hours and convenience.

If we find markets where PFCs are not in direct competition with existing solutions and offer distinct benefits for a specific problem, we can see a market evolving. In emerging economies, this can mean small off-grid generators, recharging devices and hybrid solutions. Customer values in niche solutions are still driven by cost, convenience and operating hours, although niche solutions can be less cost driven.

When attempting to assess the penetration of PFCs in the small scale portable devices such as PDA's, Delphi experts were divided into optimistic and pessimistic evaluations. As we see, there are several scenarios of technological development of both PFCs and competing technologies, mainly batteries.

An optimistic evaluation would see a 100% penetration of PFCs to portable devices. More conservative or down to pessimistic evaluations would assess the penetration to be in the range of 50% down to as low as 5%. The pessimistic assessments are based on the fact that for most devices, the current and future batteries will give an adequate operating time. PFCs are not seen as giving any specific advantage compared with competing devices. There are also unanswered questions in their environmental friendliness.

Consumer perception is also against the large scale use of a PFC. Consumers perceive recharging as being ''free'' as the power drawn is small. This could amount to unwillingness to pay for fuel in any form. In conclusion, the possibilities of commercial PFC applications in the PFC market are dependent on several factors. In high-value applications, we see nearly commercial products. However for the market penetration of PFCs in portable applications to increase even to the lower percentages will take up to ten years.

Convenience of use is one of the most important factors in market penetration. The ubiquitous availability of power outlets for recharging devices against the immature PFC fuel infrastructure is working against PFCs. However, applications where convenience can be made to work for PFCs would be a viable solution.

Cost is also argued to be a factor. However, portable power sources are expensive in their current state if we purely look at it as a $/KW problem. It has to be noted that the value of a portable power source, conventional or PFC based, is a perceived customer value. Market penetration is in this way driven by customer value and not by a predefined cost target.

We can, however, see a barrier price, where the price of a small portable power source is perceived as being significantly higher than conventional solutions. For the possibility to compete with existing technologies we can accept a clear premium which is based on the perceived benefits of PFC, but a premium exceeding 25% will be unlikely.

This portrays the general concept of FC technology as a marginal power source for a narrow scope of solutions. Even though the increase in the numeric volume of portable systems can significantly increase the number of FC power systems delivered annually, FCs will be a marginal power source when looked at in the light of the overall energy produced. FCs will concentrate in small systems in both stationary and portable solutions.

The total installed electrical power production capacity is huge. The fractions of FC power are unlikely to amount to any significant energy production. The significance can, however, come from decentralized solutions where a FC works as a part

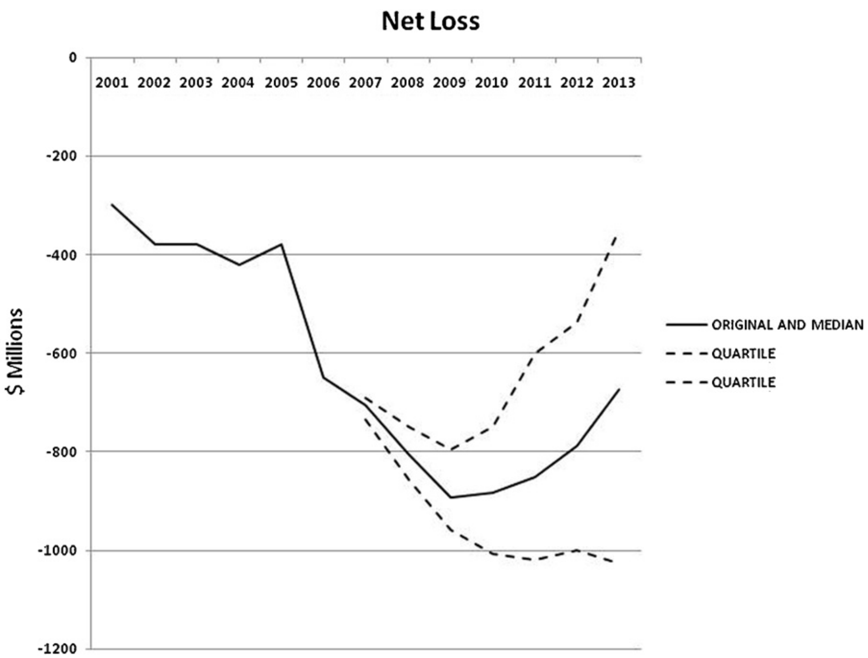

Fig. 3. Net loss estimation by the Delphi Group participants (graph until the year 2006 are actual figures presented in the PWC report).

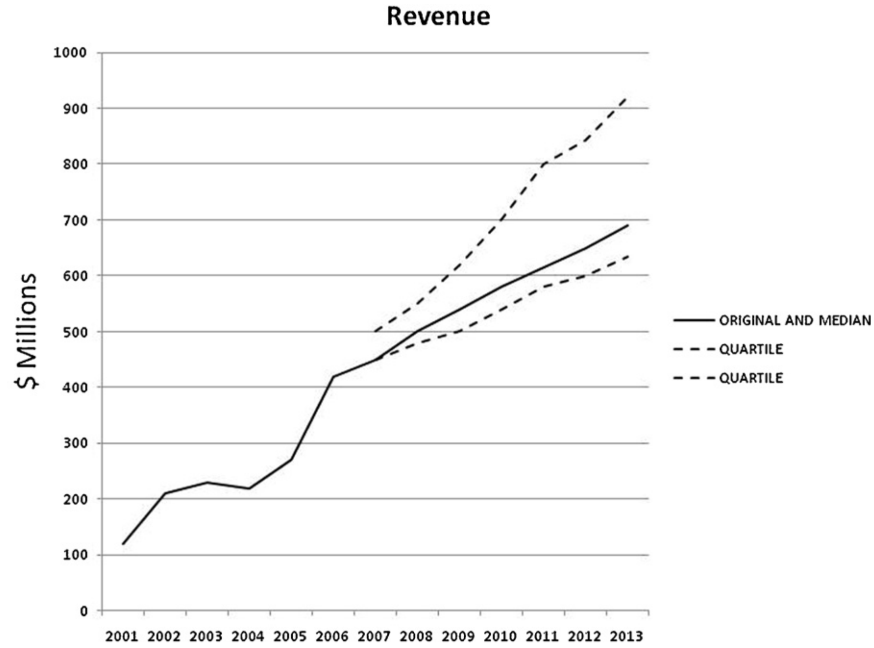

Fig. 4. Revenue estimation by the Delphi Group participants (graph until the year 2006 are actual figures presented in the PWC report).

of the system. Although solar power combined with wind power makes more sense than FCs in regard to not having a transportable fuel. PFCs can be seen as having a possibility as a co-generator. It is however worthwhile to keep in mind that in the long run the cheapest form to produce energy even in large decentralized solutions will prevail.

4.8. Fuel cell industry

A clear indicator of the FC market is net loss seen in Fig. 3. As a developing, not yet mature technology, we understand that a substantial amount of investor money is spent on developing possibilities for the future. Positive returns on investments

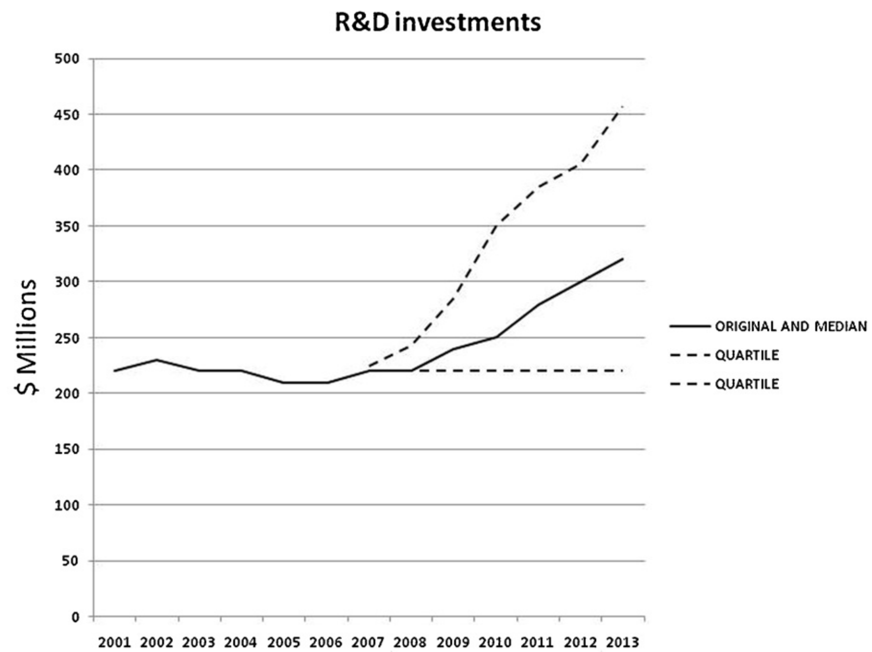

Fig. 5. R&D investment estimation by the Delphi Group participants (graph until the year 2006 are actual figures presented in the PWC report).

should, however, be seen in the foreseeable future. With FCs, the net loss of the industry will keep on increasing during the years to come. There are different views on the possible turning point for the industry. Some of the participants thought that 2009–2010 will turn the trend of increased net loss around. It will, however, take several years until the industry is profitable. For some of the experts the years 2013–2015 were seen as a more likely turning point. The optimistic estimates were, in several cases, re-evaluated and lowered because of the ongoing economic downturn.

It is also important to note that the turning point in no way means that the business is profitable. Estimates for the point of profitability could not even be seen in the upper quartile of the answers. However, it was also pointed out that a part of the industry is already making profit. Vendors selling FC components are starting to see profits from FC products. In this scenario the developers, who are making or have made the R&D investments, are the ones having to deal with the losses.

Scenarios where PFC companies reach profitable business are highly related to government business and venture capitals cutting losses in poorly performing companies. The increase in losses will force the weak players out of business. As seen from the estimates, the industry as a whole cannot be seen as being profitable in a time frame that could be seen to be interesting to investors. However if we could exclude weak players from the estimate we could move more quickly to positive territory. Due to the net loss curve estimated, it will also be more difficult to get private money to be invested in FC companies. This will make government support increasingly important. We will see an increase in government support in the next few years. The support schemes can be seen as being direct R&D funding, industry support by incentives or subsidized market by large governmental businesses.

The indicator for the turning point can be seen by assessing the cumulated revenue. This has been evaluated in Fig. 4. In a straight forward analysis a developing technology is R&D driven and early possibilities of revenue can only compensate for some of the cumulated loss.

While the technology matures there are several forms of R&D work that have to be done, such as preproduction work – building plants, etc. This will increase the need for R&D expenses even more. However, it was pointed out that the situation is highly different from application to application. The experts argue that, a breakthrough product could even yield profit quite rapidly.

It was seen that in the future, there was a definite need to cut R&D expenditure until we can see revenue. There is, however, a need to increase the R&D expenditures to reduce the cost of the technology and to make full commercialization possible. The risk was seen by the experts that if there is not an increase in R&D expenditure, even though we do not see a revenue increase, the technology will not be commercial any time soon. Assessment on the R&D investment needed is seen in Fig. 5.

Currently there is significant government funding towards FC development in different parts of the world. FCs compete with other R&D fields for the same government funding, so it is unlikely that there could be a significant increase in R&D funding, if the money is not private funding.

It is however possible that we see a steady increase in profits as the current products gain more volume. Volumes can increase because of several different factors, but one of these is the increased interest in FCs in different parts of the world.

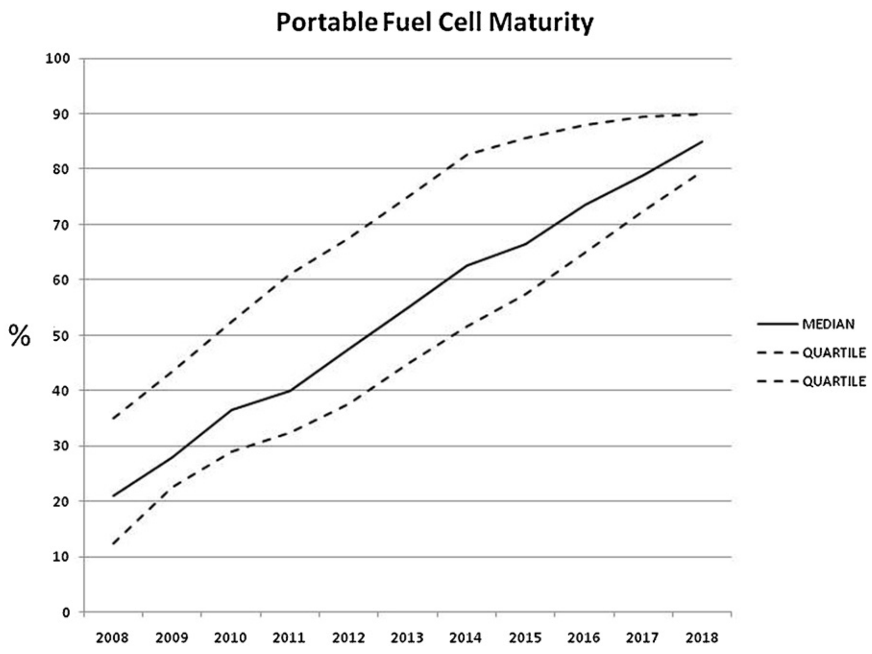

Fig. 6. Technology maturity estimation by the Delphi participants (graph until the year 2006 are actual figures presented in the PWC report).

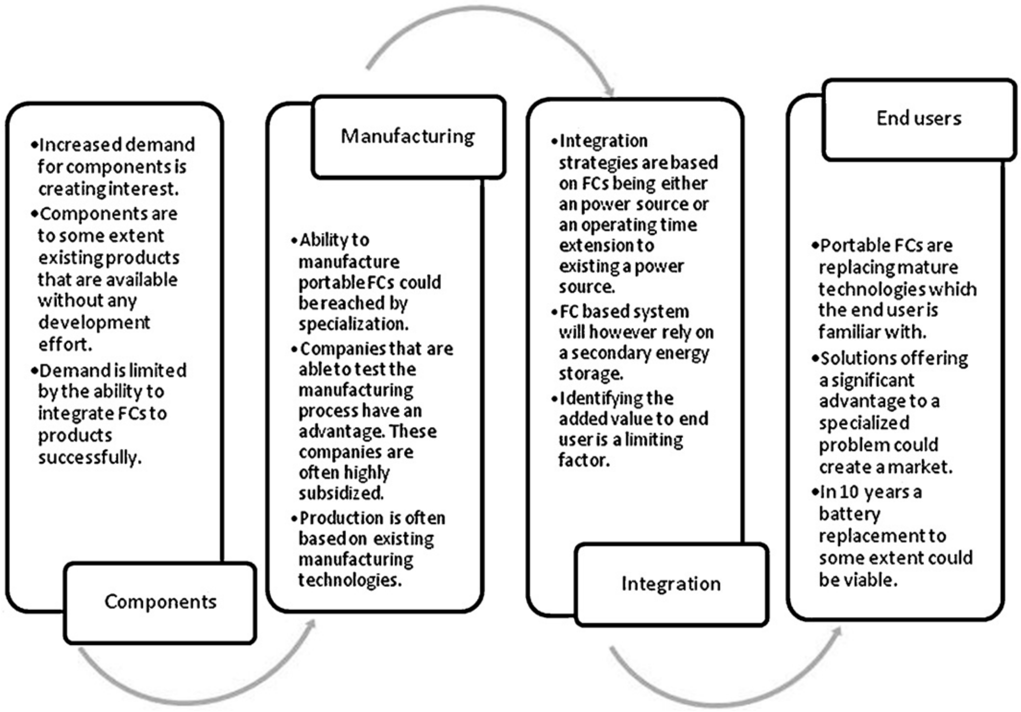

Fig. 7. Value system challenges in PFCs.

This development is driven by the increased competition for conventional energy sources. This will push the development of the technology and make a steady revenue increase possible.

As said before, PFCs are seen as a slowly maturing technology. It was stated that currently we are in the early stages of technological maturity, as seen in Fig. 5. This could be referred as being in the beginning of the S-curve. It was pointed out that it would be easy to predict that the PFC is fully commercial in the next 10 years, but there is no basis to support this claim. Hybrid technologies and battery technologies will take precedence on PFCs. The experts claim that batteries provide too good of a solution for portable devices so that it would be threatened by emerging PFC technology in the short term.

There has been substantial development happening recently. There have been several prototype demonstrations by large companies. Manufacturing equipment has been designed and prototyped. Safety issues have been taken into consideration and there are legislation and guidelines in place. These are all positive things effecting maturity, however cost, convenience, and lifetime issues remain as significant hurdles (Fig. 6).

Although the experts pointed out that even in a lower maturity level, such as 50%, there are good business opportunities it the emerging portable device market.

4.9. Summary of findings

To summarise the discussion of the experts Fig. 7 was formed. It strives to further elaborate on the interaction of different aspect of PFC development.

The chain of development leading to increased demand and ultimately revenue is focused on the ability to show a practical application that would enable value being produced to the end user. The chain of value creation is complete only if the end user has a significant advantage in replacing an existing familiar technology with a PFC.

As seen from Fig. 7, significant hurdles are in place in integration. Companies that currently integrate existing technologies into their end products will not change their product design based on it being offered from FC manufacturers. Customer requirements that are best met using PFCs are the significant factor effecting the widespread application of the technology.

5. Discussion

The complexities of a new technology penetrating an established market, such as PFCs penetrating to the established power source market, are hard to formalise. Interactions between policies, consumer perception, R&D efforts and supporting infrastructure are complex. The Delphi study showed that there is no need for enthusiasm towards PFC technology. For the technology to be more mature, significant R&D efforts, which cannot be funded by revenue, have to be made. Public policy and funding are significant in this R&D taking place.

Significant number of uncertainties towards the technology still exists. Uncertainties have also strengthened by several failed promises of a commercialization, which have inflated expectations towards the technology. The expert opinion results however showed a practical view on the expectations. The forecast did not expect PFCs commercializing in the near future. Despite this, governments, research organizations and industry are putting increased effort into developing FC systems. The European Union's 7th framework program has allocated significant resources on the development of fuel cell and hydrogen technology [42]. Similar efforts can be found in the USA and Japan [43]. Although these programs focus on FCs widely, there is a significant portion of the effort put to the development of portable devices.

As noted earlier by several authors [9,13] and by the Delphi experts, PFCs are restricted with similar expectation on cost and convenience as existing technologies. The Delphi study pointed out that there is still a long way to go before these expectations can be met. Although we have seen practical demonstrations from companies such as Fujitsu, IBM, LG, Motorola, NTT, Sanyo, Sony, Casio, Polyfuel and Toshiba which have all presented a PFC prototypes [10,44,45] these have not turned into commercially viable products. Companies, such as Toshiba, Samsung and Hitachi, have however had high expectations of commercialization [15,16,46].

The Delphi method used in this specific study was limited by fact that the participants of the expert group were significantly based in Europe or North America. This can be seen as setting the tone for several comments on for example the lack of large companies within the industry. As we can see there are several large companies, such as Toshiba and Sony, developing PFCs in Asia. The limitations set by this regional bias should be noted. This emphasizes the requirement of focusing on participant selection noted by for example Linstone and Turoff [30].

6. Conclusion

This study analyzed the prospects of portable fuel cells with an expert opinion study. The study showed that the experts had a practical view on the expectations towards PFCs. The study did not find views expecting rapid commercialization. Expectations were directed more towards finding the competitive edge against existing mature technological solutions.

As a management implication, the study pointed out the challenges of PFCs competing with the existing mature technologies. Expectations of rapid commercialization could be seen as unwarranted. The results of the study are seen as adding value on the single expert based monitoring efforts done by industry by creating open debate on the practicality of existing expectations towards the technology.

Acknowledgements

The research was funded by industry partners and the Finnish Funding Agency for Technology and Innovation. The authors would like to thank the Delphi group members.

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Publication III

Arho Suominen and Aulis Tuominen. Scenarios in technology and research policy: case portable fuel cells, *Journal of Strategic Change Management*, Vol. 3, Nos. 1/2, 2011.

Scenarios in technology and research policy: case portable fuel cells

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Abstract: The purpose of this paper is to build scenarios in technology and research policy for portable fuel cells. In portable devices, the transitions from batteries to a fuel cell have been forecasted for a long time. This has resulted in several policy decisions made by governments and strategic decisions made by industry. Results of concrete development have, however, been lacking. Promises of commercialisation have been abundant in industry, but adoption to portable devices in niche solutions has been difficult, not to even expect adoption to applications such as mobile phones. The study builds scenarios by drawing from a two-year study on the commercialisation of portable fuel cells. The study uses results from previous bibliometric and expert opinion studies and structures previous results through a work scenario into overall scenarios in technology and research policy. These concluded on three probable development scenarios, 'crisis of confidence', 'continuing the trend of development' and 'niche applications' with different practical implications.

Keywords: scenarios; hype cycle; portable fuel cells; PFC.

Reference to this paper should be made as follows: Suominen, A., Tuominen, A. and Kantola, J. (2011) 'Scenarios in technology and research policy: case portable fuel cells', *Int. J. Strategic Change Management*, Vol. 3, Nos. 1/2, pp.32–50.

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1 Introduction

Deciding on and then committing to a specific technology, by policy-makers or industry decision-makers, is always a gamble. Would the decision of investing in the research and development (R&D) of a specific technology be made based on foresight or some other method, we are always faced with the possibility of being wrong. Too often, this has also been the case. An abundance of technology and research policy has been proven by history as being based on inadequate assumption (Ayres, 1969). Would it be that we are prone to hype about interesting futures and "...that most technologies will inevitable progress through the pattern of over enthusiasm and disillusionment" (Linden and Fenn, 2003), and does this leave us forceless in a cycle of development repeating itself like it or not? If so, it would seem as being appropriate to discuss on why we see a specific, sometimes overenthusiastic, future probable. If for nothing else than to foster our imagination and enable us to question if our underlying assumptions are correct. Discussion is however often scarce, especially on scenarios contradicting the established future state. Bounded with our own history, we attempt to see the future as an extension of the past. Taking advantage on different methodologies of foresight, we attempt to capture a view of the future before it happens and direct our endeavours accordingly.

A probable future was also apparent for the case technology, portable fuel cells (PFC). A clear future of large scale commercialisation of the technology was expected years ago (Fuel Cells Bulletin, 2003b, 2007d, 2002a). Working from innovation to adoption, the large-scale application of the technology was seen a few years away. However, concrete results have been lacking in PFCs as well as in larger systems described by Ruef and Markard (2010).

Going back in time and understanding the context of the case study, we have seen in recent year's different technologies, which are perceived as environmentally friendly having an increased amount of attention. Growing environmental awareness has made new energy solutions, such as wind power, solar energy and fuel cells (FCs), exciting technological alternatives to existing technologies. In this mix of 'new' technologies, FCs have been seen as one viable technology. FC is an electrochemical device that produces electricity through a reaction between a fuel and an oxidant. The most significant difference to existing electricity production methods is the possibility to produce electricity without moving parts in a single process (Barbir, 2005). As an invention, FCs have been around for a significant time. The principle of FCs was invented already in 1838 by a German scientist Schönbein, to be proven by Sir William Robert Grove one year later (Kurzweil and Garche, 2009). Since then, the technology had for decades been only of mediocre interest. Industry has been unable to find practical, commercially viable, applications for the technology. Although there was an increase in interest due to the space programmes in the 1950s, only in the past 20 years have FCs taken leaps forward in technology maturity. Due to their versatility, it has been thought that FCs can be adapted to a variety of applications from large stationary solutions to small milliwatt scale systems (Cropper et al., 2004). High expectations have especially risen towards the application of portable scale FCs, which have sparked a significant amount of industry and policy interest within the last 20 years. The possibility of using an FC in a portable device has been driven by the high power and lifetime requirements of current portable devices. These requirements have been argued to be hard to meet with conventional rechargeable battery systems, due to their limited specific energy and operational lifespan (Broussely and Archdale, 2004; Eckfeld et al., 2003; Dillon et al., 2004).

The development of FC technology has taken steps forward since it was first applied in a practical way. In the 1970s, the focus was on larger systems. Driven by the oil crisis, possible future energy sources received a significant amount of attention. It took several years before smaller FCs were considered (Cropper et al., 2004). Significant interest towards PFCs, driven of course by the growth in number of small portable devices, has been seen within the last two decades. Altogether, the early 2000s was a time of increased amount of attention to FCs as a whole. This development can be awarded to several companies which have put significant effort into the development of PFCs (Kamarudin et al., 2009).

Focusing on PFCs, defined in this paper as movable FCs with the purpose of producing usable energy, commercial expectations have risen significantly in the last two decades. PFC, ranging from power systems in consumer electronics to larger back-up power systems, have all seen increased industry activity. In smaller PFCs, companies such as MTI Micro Fuel Cell (MTI) started PFC technology development in the early 2000 (Fuel Cells Bulletin, 2001). Driven by the increased expectations, by for example large military contracts, companies have directed development towards handheld power devices based on FC technology (Fuel Cells Bulletin, 2004a, 2004b). Later, development has also moved towards consumer solutions, as for example MTI has partnered with large consumer electronics manufacturers such as Samsung (Fuel Cells Bulletin, 2007a) to further develop a practical solution for the consumer market. In larger portable applications, companies such as the Japanese-based Yuasa Corporation, US-based Lynntech and the German company Smart Fuel Cell (SFC) have worked towards commercialisation. Having ambitious goals of rapid market penetration, (Fuel Cells Bulletin, 2002b, 2002c) that have to some extent fallen short, modest goals have been met by SFC, that has been able to produce a commercially available system and apply them to a practical end-user application (Fuel Cells Bulletin, 2003c, 2007b).

In addition to the previously mentioned, companies such as Samsung, NEC, Fujitsu, IBM, LG, Motorola, NTT, Sanyo, Sony, Casio, Polyfuel, and Toshiba have all tried to take advantage of PFCs. Resulting in several prototypes, which focused on demonstrating the practicality of the technology (Wee, 2006; Fuel Cells Bulletin, 2002a, 2003b, 2003a). Many of the companies also, like Yuasa, had high expectations on commercialisation. Toshiba suggested that it would commercialise FC systems in 2005 (Fuel Cells Bulletin, 2003b). Samsung claimed to be ready for commercialisation, with a laptop docking station, by the end of 2007 (Fuel Cells Bulletin, 2007c). Hitachi was expected to commercialise a small FC, with the manufacturing capability 2,000–3,000 units yearly, by the end of 2007 (Fuel Cells Bulletin, 2007d). These efforts did not deliver wanted results even though several scholars (Rashidi et al., 2009; Wee, 2006) have analysed the cost of using a FC powered device in comparison to battery-based systems, and found that a FC power source would be more cost-efficient after one year. However, as Agnolucci (2007) has pointed out, consumers are more interested in the physical size and weight of the system than its cost-efficiency. However, Toshiba was the first to present a commercial PFC mobile charger available at the commercial market (Fuel Cells Bulletin, 2009).

The above mentioned commercial interest can be to some extent accounted to the amount of research funding directed towards FCs as a whole. Governments have directed a significant amount of resources for the further development of FCs and within this PFCs. Expectations of PFCs being the 'early markets' [Fuel Cell and Hydrogen Joint Undertaking (FCH JU), 2008] application of FC technology as well as previously mentioned commercial endeavours have to some extent driven the technology forward.

The research question set in this paper asks if PFCs are able to meet the expectations made or are we faced with 'ceased operations' (Turner, 2009) and can we build probable scenarios in technology and research policy that would lead to the expected commercial future? This paper discusses possible future scenarios in technology and research policy in PFCs. The work is structures such that the following section reviews key literature on scenarios. Section 3 explains the methodology data gathered for the scenario work. Section 4 elaborates on the background and assumptions made before building the scenarios. Section 5 describes the produced thematic scenarios which are then further discussed in the concluding section.

2 Literature review

Scenarios, in the context of technological foresight, can be defined as "a time-ordered, episodic sequence of events bearing a logical (cause-effect) relationship to one another and designed to illumine a hypothetical future situation... A scenario is not and is not intended to be wither a prediction of a forecast" (Ayres, 1969). In addition to the definition by Ayers, scenarios have been defined "as focused descriptions of fundamentally different futures presented in coherent script-like or narrative fashion" (Schoemaker, 1993) or as "a hypothetical sequence of events constructed for the purpose of focusing attention on causal processes and decision points" (Kahn and Wiener, 1967).

The aim of scenario work, despite the different definitions we might use is to identify trends and uncertainties while forming them into multiple pictures of the future. Not covering all of the possible futures, but discovering the boundaries of development (Schoemaker, 1993). The importance of the scenario approach lies in making us more aware of alternate futures by helping us to overcome our limitations, and simultaneously accepting that the future should be considered as being multiple. A view which is supported by several authors (Godet and Roubelat, 1996; Mannermaa, 1991).

Not to go back as far as Bradfield et al. (2005), who trace scenario work back to Plato, different scenario techniques have been used since the World War II. At first, used as a military strategy tool scenarios were soon applied as a public policy tool. The early work of Kahn (1965) is often regarded as being significant in creating modern-day scenario work (Cooke, 1991). Although it should be noted that Kahn focused mostly on social forecasting and public policy, the more recent application to industrial planning, which began at the early 1970s, can be regarded to several scholars. The method developed by Kahn and Wiener, know as scenario writing, focused on a scenario expert led macroeconomic studies. Scenario planning, on the other hand, focuses on connecting strategic planning into scenario work often in a more microeconomic perspective (Wilson, 1997).

One of the first industrial applications of scenarios was the work that began in Royal Dutch/Shell in the early 1970s. Applying what had been previously used as public policy tool scenarios, or in this regard scenario planning, was taken to active use in industry. By the mid 1970s there were several institution that applied scenario planning in different contexts, and by the late 1970s, 22% of 'Fortune 1000' companies were using scenario analysis (Linneman and Klein, 1979).

Establishing that scenarios are widely applied, we focus on why they should be used. Becker (1983) has described three clear uses for scenarios. First, scenarios are practical in studying if policies or other actions would affect the realisation of what is analysed. Secondly, scenarios can be used to analyse the impact of alternate scenarios. Lastly, scenarios may be used to provide a common background for planning. Porter et al. (1991) further explain that scenarios often enable combining both qualitative and quantitative information. In addition, Martino (1993) sees scenarios as a way to merge a set of different forecasts to provide an overall picture of a topic. Like Becker, Martino describes scenarios as having three purposes. Firstly, to elaborate on the interactions of several trends while forming a holistic picture of the future. Secondly, to work as a tool in checking the internal consistency of a set of forecasts. Finally, to depict a future situation in a way that it would be understandable to a non-expert. These purposes are seen to some extent following the overall definition of scenarios.

To some extent understanding what are scenarios and why would someone use scenarios, we should further define how scenarios could be constructed. In the context of scenario planning several authors have described in detail the techniques and methodologies used to construct scenarios (Bradfield et al., 2005; Schnaars, 1987; Porter et al., 1991; Martino, 1993; Schoemaker, 1993). However, especially in the context of scenario planning, scenario methodologies have been referred to as being a 'methodological chaos' (Martelli, 2001). Some has even gone as far as saying that "There is no such thing as the scenario method" (Mannermaa, 1991). Scenario work is seen as having a significant degree of freedom in the sense of methodology, however, being true to the purpose of constructing several different futures and paths towards the futures.

3 Method and data

In this study, we follow the conceptualisation made by Schnaars (1987) on scenario development, the study used the practical approach outlined by Linneman and Klein in Schnaars (Schnaars, 1987) and Porter et al. (1991) to develop scenarios for PFC development. The study focused on a qualitative and contextual description of future developments rather than approaching the future from a quantified view point. However quantitative data was used to support the scenarios. The study also viewed the future as a set of possible futures. Focusing on structuring the underlying assumptions which the possible scenarios are based on, as suggested by Ascher (1979), rather than methodological questions. Comprehensiveness was approached by loosely applying the scenario filter model suggested by Meristö et al. (2010). This approach filters scenarios by three perspectives markets, society, and technology.

The time horizon selected for the study was set, as suggested by Armstrong, to a time in which large changes in the environment can be expected to occur (Armstrong, 1978). Structuring, or arraying as described by Schnaars (1987), the scenarios to themes is seen as a valid approach as there are more that a single unknown to take into consideration. The practical workflow, based on the checklist provided by Porter et al. (1991), is described in Table 1. The workflow is similar to those often used for scenario work. The workflow moves from identifying topical dimensions to the key impacting factors and then working towards possible futures from each of the identified factors.

