ANALYSIS OF ISSUES AND TRENDS IN THE GROWTH OF FUEL CELL FIRMS

by

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MS Aerospace Engineering, Indian Institute of Science at Bangalore, India, 1990

Submitted to the Sloan School of Management in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

Recent scientific progress has shown significant signs that fuel cells will become a tremendous and significant part of distributed energy markets in the future. Fuel Cell technology though first discovered in late 1830s by Sir William Grove, a Welsh judge and scientist only took off when NASA first introduced them in the Gemini space program in 1960s. Technology evolution and the need for a clean energy source for the space program caused the renewed interest in Fuel Cells. A significant amount of progress and numerous investments have been made securing a future for Fuel Cells. The question that remains is not if Fuel Cells will develop into an industry, but when might it evolve and deliver on the promises so intrepidly set forth by researchers, corporations, and investors. The question has been debated many times over in the popular press. For certain, no one is exactly sure what 'when' really means. What this thesis is more interested in is the "how". How will Fuel Cells technology and markets evolve? What factors will determine the industry structure that will influence the development of this industry? How large can we expect this industry to grow? What will be the key drivers for growth? How will different members of this industry facilitate the development of this technology? What form will the industry take? What are some of the current challenges facing the fuel cell manufacturing companies in their growth?

This Thesis investigates the formation and growth of Fuel Cell firms in Massachusetts, New York and Connecticut (within 150 miles of Boston) and the current issues facing the upper Management / Founders of these companies. By studying the key factors and developments in these industries different lessons and patterns can be extrapolated which may help answer some of the burning questions surrounding fuel cell industry evolution and where they are on the technology S curve. The basic framework used in this study is taken from the paper written by Gransey to analyze High-tech firms' growth. Eight firms were interviewed using a questionnaire format developed earlier by Prof Elicia Maine to study the materials industry growth.

The results of this analysis do indeed conclude that the firms felt that fuel cell is a great product, but it has limitations. It is impossible at this point to beat the grid in cost or reliability with a single piece of equipment- the grid has multiple redundant generating devices and is virtually free. The value of a fuel cell is the ability to have much higher power quality at your location to increase your grid reliability an additional 9 times. It is currently expensive to do this, but no other technology has this capability. Several companies have been formed with lot of optimism and potential for a huge payoff. People are less likely to share ideas in this industry compared to other industries. Secrecy is the norm in this industry and they rely on the patent protection early

on and seem to have lot of interactions with the local lawyers for IP filing and protection. Most of the firms did not participate in local industry organizations for the fear of exposing their perceived advantage. Currently fuel cell firms are facing economic challenges due to the downturn in the economy which in turn resulted in the slow down in fuel cell technology research investments. Also as the company grows they are realizing that the market risk is higher than what they have anticipated when they started. This may have an interesting consequence related to the sales and marketing strategy of these companies. Risk is still high, less technology risk than economic and market risk.

Thesis Supervisor: Stephen R. Connors
Title: Director, Analysis Group Regional Electricity Alternatives (AGREA)

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Acknowledgement

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I would like to thank Roberto Cordaro (Nuvera fuel cells), Michael Hsu (ZTek), