

Research Paper

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

Arho Suominen* and Aulis Tuominen**

* Department of Information Technology, University of Turku, 20014 University of Turku, Finland, arho.suominen@utu.fi

** Department of Information Technology, University of Turku, 20014 University of Turku, Finland, aulis.tuominen@utu.fi

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 deve-

lopment 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 life-cycle 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 though 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 Bretzman and Moguee (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 cell technology

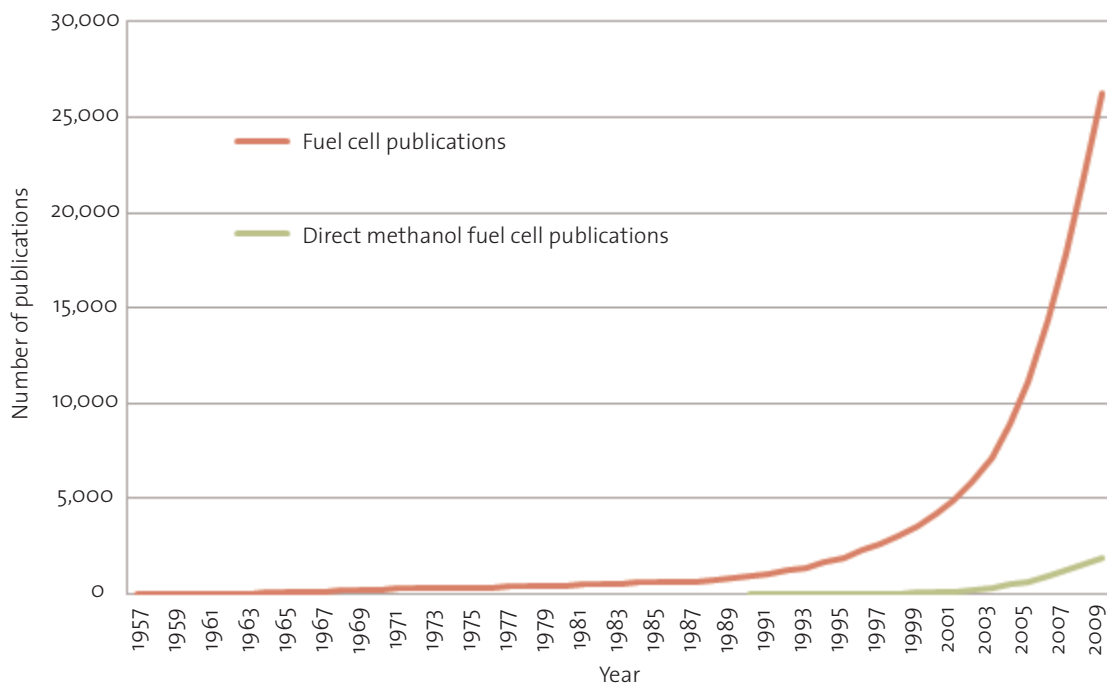
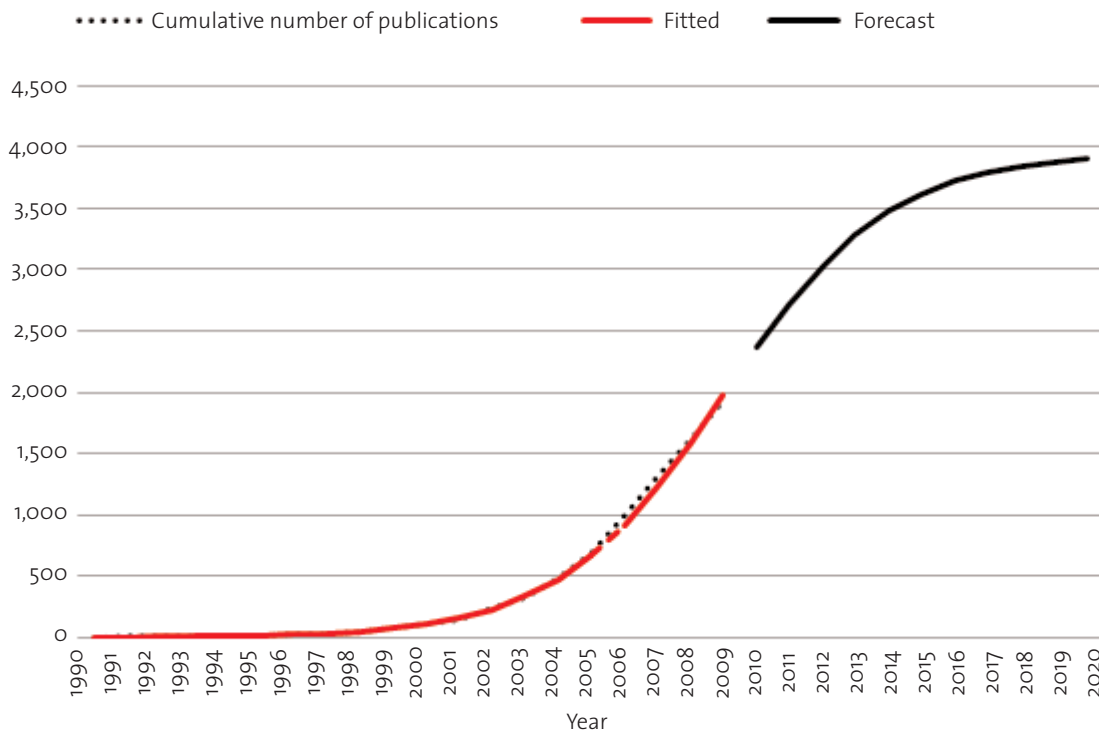


Figure 2 Cumulative journal and conference publications and trend extrapolation of Direct Methanol Fuel Cell technology



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 University 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 identified. 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

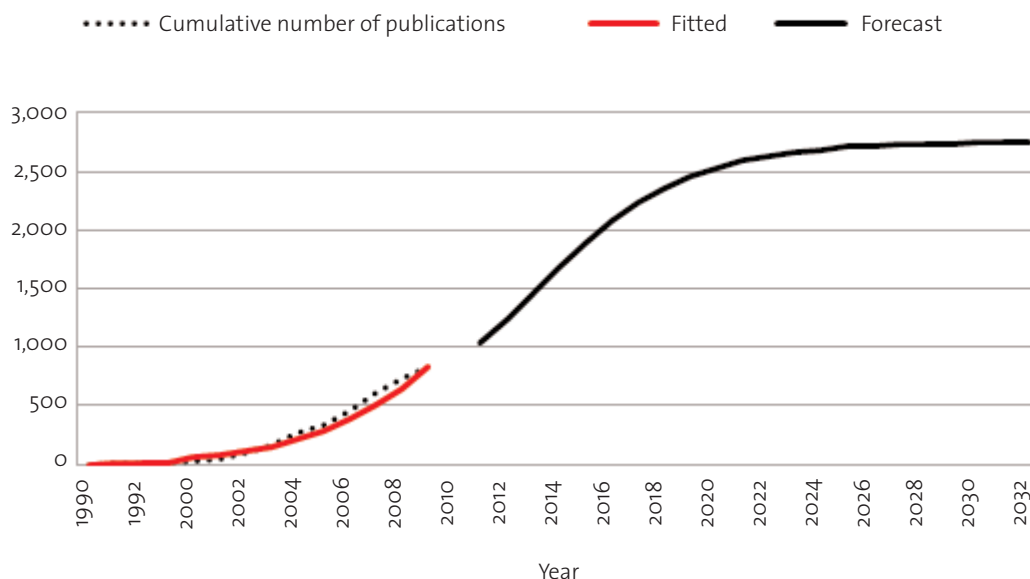
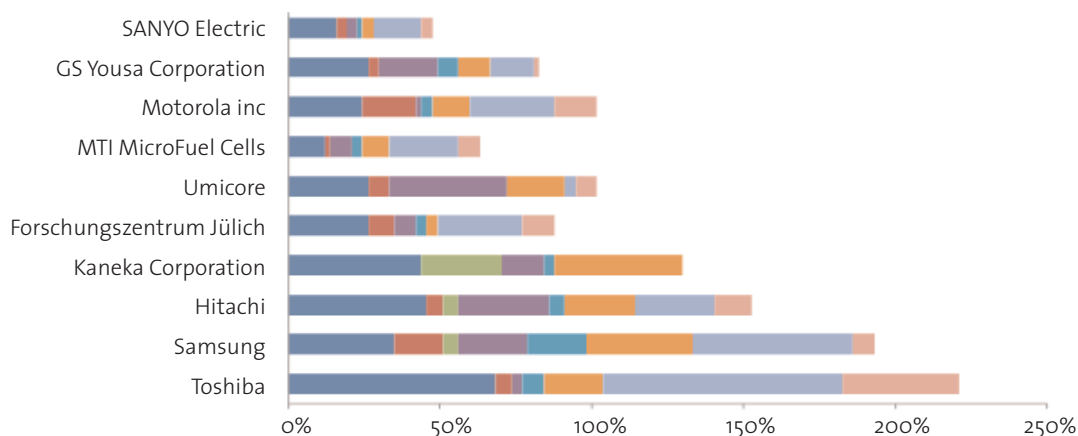


Table 2 Ten most frequent Direct Methanol Fuel Cell patent applicants. (Based on the Espacenet database)

	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.

- Fuel cells with solid electrolytes
- Grouping of fuel cells into batteries, e.g. modules
- Conductors or conductive bodies
- Electrodes
- Combination of fuel cell with means of production of reactants or for treatment of residues
- Details of non-active parts
- Auxiliary arrangements of processes, e.g. for control of pressure, for circulation of fluids
- Fuel cells; Manufacture thereof



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 fuelling 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 MTI's 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.

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