Table 1 Workflow and method selected for scenarios work

Scenario workflow, adopted (Porter et al., 1991)		*Scenarios generating procedure by Linneman and Klein, adopted (Schnaars, 1987)*
1	Indentify topical dimensions	Number of scenarios three or four
2	Indentify audience	Length of scenarios one or two paragraphs
3	Specify time frame	No base scenario
4	Specify underlying assumptions	Alternative scenarios are themed
5	Set out the main drivers	Scenarios consider only the key factors
6	Decide on the number scenarios	Scenarios select plausible combinations of key factors.
7	Build scenarios	

The focus was to identify feasible thematic scenarios which would represent plausible combinations of key factors.

The study draws the data used from a two-year project on PFCs, which was a part of the Finnish National Fuel Cell programme. Organised by the Finnish Funding Agency for Technology and Innovation, the programme focused on "to speed the development and application of innovative fuel cell technologies for growing global markets. The programme's focus areas include stationary fuel cell applications, fuel cell power modules for utility vehicles and portable low-power solutions" (Tekes, 2011). In this context, the project focused on the commercialisation of PFCs. During the project, expert opinion was gathered through a Delphi study (Suominen et al., unpublished) and qualitative data was analysed by a bibliometric study (Suominen and Tuominen, 2010). This study structures previous results through scenario work into overall scenarios in technology and research policy as suggested by Martino (1993).

4 Background and assumptions

4.1 Topical dimension

The research conducted focused on providing and technology and research policy focused scenarios on PFC technology. The paper has two significant dimensions, one focusing clearly on industrial technology selection and the second on policy implications.

Industry technology policy is naturally based on the assumption of the technology being a current or future source of competitive advantage. A new technological opportunity naturally creates new companies, as for example spin-offs, or directs the R&D of existing industry towards the new technology. In the case of PFCs, both of the above mentioned have happened. To some extent it can be argued that in North America and in Europe, PFCs are a technology of choice for new ventures. In Asia on the other hand, large globally operating consumer electronics manufacturers, such as Toshiba, Samsung, Sharp and Sony, have worked on fuel cell commercialisation. If to some extent we might see a 'bandwagon effect' on industry taking up PFCs as an interesting future technology, industry has also had disappointments (BBC, 2005; Turner, 2009). Would we then argue, that the final barrier of commercialisation is the lack of proper supply chain (Sherriff, 2006) or the lack of products (Jerram, 2011), the fact that a critical mass of industry is involved in PFCs could be argued to be a significant factor to follow.

In a policy dimension, FCs have been gaining increased interest from policy-makers as well as industry. Ranging from smaller national programmes to large hydrogen economy programmes in countries such as the USA, Canada, Japan and the European Union, FC development has been given significant R&D funding for the last two decades. Large cooperation initiatives such as The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) or the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) in the European Union have been established. Initiatives were described by OECD as "This global effort is expected to continue over the next years as major countries have planned multi-annual investment. This includes: $1.7 billion over 5 years in the United States; up to €2 billion, including renewable energy, in the 6th Framework Program of the European Union; more than ¥30 billion a year in Japan; and multi-annual programs in place in other countries such as Canada, Germany, Italy." (OECD/IEA, 2004).

The potential of using FCs in portable applications was noted by several regions, such as Australia and Canada, which all had funding schemes in place for FCs in portable and micro applications. Several large funding schemes have been initiated since the early 2000s, one of the most recent being the European Union and Industry matched funding of 1 billion Euro launched in 2008. Future research policy is one of the most significant dimensions incorporated to the scenarios. Steady progression by a trend of development is directed significantly by R&D funding directed towards FCs. Refocusing, such as the one suggested by the Department of Energy (DoE) in the USA (US Department of Energy, 2009), which could ultimately move funding away from FC initiatives can have a significant effect on future scenarios.

4.2 Time frame

The time frame of the study was designed for ten years on the basis of having practical scenarios, which would have a believable development path. Although scenarios are typically used to long range forecasting, in which development is more uncertain, practical application have been limited to a time horizon of 5–15 years (Schnaars, 1987) or from 5–20 years (Porter et al., 1991). Porter et al. (1991) explain that by limiting the time frame, the author enables several forecasting techniques such as trend extrapolations, expert opinion and different modelling tools being integrated into the scenarios. These tools are often limited in the practical time frame of forecasting. As noted by Ayres (1969) "...the usual analyst's rule of thumb is that the projection foreward should not exceed the time span of the base line data". In this study, the selected time horizon of ten years is easily within this rule of thumb and within the time frames suggested in previous research.

4.3 Underlying assumptions

The underlying assumptions made in a scenario study have been found to be the most important factor in determining the quality of the overall forecast (Ascher, 1979). In this study, the assumptions made are structured in categories technical, commercial, and policy assumptions.

The technical assumptions focus first on defining PFCs. As mentioned before, in the context of this study, PFCs are defined as movable FCs with the purpose of producing usable energy. This extends the definition to small truly portable micro applications to heavier, but still humanly movable, systems. As such the technical assumptions made differ. The starting point for the study is however that using FCs in portable applications is a relatively new topic. Development on PFCs can be seen as starting in the 1990s (Dyer, 2002), making it a technology in its infancy. Interests towards smaller FCs have been increasing as the need for portable energy increases. When discussing on the need for PFCs, a comparison to batteries is often made. Technical assumption made, as such, focus on the assumptions made comparing batteries and FCs. In the study, it is noted that in theory the energy density of FCs (methanol 6,000 Wh/kg) exceeds batteries (Lithium-ion 600 Wh/kg) significantly and that when focusing on portable device with high energy need the volume of the energy source is significantly smaller as a FC (Dyer, 2002; Dillon et al., 2004). FCs, in their current state, are not able to meet this theoretical energy density, and underperform current battery systems. However, the assumption made in this study is that "...The chances of finding a practical new battery system with a significantly higher energy density in the next 10 years are extremely small. There is simply no such concept being presently actively studied at research level, as was the case for many years for rechargeable lithium..." (Broussely and Archdale, 2004) and the discovery of a totally new energy storage with significantly higher energy density would be unlikely or require a significant discontinuity in battery development.

Commercial assumption made for the scenarios focus on the overall consumption of portable energy will increase in the future while at the same time requirements for reliability of service and operating time will increase. For example, the predictions by Deloitte estimate that in the year 2011 half of the computing devices sold will not be personal computers. Expectations of more that 400 million tablet computers or smart phones being sold in 2011 would show a sharp increase in portable devices sold, as well as, broadening customer expectation on the use case of a portable device (Lee and Stewart, 2011).

Policy assumptions made for the scenarios are focused on perceived environmentally friendly technologies having similar or increased focus in future policy decisions. This is not focused on FCs *per se*, but to the abundance of current and future technologies considered energy efficient or environmentally friendly.

4.4 Main drivers

In the study, three specific perspectives, technology, markets, and society have been considered. Focusing on understanding the interaction between the perspectives and on their combined impact on the innovative action the main drivers were identified.

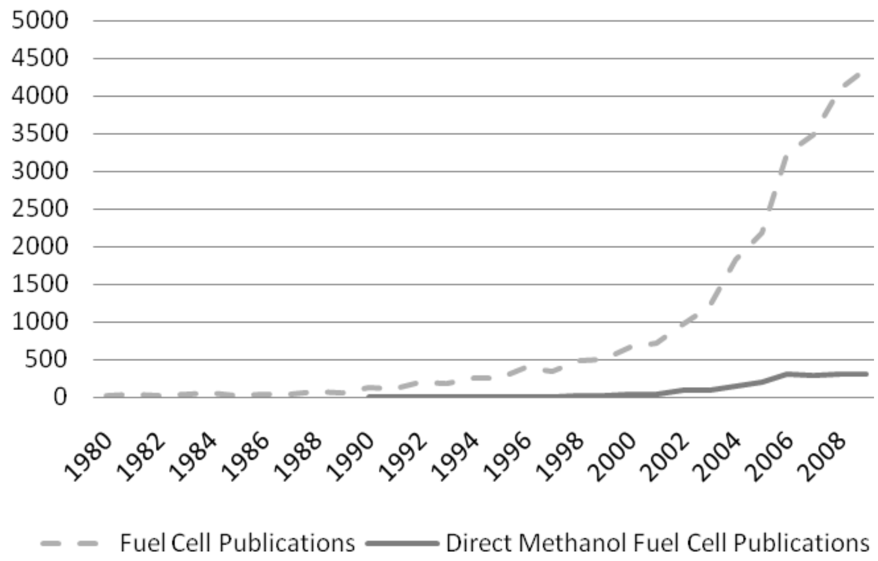
4.4.1 Technology drivers

In a technical perspective, the increases in scientific publications on FCs have had a significant increase in the last decades. As seen from Figure 1, the numbers of publications have increased rapidly since the late 1980s increasing to a period of near exponential growth in the 2000s. To distinguish between PFCs and the overall increase in FCs, a sub-category of fuel cell known as direct methanol FCs is used. Although not arguing that this would describe all of the publications in PFCs, it is used to elaborate on how PFCs have developed. As seen from the Figure 1, the overall developments of FCs far precede that of its portable applications. This is also supported by scholars (Dyer, 2002; Kamarudin et al., 2009).

In applying the technology commercially, several barriers have been seen. In the Fuel Cell Report to Congress (US Department of Energy, 2003), PFCs were categorised as facing several medium difficulty technological barriers, these being cost, durability and fuel and fuels packaging. In addition system miniaturisation was seen as a high difficulty level barrier. Since the report being published, PFC have been increasingly studied. Focusing on the challenges stated several studies have published incremental developments into the technology. Studies, especially on Direct Methanol Fuel Cells (Kamarudin et al., 2009; Wee, 2006), show several significant technological barriers still remaining to be solved. Resulting in the technology lacking on the perceived technical benefit of providing significantly more energy than existing solutions.

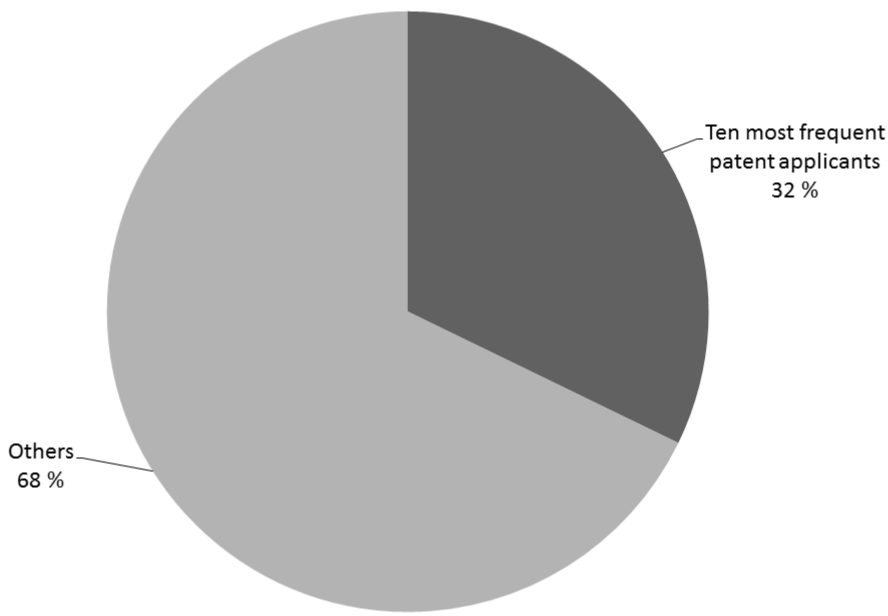
In analysing technological life-cycle and technical development Ayres (1987) has suggested that a technology would, as it reaches the stage of childhood, be dominated by inventors and innovators that try to protect their research work through patents and secrecy. In this process, Ayres suggests that the most dominant firms can be expected to capture a significant portion of the total benefits of the inventions. Within PFCs, again modelled through the development of DMFCs, a sharp increase in patents and a process of consolidation of patents to a few large organisations is clearly visible in Figure 2. Arguments can be made that PFCs are technically in their childhood. A stage in which "...there is typically an intense competition among entrepreneurs for market niches, based primarily on design and cost-effectiveness improvements..." (Ayres, 1987).

Figure 1 Number of fuel cell and direct methanol fuel cell related journal articles



Source: ISI Web of Science

Figure 2 Number of direct methanol fuel cell applicant of the ten most frequent applicants in comparison to all applications



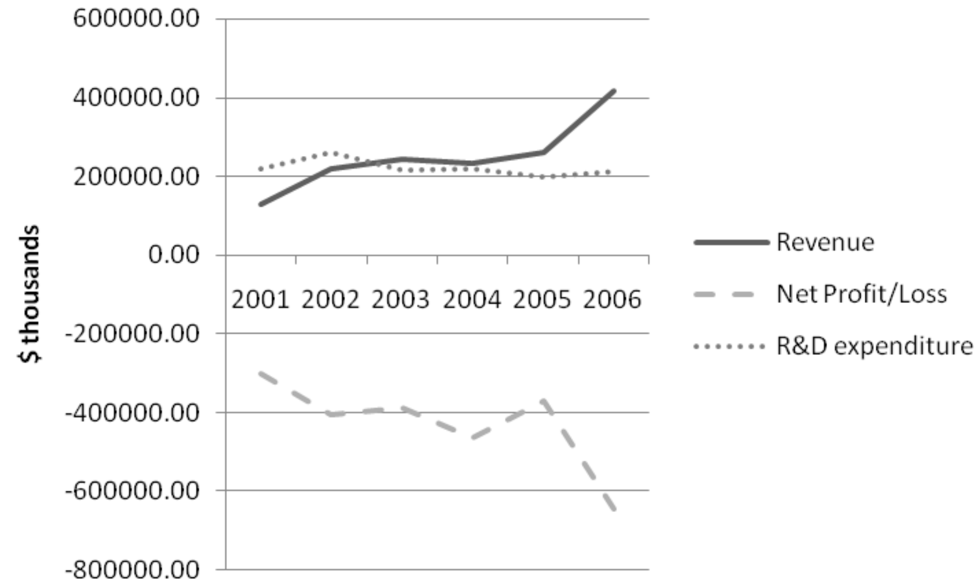
Source: Espacenet database

The development poses a question on the technological main driver, efficiency, and will it reach the level adequate for technical success. Holton (in Ayres, 1969) argued that as a 'gold rush' phenomena of research, seen as a strong increase in publication with PFCs in Figure 1, occurs it would be followed by a decrease of interest as progress becomes harder and harder. This results in either a technology becoming dormant or moving forward extremely slowly. It is significant progress in technical development done before interest dies is significant.

4.4.2 Market drivers

In a market perspective, the main drivers of summarised by Agnolucci (2007) as size, cost and practicality. Agnolucci even finds it odd that PFCs, although seen as promising, have not been able to penetrate the market. Hellman and van den Hoed (2007) have found that FCs have several market related characteristics such as 'Lack of cost and performance competitiveness', 'Non-traditional performance indicators', 'Emerging industry', 'Low return on high investments', and 'B2B collaboration', which explain the market development of FCs. The first two, categorised by the authors as the characteristics of the market for FCs, focus on the performance indicators valuable for the end user. They argue that companies are faced with a dilemma of developing products not to a market demand but rather to gain operational experience. As well, it remains uncertain if practical solutions attracting even early adopter could be developed. This is made more severe by the fact that FCs often lacks traditional performance indicators (Hellman and van den Hoed, 2007). In the case of PFCs, this might lead to non-adoption as for example consumers perceive battery recharging as being 'free' while you would have to pay for fuel for a PFC.

Figure 3 Revenue, net loss, and R&D expenditure of selected fuel cell companies



Source: PriceWaterhouseCoopers (2005, 2006, 2007)

The last three characteristics, categorised as contextual by Hellman and van den Hoed (2007), have found that there are several inhibiting market related negative drivers. Illustrated in Figure 3, we see that in its current state the technology requires a consistent R&D investment while the industry is still increasing in net loss. Subsequently alliances and joint ventures, or B2B collaborations, are a necessity to gain more revenue.

PFCs that gain revenue have historically focused on low-end applications. Units delivered have been applied to toys and other demonstration by Chinese and Taiwanese companies. European and USA based companies focus mainly on military solutions and other niche applications (Butler, 2009). Experiencing rapid increase the portable FC deliveries, we have seen a near four time increase in the number of portable units shipped from 2005 to 2008. This, however, still resulting in only little over 9,000 units shipped worldwide.

Efforts on commercialisation, even though several scholars (Rashidi et al., 2009; Wee, 2006) have found that a FC power source would be more cost-efficient after one year of use, have not proven to be successful. Even though several small portable devices have been prototyped (Flipsen, 2005; Fuel Cells Bulletin, 2002a, 2003b) the development of the FC products in mobile devices is dictated by the development of lithium batteries and innovations making devices more energy efficient, smaller in size and weight, and the ease of use of the systems (Agnolucci, 2007). Subsequently integrated commercial FC systems have not been available.

4.4.3 Society drivers

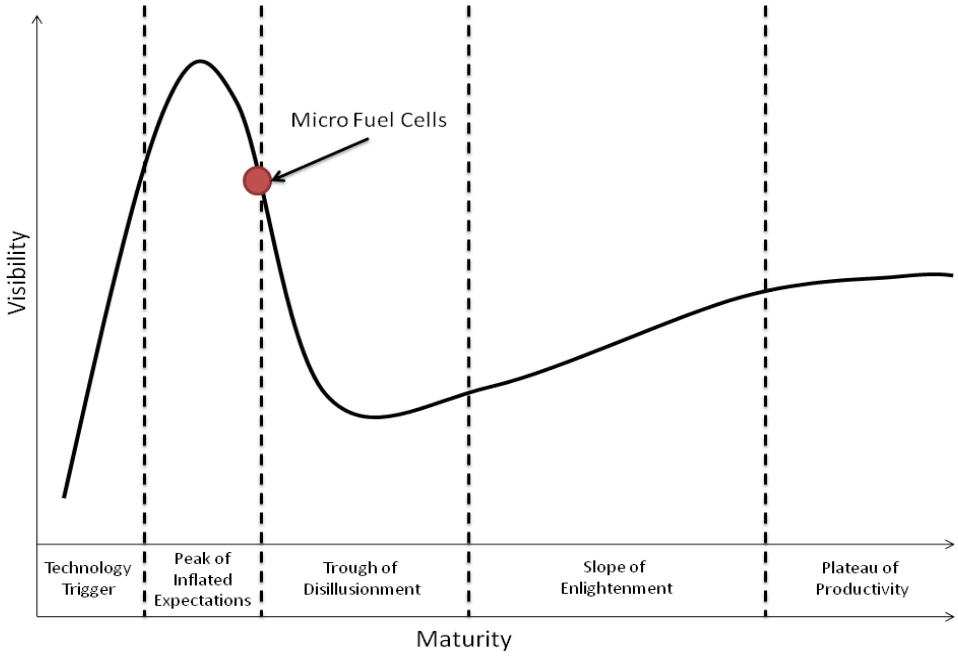
Pressure in taking advantage of environmentally friendly technologies has increased social and policy interest towards technologies such as photovoltaic and FCs. PFCs have been under a policy-push since the early 2000s when the development of PFCs began. Increased social visibility pushed PFCs to a Hype Cycle (Linden and Fenn, 2003), seen in Figure 4, and in 2005 Gartner reported that small micro FCs have reached the ‘peak of inflated expectation’ and that the ‘plateau of productivity’ would be five to ten years in the future.

Research policy has been since directed towards further developing PFCs to the productivity phase. Most prominently depicted in the large European Union and industry effort, FCH JU, in which PFC products are seen as early markets products. European Union efforts see early market products as a significant policy effort, which is “Given the key importance...”. In the policy actions early markets are seen significant

> “...in preparing for the widespread deployment of fuel cells and hydrogen technologies...The main goal will be to show the technology readiness of (i) portable and micro fuel cells for applications in education, industrial tools, recreational, sub-micro CHP, etc; (ii) portable generators, back-up power and UPS-systems; (iii) specialty and industrial vehicles (e.g. forklifts) including related hydrogen refuelling infrastructure.” (FCH JU, 2008)

Explicit goals and expectations set by similar programmes are setting the technology up for a success/fail situation as it is being evaluated by clear targets. In this, a significant societal driver is the ability to meet and sustain social and policy interest towards the technology as it moves towards productivity, specifically in a situation where targets are not met.

Figure 4 Micro FCs in Gartner Hype Cycle in 2005 (see online version for colours)



Source: Adopted from Fenn and Linden (2005)

5 Scenarios for PFC

From the historical background described in the study as well as based on the two-year study, three thematic scenarios are suggested. While maintain that, "However, a scenario is not an end in itself. It only has meaning as an aid to decision-making in so far as it clarifies the consequences of current decisions." (Durance and Godet, 2010). The scenarios are seen as opening discussion on the plausible futures of PFCs.

5.1 A crisis of confidence

In the near future, a crisis of confidence emerges. Moving along the Hype Cycle, although gathering significant R&D funding from policy-makers, a path to 'the slope of enlightenment' for PFC business is not found. For PFCs holding up to the role of 'early markets' (FCH JU, 2008) is too high of a barrier. Although having several advantages, PFCs fail to be competitive in any of the segments. Inability to meet the 'early market' demand pushes PFCs to a crisis of confidence. This will turn subsidies and venture capital, which is still needed as seen from Figure 3, away from PFC R&D. This will ultimately force small endeavours that rely on external funding, to cease operations, while larger companies redirect funding to more successful projects. As practical implementations fail to deliver expected results and the end users expectations on cost, size and practicality of use are not met developers of the technology slowly jump out of the bandwagon.

This will follow from and contribute to several factors.

- The crisis of confidence slowly moves funding, both research and venture capital, towards more prominent technologies. This will increase funding in other technologies, such as photovoltaic, perceived as environmentally friendly.
- Lack of research funding moves researchers to pursue other possibilities. This eventually slows the rate of development in PFCs. Possibly increasing development in for example battery development.
- Lack of venture capital ceases operations in small companies that are unable to sustain development by revenue. This can lead to viable ventures being ceased as the crisis moves venture capital away from the technology as a whole.

5.2 Continuing the trend of development

Development trends continue on a growth curve. The number of research publications, seen in Figure 1, develop in the form of an S-shaped growth curve (Suominen and Tuominen, 2010) allowing for an exponential growth of research results in the near future. The Immaterial Property Rights for the technology are clustered into tight patent families protecting key inventions. The number of patents and the cluster of significant IPR owners increase as significant invention and future competitive advantage are being protected. The commercialisation path for the technology resembles a 'disruptive innovation' (Christensen, 1997; Christensen and Raynor, 2003) by creating new markets or reshaping existing markets by delivering a simple, convenient solution to a customer base otherwise ignored, by creating a very different value proposition. This development scenario is based on the increase in low-cost applications of FCs (Butler, 2009), that take advantage of the technology in a disruptive way enabling mass markets and economy of scale to develop. The move towards the 'slope of enlightenment' enables existing ventures to gain revenue and ultimately turning the net loss-curve, seen in Figure 3, around to a more positive territory.

This will follow from and contribute to several factors.

- Short-term research results enable industry to meet the expectations set to this 'early market' application of FCs. This however moves the focus of research to applied research focusing on incremental developments in the technology as a whole.
- In a market driven scenario, we would see the growth of one to two companies that are able to use the technology in a disruptive way being successful. A disruptive innovation leads to the possibility to produce in mass and taking advantage of operational experience as well as economy of scale. This disruptiveness has a high change of being something that has not or can not be patented, and thus even favours smaller ventures.
- A significant portion of current PFC industry is either forced out by the few successful companies or forced to follow development by imitation.
- In the more long-term, as economy of scale reduces the cost structure, PFCs are introduced to the increasing array of mobile computing devices (tablets, smart phones).

5.3 Niche application

The 'slope of enlightenment' is reached as unpractical technical applications and ventures are forced out of the game and viable business ventures are given sufficient funding to further develop. In a technology driven scenario specific niche solution, such as Auxiliary power units (APUs), small power generators, and military solutions that have a distinct customer value will provide a viable market for a handful of specialised companies. However, even in the mid-term forecast, mass production outside the specialised applications is unlikely. The companies reaching adequate revenue operate in a specific ecosystem in which the product they sell might be highly competitive.

This will follow from and contribute to several factors.

- Large consumer electronics applications, produced in mass productions, are an unlikely PFC product.
- Overall the industry will reach the 'plateau of productivity' with a small number of companies and products.
- Companies will most likely remain as individual companies developing, manufacturing and selling their product to a specific market.

6 Discussion and conclusions

PFCs are in an interesting technological path. As an invention, FCs are a relatively old, but the application of the technology has been scarce. One could argue that much to the widespread use of fossil fuels, other technologies have not received adequate attention. With each energy crises, new sources of energy have received increased attention. FCs have, however, been unable to take advantage of this. FCs have to some extent remained, in a market penetration point of view, a stagnant technology.

PFCs, which are the newest addition to the application range of FCs, have been seen as a road to mass market. However, commercialisation promises have not resulted in success stories. Would this be because of technical difficulties or 'inflated expectations' is to some extent irrelevant, scenarios to the future are however of practical value.

In the last two scenarios, PFCs develop either by 'continuing the trend of development' or 'niche applications'. The scenarios differ in the volume of business, as one focus purely on the formation of a niche market and the other on a disruptive innovation enabling a mass market to be formed.

In the first scenario, 'a crisis of confidence', the development of PFCs is more driven by social and policy environment towards the technology in comparison to being analysed by its merits. Significant shifts in policy might result in PFCs lacking needed funds to develop and as FCs as a whole have been prone to 'hype' (Ruef and Markard, 2010) the scenarios should be taken seriously. Signals that would lower confidence, such as large companies pulling away (BBC, 2005) or smaller ventures being unable to gather much needed funding (Turner, 2009), added with increased policy demands, such as the expectations of 'early markets' applications (FCH JU, 2008), could be seen as a challenging. In this scenario it can be likely that both research efforts as well as industry efforts are directed elsewhere, and PFCs as a technology will become dormant for a period of time.

It seems that the expectations set for PFCs are high and resemble to a degree 'the inflated expectations' described in Hype Cycles (Linden and Fenn, 2003). To some extent, this could even be seen as the deciding factor in PFC development. To which extent we are able to accept lowered expectations before 'pulling the plug'.

If we hope for a mass market future for the technology, one should expect a disruption of some type happening. Demonstrations on mobile phones, laptops, and mobile phone charges have not been able to interest even early adopters; as such a more innovative commercial approach to the technology might be useful. However, if we accept that PFCs are a technology of choice for niche solutions for a narrow target market we might be able to find viable business models even in the short-term.

As a management implication to the above mentioned scenarios, the authors would refer to foresight. Foresight in this involving the recognition, in comparison to forecasting, that we can shape or even create our future (Martin, 2010). In the case study this would emphasise that by elaborating on possible futures decision-makers can take action to shape the technology and research policy to a direction of their choosing. In regard to foresight, a practical implication would also be the notion that "technical experts tend to be too optimistic in the short-term, failing to appreciate implementation problems, and too pessimistic in the long-term, failing in their imagination in regard to major impacts and new solutions" (Linstone, 2011). In the context of this study, the optimism is apparent, but where do we fail in imagination remains to challenge our thinking.

Acknowledgements

The research was funded by the Finnish Funding Agency for Technology and Innovation (TEKES).

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Publication IV

Arho Suominen and Marko Seppänen. Setting the upper bound of growth in trend extrapolations. *In Proceedings of the IAMOT 2011 Conference*, April 2011.

International Association for Management of Technology
IAMOT 2011Proceedings

SETTING THE UPPER BOUND OF GROWTH IN TREND EXTRAPOLATIONS

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ABSTRACT This paper reports the findings of a study on the trend extrapolations of a case technology, white light emitting diodes. The study takes advantage of bibliometric data made available by different databases as a measure of technological advancements. The case technology was modeled through its current technological life cycle by using databases, such as Science Citation Index, Compendex, US Patent and Trademark Organization and News Services. The analysis shows that the trend extrapolations modeled the developments with a good statistical fit by explaining a significant portion of the variance in each of the sets of quantitative data. Analyzing the practical aspect of the trend extrapolations made the study points out two factors affecting the practical analysis of the trend extrapolations made. First, the statistically fitted model lacked for ability to produce a practically plausible model fit, and second, the possibility to vary the upper bound of growth while still having a statistically good model fit is extensive. Agreeing on a valid upper bound of growth is a significant factor affecting the validity of the model as with a variety of upper bound levels a valid model was produced. As future research, the results suggest further analysis on the context of trend extrapolations made from bibliometric data.

Keywords*: forecasting, trend extrapolation, growth, Fisher-Pry, Gompertz, case, white light emitting diodes*

Introduction

Different foresight methods have long since been used to gain understanding on the developments of a specific technology. Using historical events and the current state are often used to evaluate plausible future developments. (Watts and Porter 1997) In analyzing technological development, foresight has been gained by a variety of methods, which can be roughly divided as both quantitative and qualitative tools of measuring new technological opportunities (Vanston 1995). In quantitative analysis trend extrapolation, referred to as the "*workhorse of technological forecasting*", is perhaps the most used method (Lecz and Lanford Jr 1973). Based on the analysis of time series data on selected parameters, trend extrapolations are used to forecast the trend of development into the future. In modeling the complex socioeconomic system of technological development, extrapolations are often based on different S-shaped growth curve models. Empirical evaluations on the models, such as the

Fisher-Pry model, have validated them as powerful tools in describing technological development. However, by using S-shaped growth curves the researcher is in most cases bound by the following underlying assumptions: 1) "the upper bound of growth is known", 2) "the chosen growth curve to be fitted to the historical data is the correct one", and 3) “the historical data gives the coefficients of the chosen growth curve formula correctly" (Martino 1993).

The empirical evaluations made to validate the growth models have been based on modeling tangible developments (Martino 1993, Porter, et al. 1991, Ayres 1969), such as the Moore’s Law. The possibility to extend the same approach to bibliometric information, and use this to model technological development has also been suggested (Daim, et al. 2006, Bengisu and Nekhili 2006). Bibliometrics takes advantage of the quantifiable information within databases, such as the number of articles in science databases directed towards a specific topic, and uses this as the basis of evaluating technological development. Using multiple databases in bibliometric evaluations has also been suggested to capture the Technology Life Cycle (TLC) of a specific technology (Martino 2003, Nelson 2009). The quantified information is thereafter also used as a basis for trend extrapolations to the future. These approaches, however, accept the underlying assumption that the bibliometric data models technological development similarly than what a more concrete basis for evaluation, such as using the lumen/watt efficiency of white LEDs, would.

In this paper, we report the findings of a study on the trend extrapolations of a case technology, white light emitting diodes. The study takes advantage of bibliometric data made available by different databases as measures of technological advancements. The case technology was modeled through its current TLC by using databases, such as Science Citation Index, Compendex, US Patent and Trademark Organization and News Services.

Trend Extrapolations in Technological Forecasting

Technological forecasting focuses on providing timely information on the prospects of a technology (Watts and Porter 1997). The process of forecasting, as such, can be done with different methods, some of which are qualitative and others that rely on the quantification of information embedded into databases. The latter often refers to analyzing textual databases with quantitative methods, which is referred to as bibliometrics (Borgman and Furner 2002). Bibliometric methods are tools that extract information from large databases, uncovering the underlying structure of the databases and producing information from the apparently unstructured dataset. (Daim, et al. 2006) The data gathered can be then used to model the current state of a technology (Chao, Yang and Jen 2007) or it can be used as a basis for extrapolations on future development.

Forecasts – or trend extrapolations as the forecasts in this context are often referred to – are often done by using an S-shaped growth curve model. S-shaped growth curves have been seen as fitting well in modeling technological growth processes (Porter, et al. 1991, Martino 1993), although other forecast models, such as ARIMA (Christodoulos, Michalakelis and Varoutas 2010), have also been suggested. The application of trend extrapolations to quantitative information embedded in databases could be argued to be an extension of their use in modeling concrete technological development. Trend extrapolations have been based on the notion that "*A specific technical approach to solving a problem will be limited by a maximum level of performance that cannot be exceeded*". (Martino 1993). Modeling the S-shaped growth of a technical approach to this specific maximum level results in a trend extrapolation. The availability of information in databases has expanded the use of trend extrapolation to model the quantitative number of database entries. This would embed the underlying assumption that when a specific maximum number of database entries is reached this would coincide with the "maximum level of performance".

The process of trend extrapolation involves fitting a chosen growth curve to a set of data which is seen as modeling the technological development. This fitted model is then extrapolated into the future. This process, in most cases, includes that the researcher accepts several assumption:

1) "The upper bound of growth is known",
2) "The chosen growth curve to be fitted to the historical data is the correct one", and
3) "The historical data gives the coefficients of the chosen growth curve formula correctly" (Martino 1993).

To analyze the first assumption, we should note that using historical data as the only source of setting the upper bound of growth is seen as bad practice (Martino, 1983). Although we often see that the "*goodness of fit*" of historical data is presented as variable significant variable in making trend extrapolations (Huang, Guo and Porter 2010, Chung and Park 2009), the use of historical data poses several challenges in making trend extrapolations. When using bibliometric quantities as the historical data to which the trend extrapolations are based, the researcher lacks a practical point of reference to the analysis. This sets a high demand on the database used being able to capture the development of a technology. This would emphasize using several sources of information to validate the results or being able to anchor the trend of development to some other practical point of reference. However, recent studies have only used one database as a source (Chao, Yang and Jen 2007, Kajikawa, Takeda and Matsushima 2010, Kajikawa, Yoshikawa, et al. 2008).

The second assumption focuses on the growth curve model used. Scholars are seen as using two distinct S-shaped growth models, the Fisher-Pry model and the Gompertz model, to forecast growth (Bengisu and Nekhili 2006, Watts and Porter 1997, Huang, Guo and Porter 2010, Porter, et al. 1991). In addition to the previously mentioned, several other growth models have also been suggested and analyzed (Young 1993). Both of the above mentioned growth models produce an S-shaped growth curve, which in addition to technologic development model several natural phenomena. These growth curves have a relatively slow early growth period, followed by a steep growth period which then turns to a saturation period where the growth approaches the limit set. However, the Fisher-Pry and Gompertz models, used in this study, describe technological development quite differently.

The Fisher-Pry model, named after its originators Fisher and Pry, was described by its authors as "*a substitution model of technological change*". Fisher and Pry (1971) explained that the model would be powerful in for example forecasting technological opportunities. The Fisher-Pry model is dependent on both the fraction of the technology penetration as well as on the fraction still being penetrated. This is loosely analogous with a situation where initial sales of a product will make subsequent sales easier by familiarizing prospective customers to the product. In contrast, the Gompertz model is most applicable in situations where "equipment replacement is driven by equipment deteriorations rather than technological innovation" (Porter, et al. 1991). Sometimes referred to as the mortality rate, Gompertz fits a situation where increased activity does not affect the future. This is analogous to a situation where "*initial sales do not make subsequent sales easier*". (Porter, et al. 1991)

The underlying assumption made in both models is, however, that the dynamics of the developing technology would fit that of a growth curve. In this, we could argue that the "*goodness of fit*" would be an insufficient measure of analyzing if the growth curve fits the dynamics of technological development. Assumptions, especially when using short periods of historical data, should be based on empirical evidence on similar developments.

The third assumption focuses on making the statistical fit to the actual data available, approached most commonly by using a least squares fit. In the case of S-shaped growth, a transformation to a linear form is often used. There after using a linear regression least squares approach to fit the transformed values. The statistical fit can be evaluated by the linear regression fit. In most cases the fit between the actual values and fitted values should also be evaluated.

Methodology and data

Method

The method of trend extrapolation often relies on a basic time series analysis. Using regression techniques in fitting nonlinear relationships are seen as suitable in technological forecasting. The use of the methods is derived from the historical understanding that a specific nonlinear model would describe the complex system of technological development. This has been the case with models such as Fisher-Pry and Gompertz, which have been validated by the vast number empirical studies using them.

To effectively model these non-linear relationships, we often tend to use the data as a linear function of time. This requires a transformation seen in Table 1 for both the Fisher-Pry and Gompertz curves. In both of the transformations L, which is the upper limit of growth, affects the model fit. By selecting an appropriate upper level of growth, we can use linear regression in estimating the values of the constants *a* (intercept) and *b* (slope) in the linear model equation

$$Y = a + bX + e$$

The statistical evaluation on the model validity is often done by selecting constants "*a*" and "*b*" that minimize the sum of squares errors (e) between the value of Y and the value predicted by the linear model. This straightforward statistical analysis rests heavily on the assumptions that: 1) the upper bound of growth is known and 2) the environment of the past will continue to the future. In this type of modeling, the researcher is forced to assume the development as a static process without discontinuities and as such only affecting the model through the selection of an upper bound of growth.

Table 1: Linear Transformation of Fisher-Pry and Gompertz models, adopted (Porter, et al. 1991).

Growth Model	Transformation
Fisher-Pry	$Z = \ln[(L - Y) / Y]$
Gompertz	$Z = \ln[\ln(L / Y)]$

In addition to using the least squares approach, the fitted values are evaluated by using Mean Absolute Percentage Error (MAPE) in analyzing model fit (Young 1993). By setting the upper bound of growth to minimize the MAPE, a statistical evaluation of the overall model fit is analyzed.

Case technology: Light Emitting Diode

LED technology is a practical application of semiconductor technology which has been taken advantage of for several decades. As an electronic component, LEDs have been available since the 1960's, but being restricted to wavelengths that only enabled small indicator lights. The first LED presented in 1962 (Holonyak and Bevacqua 1962), had the luminous efficiency of 0.1 lm/W. More recent development has enabled the development of white LEDs, which have a greater luminous efficiency enabling LEDs to be used for lighting.

LED is a semiconductor diode that, through a process of electrons recombining with holes, releases energy as photons. A LED consists of a structure called a p-n junction. Electrons are injected to the p-type region of the junction while holes are injected to the n-type area. The recombination process at the junction leads to the emission of light. The wavelength, or in practical terms, the color of the light is determined by the bandgap of the semiconductor, which is determined by the materials used. Although several materials have been used, for high-powered LEDs to be efficient and reliable, suitable semiconductor materials had to be fabricated.

While working towards the widespread use of LED technology, early increases in the efficiency of LEDs can be accounted to the development of semiconductor technology. The practicality of the invention, as it was used as an indicator already at the late 60's, and the rapid developments in semiconductor technology resulted in a near order of magnitude development in the lm/W efficiency of LEDs (Craford 1997). This however resulted only in the development of red, yellow and green LEDs getting more efficient. Materials that could enable efficient white light were still dependant in the development of a blue LED.

White light, with LEDs, has been produced by either combining red, green, and blue LEDs or by using phosphorous material to convert blue or UV led to a white light emitting one. (Yam and Hassan 2005) The technological breakthrough produced by Nakamura, which enabled a gallium nitride based blue and green LED (Nakamura, Mukai and Senoh 1991, Nakamura, Senoh and Mukai 1993), had a significant effect to the developments of white LEDs. The invention resulted in a thrust to the development of white LEDs and has to date enabled LEDs that can replace traditional lighting systems. It may be argued that the invention by Nakamura has enabled the development of practical white LEDs.

As a result of this development cycle, the benefits of LED technology can be taken advantage of as a light source. LEDs are highly efficient, reliable, and rugged light sources. Although LEDs as such have been used for decades, the invention by Nakamura enabled the further development of efficient and practical white LEDs. The rapid development of LED efficiency is often referred to, similarly as Moore´s Law, with Haitz's Law which forecasted an exponential rate of development in lumen/watt efficiency of LEDs, doubling occurring every 36 months. (Haitz's law 2007)

Quantitative data of the case

The databases used for this study were selected according to the Stages of Technology Growth and Sources of TLC data presented in Table 2. As such the Science Citation Index (SCI) was selected to represent fundamental research, Compendex to represent applied research, patents from the US Patent and Trademark Office to represent development, and Newspaper Abstracts Daily to represent application. In the context of this study, the Social impact of the technology has been left out of the study.

Table 2: Stages of Technology Growth and Sources of TLC data (Based on Martino, 1983; Martino, 2003)

Stages of Technology Growth	R&D stages	Typical sources of TLC data
Scientific Findings and Demonstration of laboratory feasibility	Basic Research	Science citation Index
Operating full-scale prototype or field trial	Applied Research	Engineering Index
Commercial introduction and/or operational use	Development	Patent databases
Widespread adoption / Proliferation and diffusion to other uses	Application	Newspaper Abstracts
Societal effect and/or significant economical involvement	Social Impacts	Business and Popular press

The following Table 3 shows the summary of result on the cumulative document frequency on white LEDs.

Table 3: Cumulative document frequency on white LEDs.

Year	*SCI*	*Compendex*	*Patents*	*News*
1991		1		
1992		1		
1993		1		
1994		2		
1995		2		
1996	1	3		
1997	7	6	2	5
1998	9	7	5	6
1999	17	10	15	15
2000	27	18	25	22
2001	39	38	37	41
2002	60	60	44	86
2003	87	92	67	144
2004	139	149	85	208
2005	205	229	108	285
2006	293	316	121	341
2007	414	417	128	410
2008	587	570	130	473
2009	823	764	130	565

The database where analyzed by using "*white led*", "*white leds*", "*white light emitting diode*" or "*white light emitting diodes*" as a search algorithm, This was, through a process of trial and error, seen as finding the relevant database entries. The first entries found in each of the databases were further checked by expert opinion to make sure that the starting point of each dataset was set correctly.

Results

The following Figure 1 summarizes the search results. This shows an early increase in Applied research, in Compendex, which is not supported by the theory of linear development (Järvenpää, Mäkinen and Seppänen 2011)

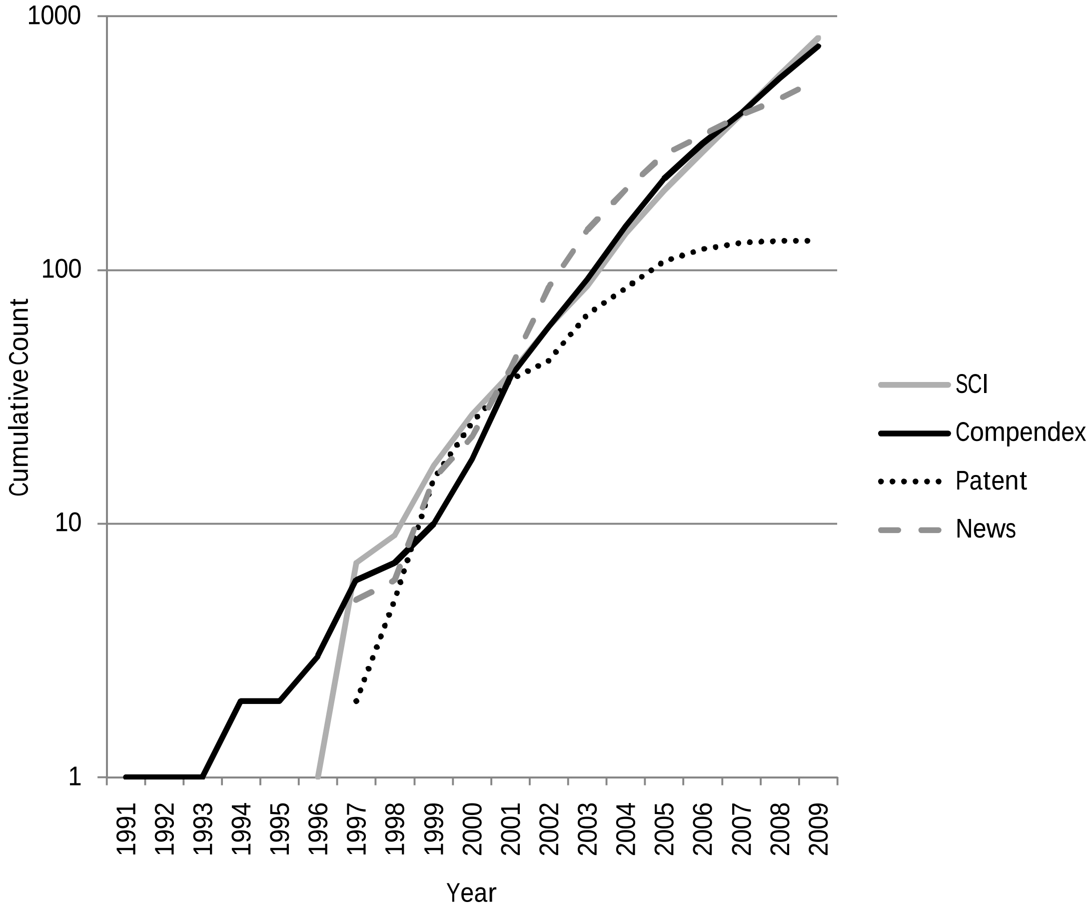

Figure 1: Summary of Table 3.

The historical data was transformed, with the equations in Table 1, to linear form. After which the upper bound of growth that would result in the highest fraction of the total variance of the dependent variable being explained by the model was selected. This is described by the coefficient determination, R^2. In Table 4 the linear regression of the indicators are shown.

Table 4: Upper bound and model fit based on R^2 values.

Model Fit		*SCI*	*Compendex*	*Patents*	*News*
Fisher-Pry	(R^2)	0.9750	0.9874	0.9874	0.9926
	Upper Bound	1148	2878	133	632
Gompertz	(R^2)	0.9904	0.9852	0.9828	0.9931
	Upper Bound	21144	$11*10^{14}$	154	1229

However, the indicator development forecasted by the highest R^2 does not seem plausible. By relying on the analysis, the described TLC of LEDs does not seem practical. In the graphical representations given as Figure 2 and Figure 3 LED development is described in normalized form throughout the TLC. The Fisher-Pry model would suggest basic research as lagging overall LED development by several years and that the first indicators, "development" and " application", would reach the upper bound of growth within a few years. This forecast would not seem plausible either by the order of development or by the upper bound of growth.

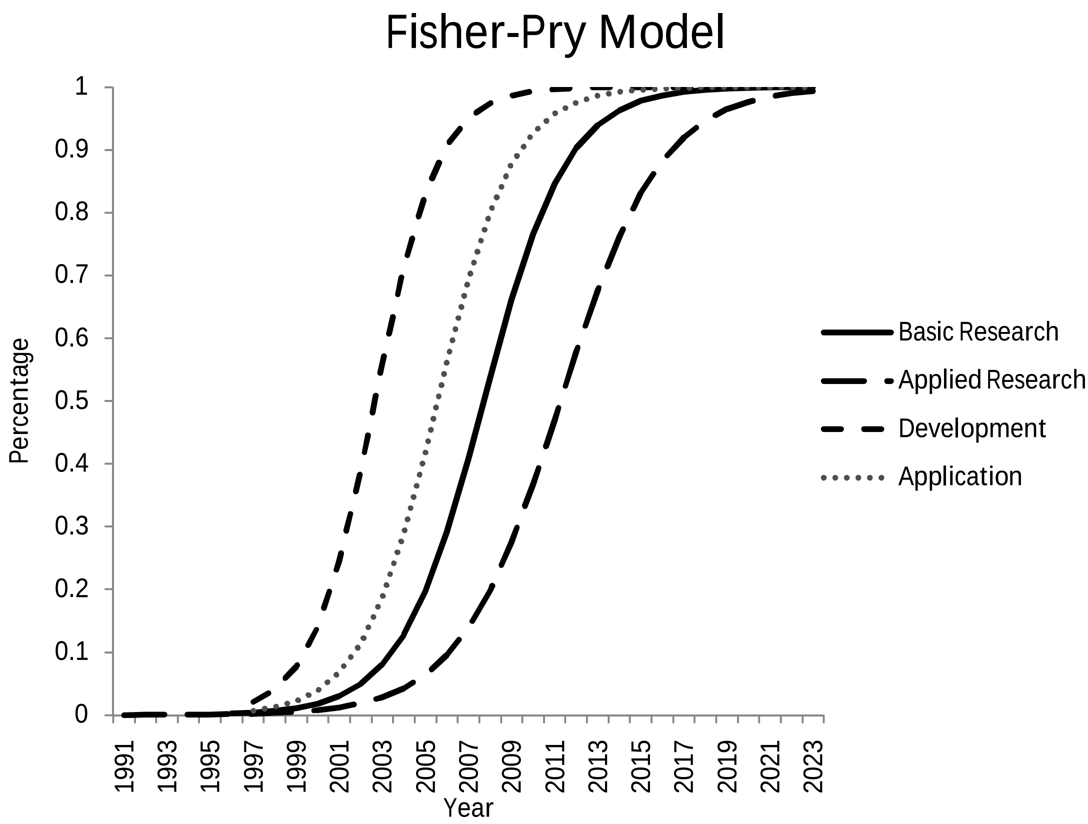

Figure 2: Summary of Fisher-Pry model fit from Table 4

In comparison, in the Gompertz model, the least squares model fit resulted in implausible upper bounds of growth for basic and applied research seen in Table 4, while retaining a similar development path for the two following indicators. These again do not seem practical either by the order of development or by the upper bound of growth.

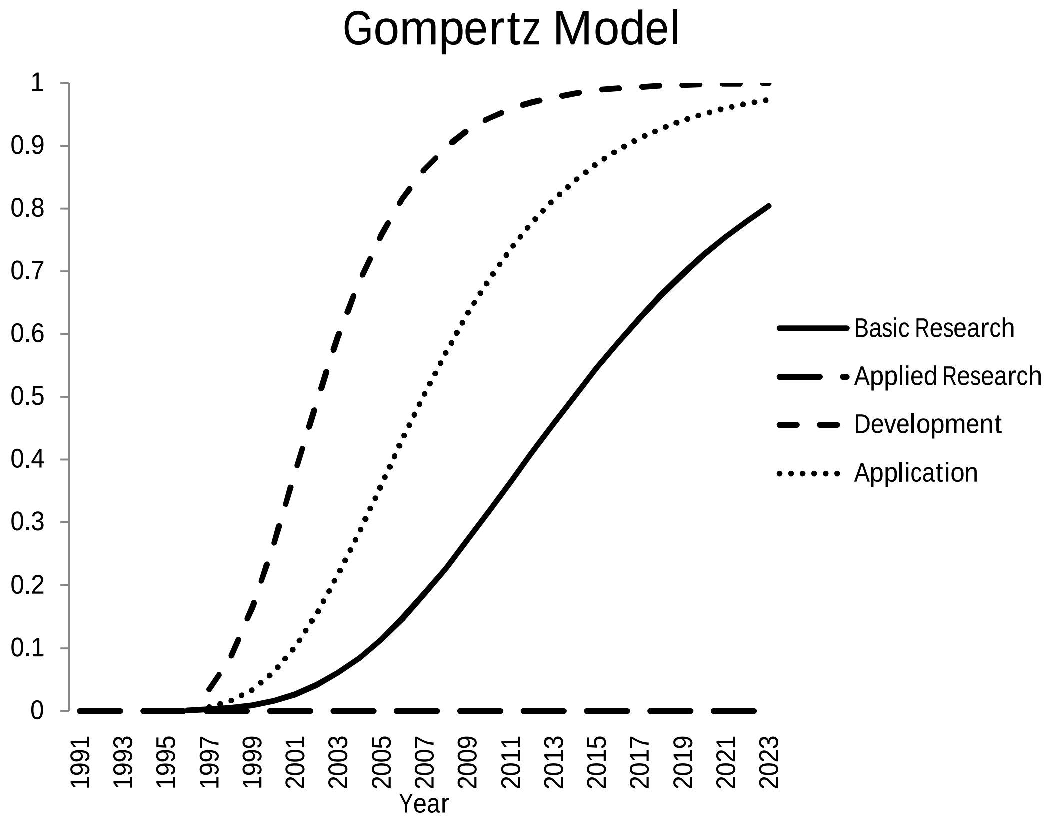

Figure 3: Summary of Gompertz model fit from Table 4

The data is further analyzed by Mean Average Percentage Error (MAPE) between the fitted value and historical data, as described in Young (1993). The upper bound of growth resulting in the smallest MAPE was selected to each of the R&D stages. This was done while accepting lower R^2 value of for the models, but by minimizing the MAPE for each of the datasets. Table 5 shows the upper bounds of growth resulted from the analysis as well as the MAPE values for the models.

Table 5: Upper bound and model fit based on MAPE.

Model Fit		*SCI*	*Compendex*	*Patent*	*News*
Fisher-Pry	MAPE	24,35%	20,59%	11,82%	9,962%
	Upper Bound	1387	2294	132	592
Gompertz	MAPE	17,16%	23,12%	7,0427%	12,94%
	Upper Bound	56621	$24*10^{15}$	160	1014

The results of the MAPE fitted forecast where extrapolated to the future and can be seen in normalized Figure 4 and Figure 5

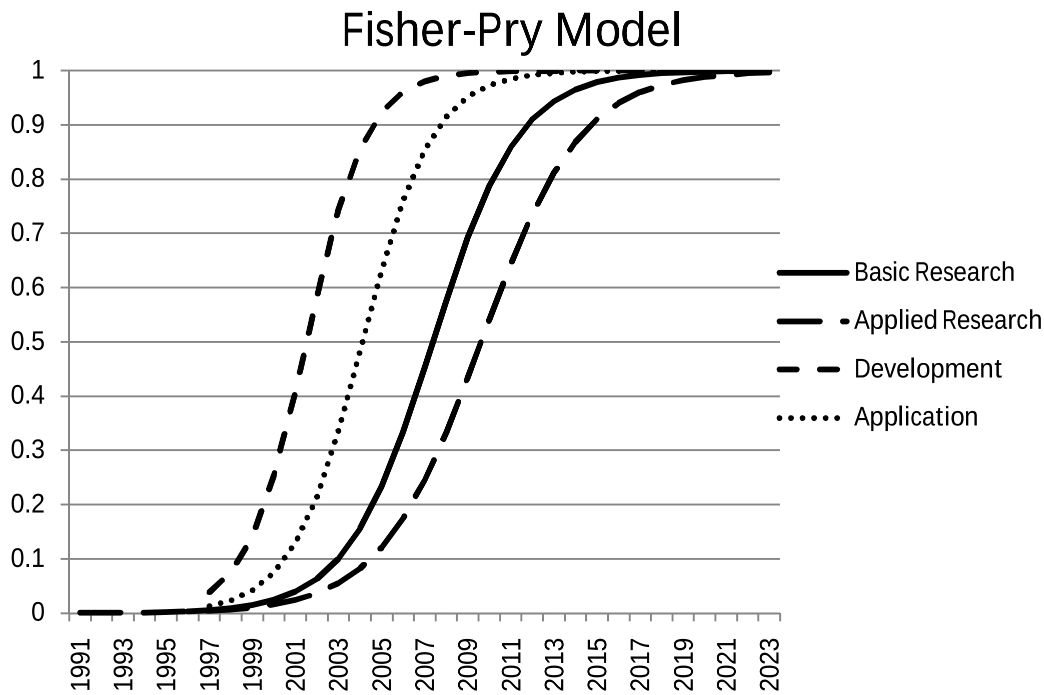

Figure 4: Summary of Fisher-Pry model fit from Table 5

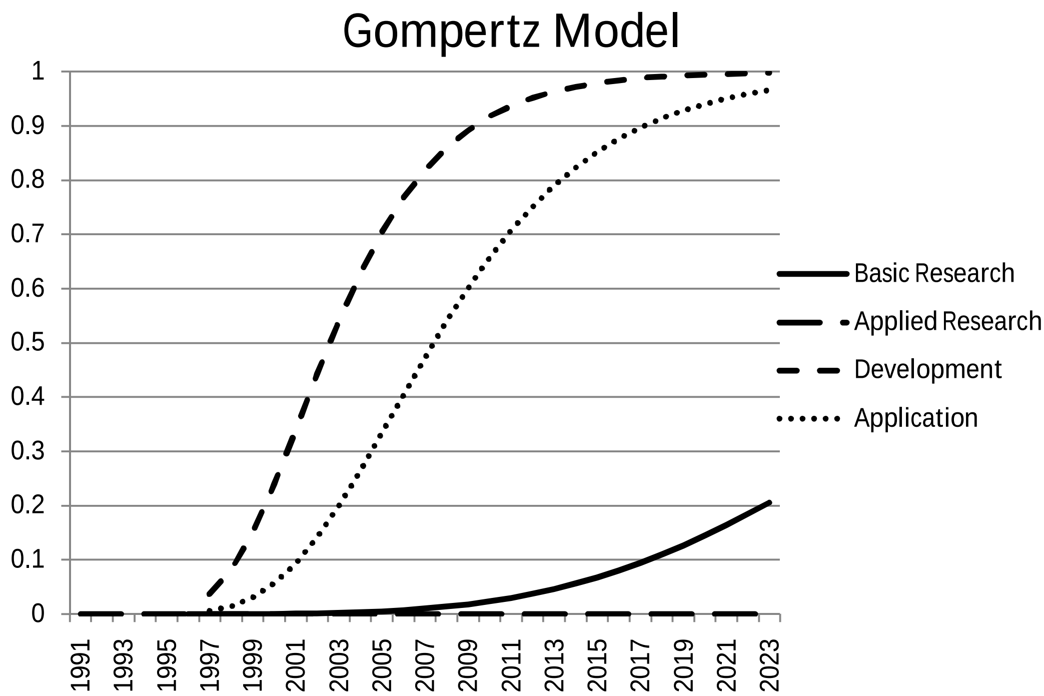

Figure 5: Summary of Gompertz model fit from Table 5

In Table 6 below summarizes how upper bounds vary depending on statistical fitting of the model and the used model. As we see, with Fisher-Pry the values of upper bounds are within the same range, but for Gompertz models, the values of upper bounds vary significantly. This underlines the effect of setting upper bound in the trend extrapolations.

Table 6 Summary of different upper bounds in above runs.

Model and run		*SCI*	*Compendex*	*Patent*	*News*
Fisher-Pry	R^2	1148	2878	133	632
	MAPE	1215	2878	131	678
Gompertz	R^2	21144	$11*10^{14}$	154	1229
	MAPE	2882	$24*10^{15}$	150	950

Conclusions

The analysis found that the trend extrapolations made modeled the developments with a good statistical fit. The model explained a significant portion of the variance in each of the datasets of quantitative data. In most cases, the R^2 value of the modeled datasets was over 0.9. When, however, analyzing the practical aspect of the trend extrapolations made, the study pointed out two factors affecting the practical analysis of the trend extrapolations made. First, the statistically fitted model lacked ability to produce a practically plausible model fit throughout the TLC. Second, the possibility to vary the upper bound of growth while still having a statistically good model was extensive.

The approach implicated that the use of trend extrapolations in quantitative data sets has challenges. Agreeing on a valid upper bound of growth is a significant factor affecting the validity of the model. Creating a practical context to the data is a significant factor in the researcher being able to validate trend extrapolation results. Furthermore, usually these types of trend extrapolations in technological context include fairly small data thus the validity of modeling can be questioned. This potential problem of small data sets and the effect of setting upper bound may lead the researcher out of the ballpark thus inducing wrong decisions. As future research, the results suggest further analysis on the context of trend extrapolations made. Context could be created by for example combining the results with the theory on TLCs and concrete technological development as seen in Figure 6.

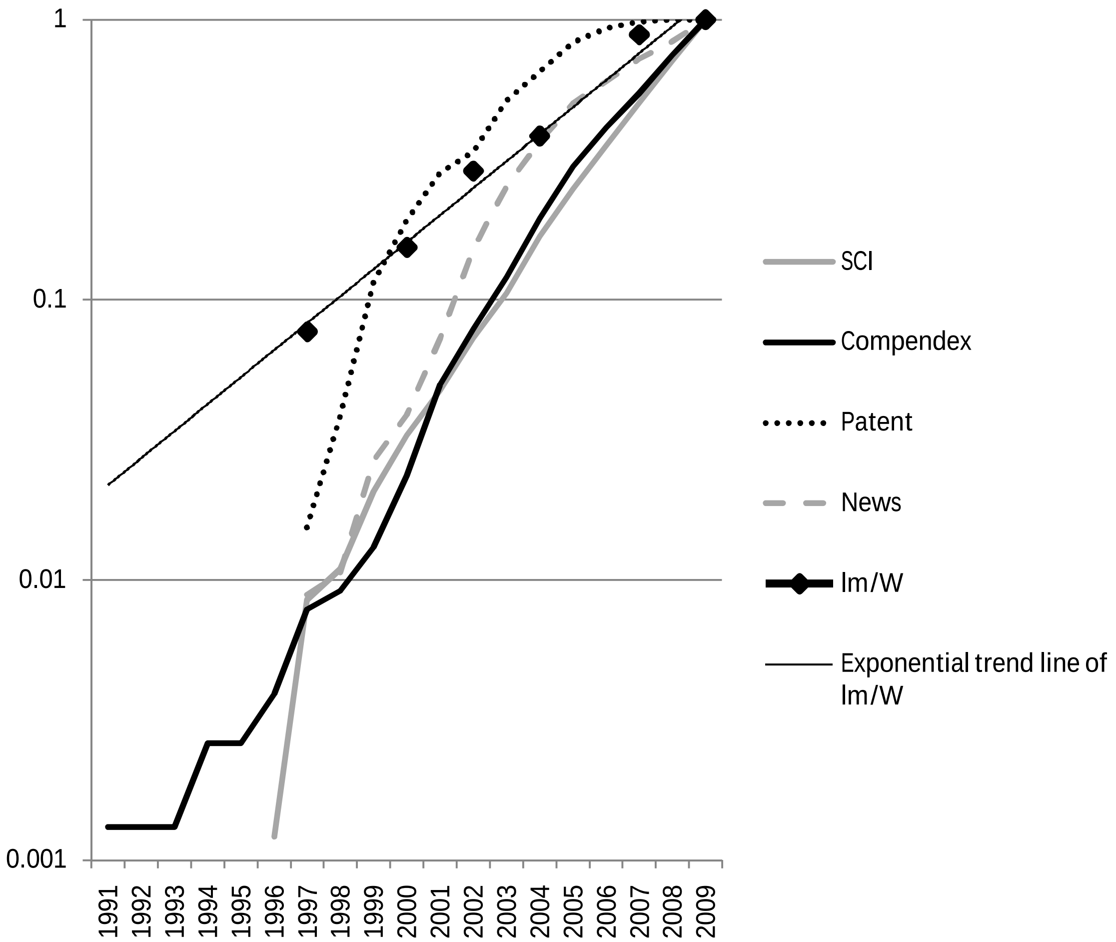

Figure 6 Figure 1 in the context of technology development. The lumen/watt efficiency development of white LED (Krames, et al. 2007, OSRAM 2009) has been included to the normalized data seen in Figure 1.

Further research on the interconnections between the actual technological development and bibliometric TLC indicators are needed. In Figure 6 this is made explicit by adding to the quantitative data extracted from the databases the trend line and data of actual white led lumen/watt development. As seen from the Figure 6 the bibliometric data, to some extent is similar to the actual development. However, if there is a significant correlation between the data is subject to further study.

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Publication V

Arho Suominen and Aulis Tuominen. The Acquisition of Emerging Direct Methanol Fuel Cell Technology by Industry. *In Proceedings of the IAMOT 2010 Conference,* Mar 2010.

International Association for Management of Technology
IAMOT 2010Proceedings

THE ACQUISITION OF EMERGING DIRECT METHANOL FUEL CELL TECHNOLOGY BY THE CONSUMER ELECTRONICS INDUSTRY

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This paper presents the Emerging Fuel Cell Technology Development efforts done in the University of Turku. The paper reports on patent analysis done to assess the adoption of Direct Methanol Fuel Cell Technology by industry. As a methodology the paper describes a patent database analysis combined with a historical analysis. A patent database was analyzed to assess the overall adoption of Fuel Cell technology and the differences in comparison to Direct Methanol Fuel Cell Technology. The industry with the most IPR related to Direct Methanol Fuel Cell technology were further analyzed by text mining

Keywords: Emerging Technology, Patent Analysis, Text Mining, Direct Methanol Fuel Cell

Introduction

Fuel cells have been seen as one of the most significant future energy technology. Different types of fuel cells (FCs) have been seen as feasible in different solutions ranging from large stationary solutions to small portable solutions. Technology transfer from research labs to industry has generated a growing market, with worldwide sales of US $ 387 million in 2006. The majority of the industry is focusing on larger systems, such as stationary systems and transport solutions. However, there is a significant portion of industry focusing on portable solutions. A good example of this being Toshiba. The aspiration of using FCs in portable applications is driven by the high power and lifetime requirements of portable systems, such as PDAs, mobile phones, and laptops. These requirements are hard to meet with conventional rechargeable batteries. This is due to their limited specific energy and operational lifecycle. Factors such as easy and fast recharging during operation also increase the competitiveness of FCs such as as Direct Methanol Fuel Cells (DMFCs). (Broussely & Archdale, 2004; Eckfeld et al., 2003; Dillon et al., 2004.)

The organizations putting emphasize on portable FC technology and in specific on DMFCs have made a strategic choice of applying FC technology to their business. This paper analyzes the section of industry focusing on DMFC technology. Patent analysis has been seen as a viable choice in this kind of analysis (Liu et al. 1997; Abraham et al. 2001) As proposed by Lee et al. (2009) a patent analysis can support the R&D roadmap in four sections: monitoring, collaboration, diversification and benchmarking. Lee et al. (2009) divide these in modules. The first module, the monitoring module, focuses on the relationships between key actors. The collaboration module supports the R&D phase of the technology roadmap by pointing out collaboration possibilities within the industry. The diversification module facilitates the search for future application areas. The final module, the benchmarking module, will show the technological assets and similarities found in a more mature industry.

In the case of FCs, which is a low maturity stage technology, the focus is put towards the monitoring module.
The methodology used in the paper analyzes patent data gathered from WIPO Patentscope and Espacenet databases. The analysis focused on DMFC technology and FC technology overall. The data was divided into crude data such as number of patents yearly and applicants. The most significant patent holders where thereafter linked with key demonstrational and commercialization efforts. These were analyzed with a text mining tool from the Fuel Cells Bulletin Journal series.

Direct Methanol Fuel Cell Technology

Overview

Environmental awareness and the need for new sources of energy have driven the development of FC technology. FCs are seen as being one of the new energy technologies, which will enable safe and environmentally friendly energy to be produced with an affordable price. FC is an electrochemical device that is able to produce electricity through a reaction between a fuel and an oxidant. The most significant difference with existing mature energy production technologies is the possibility to produce energy without moving parts in a single process. (Barbir, 2005.)
FC, as technology, is not new. The principle of FCs was already invented in 1838 by a German scientist Schönbein and thereafter proven by Sir William Robert Grove. For several decades the technology was not taken advantage of. Only decades later, partly due to the space programs, new interest in the possibilities of the technology has began to grow. Only more recently has research organizations and industry, in a large scale, started to recognize the possibilities of the technology. As seen from Figure 1, the number of journal papers related to FCs have been growing rapidly. This would arguable be seen as increased research interest.

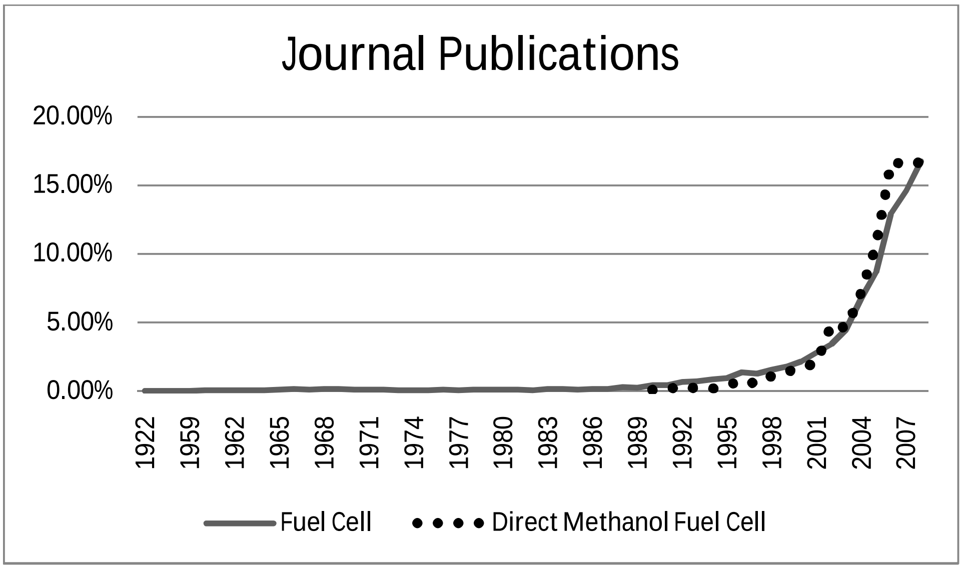

Figure 1: Yearly percentage of journal publications analyzed for FC and DMFC related publications. (Source: ISI Web of Science).

Through their versatility, FCs can be adopted to a variety of end-use applications. FCs range from small milliwatt scale systems to large stationary power plants. (Cropper et al., 2004). In smaller portable solutions, the technology driver is not the environmental friendliness of the end product. Portable FCs are mostly developed to meet the high power and lifetime demand of current and future portable devices. The increased energy need is seen as hard to meet with conventional rechargeable battery systems, due to their limitations in lifespan and specific energy (Broussely & Archdale, 2004; Eckfeld et al., 2003; Dillon et al., 2004). Even thought the existing lithium based energy sources enable energy densities up to 475 Wh L^{-1} and 220 Wh kg $^{-1}$ and while the technology is expected to develop in the growth path of 5 to 10 percent yearly, the development is expected to diminish in the near future due to physical constraints (Ryynänen & Tasa, 2005 cited in van der Voorta & Flipsen, 2006; Broussely & Archdale, 2006) In comparison, the theoretical energy density of DMFCs are near 5000 Wh/l from which the current practical energy density is in the range of 250 – 1000 Wh/l (Dyer, 2002; Flipsen, 2007)

Direct Methanol Fuel Cell Technology

FC technology can be divided into several sub-groups such as Solid Oxide (SOFC), Molten Carbonate (MCFC), Alkaline (AFC), Phosphoric Acid (PAFC), and Polymer Electrolyte Membrane (PEM) fuel cells. DMFC can be categorized as a PEM fuel cell. A DMFC produces energy in a reaction between methanol fuel and an oxidant. DMFCs can also be categorized as a Direct Fuel Cells (DFC), as it uses a fuel directly without a reforming process. For example Ethanol and Formic Acid based FCs can also be categorized as DFCs. The competitive advantage of FC based power systems, in portable systems in comparison to existing batteries, is the energy density of the fuels. These can be up to ten times higher than in rechargeable batteries. This is demonstrated by for example Sony's small DMFC system as well as Samsung's laptop with 10 hour operation (Fuel Cells Bulletin, 2004c; Fuel Cells Bulletin 2008c). DFCs also operate in near ambient temperatures and as such reduce the need for thermal management. With liquid fuels transport, storing, and filling is also easily arranged with existing technologies. (Qian et al. 2006.) Methanol is a viable choice among the other liquid fuels as it has good electrochemical activity and high energy density. Methanol as a fuel is easily produced from several sources, such as biomass and natural gas.

DMFCs have, however, several drawbacks as well. Most significantly system lifetime and cost are a problem for a DMFC system. DMFC lifetime is currently limited by methanol crossover through the membrane. Gurau & Smotkin (2002) and Heinzel & Barragan (1999) have analyzed methanol crossover during operation. Crossover is one of the most significant factors lowering the expected lifetime of a DMFC and as such lessening the applicability of the technology. Cost as a restriction comes from the materials cost and Balance of Plant (BoP) required to operate a fuel cell (Agnolucci, 2007).

FCs, in portable devices, are entering a highly matured market of providing energy to devices. Existing systems, most significantly lithium based battery power, set the bar for customer expectation on usability and lifetime of a system. FCs are seen as viable, if the energy consumption of a portable device exceeds the capabilities of a existing battery systems. The energy consumption of a specific service, such as communication in mobile phone, might have degreased. This is, however complemented by the added amount of services provided by portable devices such as PDAs and mobile phones. This development is easily explained by the predictions made by Motorola Labs in 2002. Pavio et al., (2002) argued that the yearly energy usage in a mobile phone would increase from 3500 Wh in 2000 to 10500 Wh+ in 2010.

In consumer electronics it's also important to notice that FCs or DMFCs are subsystems of a product. Although different structures of fuel cells have been studied (Qian et al., 2006), the system will most likely have some FC specific electronics embedded to the integrated application. The demonstrational products presented, are to some extent build on existing products. As such they use power systems designed for existing power sources. FC power source, as all other, are highly interdependent on the product the system is embedded to and as such will require a different system design than in existing solutions.

DMFC in consumer electronics are a replacement technology, as Hellman & van den Hoed (2007) have noted. Competing technologies will keep on setting the pace for consumer expectation on cost, performance and reliability. New technologies, such as DMFCs, can be seen as going through a Cycle referred as the Gartner Hype Cycle (Linden & Fenn, 2003). The Hype Cycle presents the path of new technologies to the market. In the cycle the technology is mapped through the attention it receives in different stages before it's established in the market. These stages can be divided to five sections seen in Figure 2. These are the technology trigger, inflated expectations, disillusionment, enlightenment, and productivity. In this the technology trigger is the significant factor or event facilitating the growth of attention the technology receives.

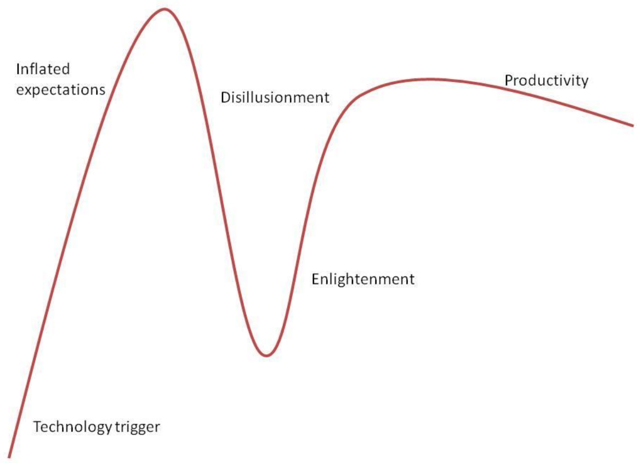

Figure 2: Gartner Hype Cycle.

In the case of fuel cells this could be argued to be the increased environmental awareness which has increased research funding through policy shifts. The increased attention sums up as inflated expectation. The emerging technology is seen as an almighty technology with endless possibilities. When the technology isn't able to meet the expectations the technology faces the disillusionment phase, where the technology, after disappointment, receives less attention. However if and when the true application of the technology is found the technology moves to the enlightenment faces. This is followed by sustainable growth and productivity.

Patent Analysis and Technology Management

Technology, as defined above, is created. This means that technology is not found in nature and can't be harvested as such. Technology is created and is a result of a process. This process creates artifacts that are used to augment, by enhancing or replacing, human ability. Technology Management (TM) can by this be understood as dealing with created artifacts that augment human capability. The growing number of technology increases the need to manage to totality of the technological world. (Van Wyk, 1988). In 1987 National Research Council (NRC) in the United States focused on the growing need of technology management. (NRC, 1987). NRC defined TM as "linking engineering, science, and management disciplines to plan, develop, and implement technological capabilities to shape and accomplish the strategic and operational objectives of an organization".
Phaal et al., (2004) divide TM activities to identification, selection, acquisition, exploitation and protection of technology. Similarly the NRC has further defined, while having a process view, TM as identification and evaluation of technology, management of R&D, integration of technology to the overall operations of the company, implementation of new technologies

and the management of obsolete/replacement of technology (NRC, 1987). In addition to the previously mentioned, TM has been analyzed by several scholars (Gregory, 1995; Levin & Barnard, 2008; Rush et al., 2007).

Cetindamar et al., (2009) have suggested that TM can be seen as a dynamic capability with six activities: identification, selection, acquisition, exploitation, protection and learning. Patent analysis can work as a tool to identify and select technology relevant to the company.

Patent analysis has been used for several purposes. These can be categorized as a macroeconomic and microeconomic view on patent analysis. A macroeconomic view can be found for example in the work of Hicks et al., (2001). They have analyzed the American innovation system and the changes happening in a national level. Large global scale surveys of a specific technology has also been made by Huang et al., (2003) and Huang et al., (2004) who have analyzed nanotechnology as a whole, largely to a research policy use. A macroeconomic use of patent analysis is also suggested by Grupp. In the work, Grupp (1994) suggests patent analysis in forming a picture of innovation dynamics in a country level.

A more microeconomics view on patent analysis and its applicability to a specific company is presented by Daim et al., (2006). They have used patent analysis to present scenario building for three emerging technologies. In addition Liu & Shyu (1997) have used patent analysis as a strategic planning tool. Similarly Lee et al. (2009) have also used patent analysis in strategy formulation. Although all of the work have a differing approach on the method, the end goal, a structured view on future technological opportunities by patent analysis, is a common similarity.

Methodology

The material for the study is based on evaluation of patent and historical data gathered from three sources. Patent data has been analyzed from the World Immaterial Property Rights Organizations (WIPO) Patentscope database and Espacenet database, which are openly available. The analysis uses the Fuel Cell Bulletin journal for textual analysis on industry development.

The selection on patent database has been made from several viable solutions. WIPO, United States Patent and Trademark (USPTO), or the European Patent Office Espacenet databases are feasible solutions. WIPO has set a goal on being a “world reference source for IP information and analysis” and as such was selected for the analysis. The results were also verified by analyzing DMFC related data from Espacenet database.

The analysis was done by a query design where in the first stage an overall query (Q1) with the search “fuel cell”, “direct methanol fuel cell” or DMFC in the title or abstract. The second query (Q2) only contained the terms “direct methanol fuel cell” or DMFC in the topic or abstract. Q2 was seen as putting focus purely on the DMFC technology development. This query design was seen as showing the differences between the general fuel cell technology development and with the more specialized DMFC development. Espacenet, which was used for verification, was only analyzed with Q2.

After the patent database analysis, the most significant IPR (Immaterial Property Right) holders were text mined from the Fuel Cells Bulletin Journal series. Fuel Cells Bulletin is a monthly newsletter reporting on the developments of the FC industry. The names of the most significant patent holders were text mined from the journal publications. By this, significant topics relating to the patent holders were indentified.

Results

The analysis focused on the number of patents applied yearly as well as to the applicants of the patents. Analysis on the number of patents applied is seen as demonstrating patenting activity. Applicants are seen as representing industry or individuals' actively gathering immaterial rights protection.

As can be seen from Figure 3 the increase in patenting activity is similar to the increase in article count. This suggests a rapid move from research to immaterial property rights protection.

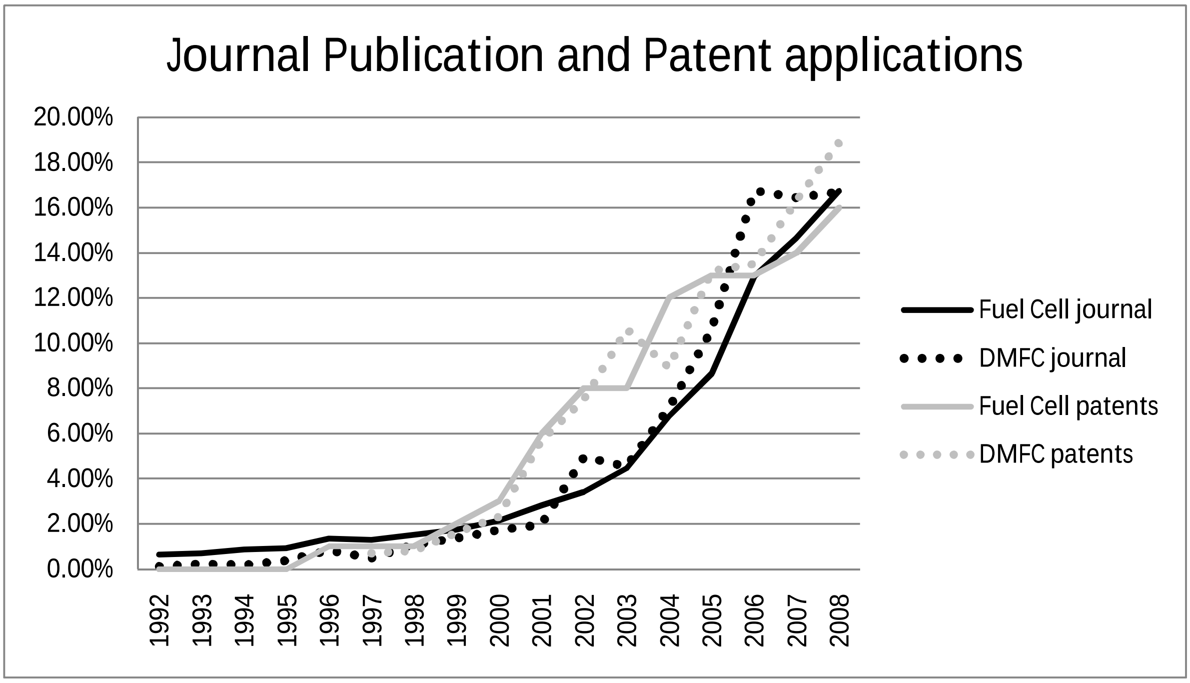

Figure 3: Yearly percentage of journal publications analyzed and patent applications for FC and DMFC related publications. (Source: ISI Web of Science and WIPO database).

It can been noted, that the number of patents applied is significantly lower than the published journal papers. As seen from Table 1, the number of patents in Q1 and Q2 increase in an almost similar rate, which is easily understandable as DMFC is one sub-section of FCs overall. In patent data DMFCs represent nearly 15 percent of the overall FC patents.

While analyzing the organizations actively patenting, showed in Table 2, we see Q1 and Q2 differing significantly. Q1 is represented by automotive companies, such as Toyota, Nissan Motor, Honda, General Motors and Daimler. These five automotive companies represent nearly 20 percent of all titles in Q1. In Q2 wide variety of different companies focusing on smaller fuel cells can be seen. This follows the theoretical arguments on DMFC usability on smaller systems, and as such is understandable. What are significant are the differences between finding from Espacenet and WIPO databases. WIPO database enables searches from the International Patent Applications, while Espacenet has a worldwide search that also searches for national patent applications.

Table 1.
Distribution of number of patents yearly from 1996-2008 (Source: WIPO database).

	Query 1		Query 2	
Year	NP	%	NP	%
2008	1040	16%	166	18.9 %
2007	858	14%	143	16.3 %
2006	832	13%	119	13.5 %
2005	796	13%	116	13.2 %
2004	726	12%	78	8.9 %
2003	536	8%	93	10.6 %
2002	505	8%	66	7.5 %
2001	356	6%	50	5.7 %
2000	215	3%	20	2.3 %
1999	140	2%	14	1.6 %
1998	82	1%	6	0.7 %
1997	77	1%	7	0.8 %
1996	51	1%	0	
1995	24	0%	0	
1994	27	0%	0	
1993	20	0%	0	
1992	21	0%	1	0.1 %

NP: number of patents

It can be seen that using different databases, or in this case limiting patent database searches to take account only WIPO database patents, gives an inadequate picture of the industry. Although, by using both of the databases, a wider picture of industry can be formed. As an example, BIC has been left out from the Espacent search, even thought it holds significant

IPR. It can be easily argued that the methodology does not identify the exact status or scope of specific company. The methodology used, enables industry analysis for strategy formulation. More precise competitor analysis would have to be done with a narrower search scope.

The companies identified by Q2 in Table 2 are from a wide variety of industry. Asian manufacturers such as Toshiba, Samsung, Hitachi and LG form a significant portion of the patens, even more significantly if only using the Espacenet Data. A significant difference, when comparing North American companies to Asian companies, is the scale and focus of the companies. Asian companies are large companies with several business sectors. While North American companies such as Ballard and MTI Microfuel cells are focused significantly on FC technology. Q2 also pointed out a significant amount of research organizations, such as Forschungszentrum Jülich Gmbh, University of California and Korea Institute of Science and Technology.

Table 2.
Distribution of patents by applicants
(Threshold in search =3)

Query 1			Query 2, WIPO			Query 2, Espacenet		
Applicant	NP	%	Applicant	NP	%	Applicant	NP	%
TOYOTA	583	9.2	SOCIETE BIC	34	3.9	TOSHIBA	57	7.3
NISSAN MOTOR	218	3.5	BALLARD POWER SYSTEMS INC.	32	3.6	SAMSUNG	45	5.8
SIEMENS	208	3.3	FORSCHUNGSZENTRUM JÜLICH GMBH	31	3.5	HITACHI LTD	28	3.6
UTC FUEL CELLS, L.L.C.	196	3.1	SIEMENS AKTIENGESELLSCHAFT	20	2.3	KANEKA CORP	24	3.1
MATSUSHITA ELECTRIC INDUSTRIAL CO. LTD.	176	2.8	COMMISSARIAT A L'ENERGIE ATOMIQUE	18	2.0	GS YUASA CORP	23	3.0
BALLARD GENERATION SYSTEMS INC.	154	2.4	TOSHIBA	18	2.0	FORSCHUNGSZENTRUM JUELICH GMBH	21	2.7
GENERAL MOTORS CORPORATION	154	2.4	THE GILLETTE COMPANY	18	2.0	UMICORE	16	2.1
HONDA	129	2.0	MTI MICROFUEL CELLS INC.	17	1.9	MOTOROLA INC	16	2.1
DAIMLER AG	117	1.9	ULTRACELL CORPORATION	17	1.9	SANYO ELECTRIC CO	16	2.1
FORSCHUNGSZENTRUM JÜLICH GMBH	113	1.8	UMICORE AG & CO. KG	17	1.9	UNIV CALIFORNIA	13	1.7
INTERNATIONAL FUEL CELLS CORPORATION	91	1.4	3M INNOVATIVE PROPERTIES COMPANY	15	1.7	MTI MICROFUEL CELLS INC	12	1.5
KABUSHIKI KAISHA TOSHIBA	89	1.4	MOTOROLA, INC.	15	1.7	MATSUSHITA ELECTRIC IND CO LTD	12	1.5
ENERDAY GMBH	65	1.0	THE REGENTS OF THE UNIVERSITY OF CALIFORNIA	14	1.6	SIEMENS AG	11	1.4
HYDROGENICS CORPORATION	60	1.0	E.I. DU PONT DE NEMOURS AND COMPANY	13	1.5	KOREA INST SCIENCE TECHNOLOGY	11	1.4
NEC CORPORATION	60	1.0	HYDROGENICS CORPORATION	13	1.5	KONICA MINOLTA HOLDINGS INC	10	1.3
3M INNOVATIVE PROPERTIES COMPANY	58	0.9	LG CHEM, LTD.	12	1.4	FUJI PHOTO FILM CO LTD	8	1.0
SONY CORPORATION	55	0.9	POLYFUEL, INC.	12	1.4	JSR CORP	8	1.0
FUELCELL ENERGY INC.	51	0.8	CABOT CORPORATION	10	1.1	SHINETSU CHEMICAL CO	8	1.0
MITSUBISHI CHEMICAL CORPORATION	49	0.8	CALIFORNIA INSTITUTE OF TECHNOLOGY	10	1.1	BALLARD POWER SYSTEMS	8	1.0
COMMISSARIAT A L'ENERGIE ATOMIQUE	48	0.8	BATTELLE MEMORIAL INSTITUTE	9	1.0	IND TECH RES INST	7	0.9

When text mining, from the Fuel Cells Bulletin, companies seen in the list of IPR holders, the analysis identified technology demonstrations and commercial activities seen in Figure 4. Companies such as MTI Micro Fuel Cell (MTI), which can be seen in Table 2, have started DMFC technology development in the early 2000 (Fuel Cells Bulletin, 2001). Based significantly on the technology of Los Alamos National Lab, MTI has been a significant developer of small portable solutions. Development has been partly driven by large military contracts with the US Marines and Army, which have focused on the development of handheld power devices based on DMFC technology (Fuel Cells Bulletin, 2004 a; Fuel Cells Bulletin, 2004 b). MTI has since gone to develop its own DMFC based systems as well as manufacturing prototypes for Samsung (Fuel Cells Bulletin 2007 a). MTI has also demonstrated a GPS system with a FC system integrated to the product. This has resulted up to 60 hours of continuous operation. (Fuel Cells Bulletin, 2008 a)

In larger systems, early enthusiasm on finding the suitable application to take advantage of the technology can be seen for example in the Japanese based Yuasa corporation, which published its DMFC technology based power production system in 2002 (Fuel Cells Bulletin, 2002 a). Yuasa, which can also be seen in Table 2, had the ambitious goal of commercialization of its technology by 2003. At the same time a US based Lynntech delivered a self-contained DMFC power production system to the US Army (Fuel Cells Bulletin, 2002 b). Both of these systems were designed for larger applications, Yuasa's system weighing from 25 to 60 kg. In the range of larger systems, such as Yuasa's and Lynntech's, the German based Smart Fuel Cell (SFC) has been able to commercially manufacture its EFOY system. Offering products to a small market, SFC has been able to sell its product. SFC manufactures a portable energy source for military systems and recreational vehicles (Fuel Cells Bulletin, 2003 a; Fuel Cells Bulletin 2007 b). SFC has been successful in growing in a specific market by attending to the consumer base in recreational vehicles (Fuel Cells Bulletin 2008b).

Early development has also been taken in Samsung, which has carried out research in both applications as well as in fundamental technology. Samsung, which has a significant patent portfolio, reached excellent power densities in a very early stage. (Fuel Cells Bulletin, 2002 c). Similarly to Samsung, the Japanese industry has also focused on small DMFCs and consumer electronics applications. NEC co-operated with Japanese research organizations in 2001 in the development of a micro fuel cell. (Fuel Cells Bulletin, 2002 c) Similarly to NEC and Samsung, several large companies have focused on DMFCs at an early stage. This has resulted in several consumer electronics demonstrators, most significantly in laptops. For example, Samsung demonstrated a laptop working with a FC power system that had the operational time of 10 hours (Fuel Cells Bulletin, 2004c). Several other companies such as Fujitsu, IBM, LG, Motorola, NTT, Sanyo, Sony, Casio, Polyfuel and Toshiba have also presented FC powered laptop prototypes. (Wee, 2007, Fuel Cells Bulletin, 2002 c, Fuel Cells Bulletin 2003 b.) Several of these companies can also be found in the most list of most patent application seen in Table 2. Although, many of those presenting prototypes don't hold a significant amount of IPR.

Many of the companies, similarly to Yuasa, had high expectations on commercialization. Toshiba suggested that it would present a commercialize fuel cell system in 2005 (Fuel Cells Bulletin 2003 c). Samsung claimed to be ready for commercialization with a laptop docking station by the end of 2007 (Fuel Cells Bulletin, 2007c). Several scholars (Rashidi et al. 2009; Wee, 2007) have analyzed the cost of using a fuel cell powered device in comparison to battery based systems. They have found that in an optimal situation a DMFC power source would be more cost-efficient after a year of use. However as Agnolucci (2007) has pointed out consumers are more interested in the physical size and weight of the system than its cost-efficiency. Subsequently the market is still waiting for the competitive DMFC application.

Mobile phones have been suggested to be this competitive application. These possibilities have been presented for example by Toshiba, and at an early stage by start-ups such as Manhattan Scientifics. (Fuel Cells Bulletin, 2004 d; Fuel Cells Bulletin, 2002 c) Similarly to laptops the cost-efficiency of DMFC systems isn't a problem (Rashidi et al. 2009). The development of the DMFC market in mobile devices is dictated by the development of lithium batteries and innovations making devices more energy efficient (Agnolucci, 2007). Companies, such as Sony, can be seen as betting on the possibility that the energy demand of a portable device will exceed the currently available technology. Sony has been for several years developing its system. Trying to meet the growing power need of a cell phone, Sony claims that its system enables a state-of-the-art cell phone to be used for watching a TV broadcast for 14 hours with only 10 ml of methanol. (Fuel Cells Bulletin, 2008c). However Integrated commercial DMFC systems have not been available. It seems more likely that a mobile phone or portable device charger would be the application enabling sustainable growth. In this product range several companies have demonstrated future products. High expectations have led to several promised market launches, such as Hitachi's small DMFC system, in this product range as well. Hitachi was expected to commercialize a small DMFC by the end of 2007, having the manufacturing capability 2000-3000 units yearly (Fuel Cells Bulletin, 2007d). However, Toshiba was the first to present a commercial DMFC based mobile charger (Fuel Cells Bulletin, 2009).

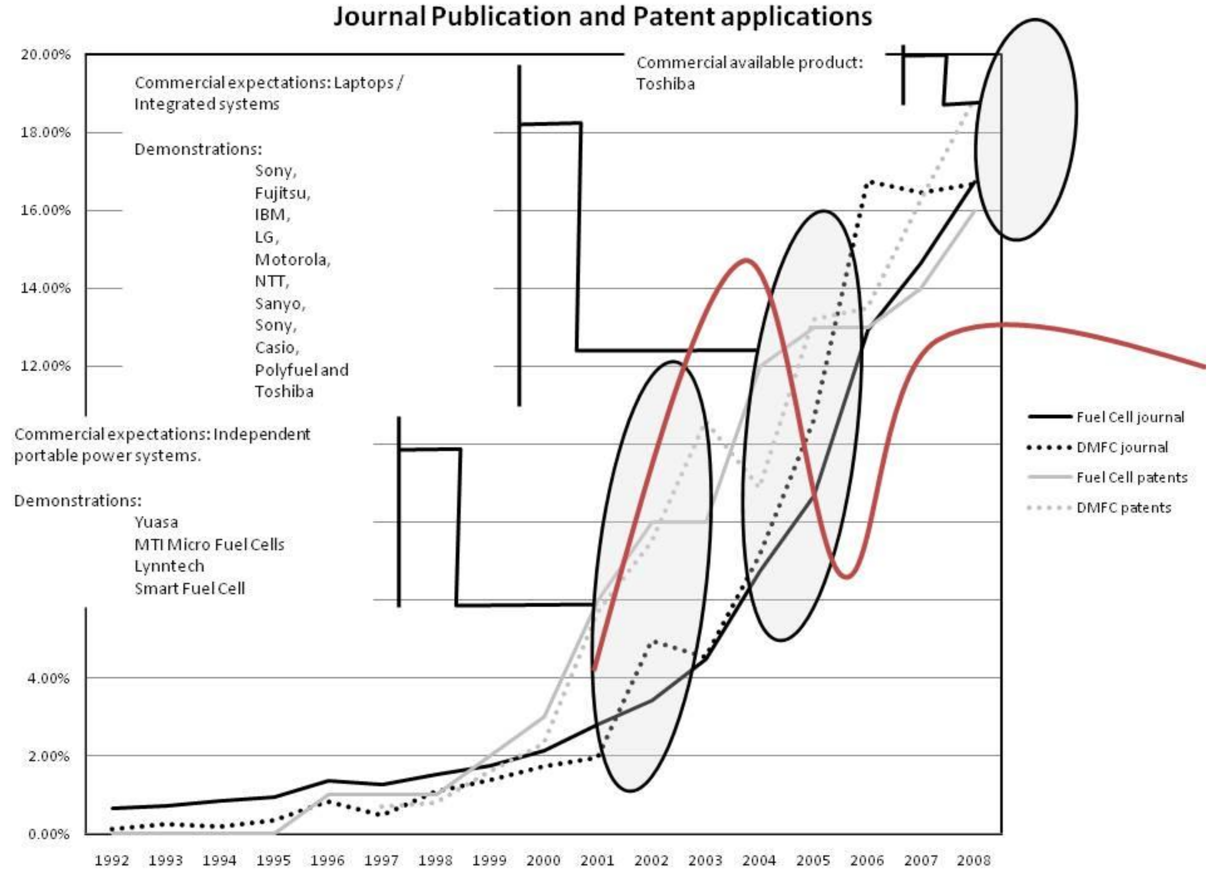

Figure 4: Found commercial expectation areas and market ready products drawn with the Gartner Hype Cycle over database values

If analyzed in relation to the Gartner's Hype Cycle portable fuel cell technology can be seen as needing the application which would enable stable growth. It could be argued that the DMFC technology is either at the peak of expectation or going strong on the slope of disillusionment. Looking at the Gartner Hype Cycle, we can see several anticipated applications of portable FCs, such as the Yuasa power system and laptop power systems from several companies, not leading up to a sustainable market. The market is still waiting for the competitive application of DMFCs.

Conclusions

The analysis found a strong increase in DMFC related patents in a timeframe on ten years. In the work done, DMFC technology was seen as being extensively patented by large Asian companies. The patents can be seen as leading to demonstration of the technology, but largely commercial product are seen as missing.

The approach was seen as facilitating the discovery of knowledge that can be used to monitor the acquisition of new technology by industry. This is seen as producing knowledge on the increased technological capabilities in a specific industry. Competitor identification is also seen as feasible by the analysis. Although a more specific analysis of competitors should be done by different methods. In the case of DMFCs, the work enabled further understanding on the most significant industry drivers pushing the technology towards the commercial market.

Acknowledgements

Researchers acknowledge the funding given by TEKES (The Finnish Funding Agency for Technology andInnovation) and industry partners.

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ISBN 978-952-12-2647-2
ISSN 1239-1883

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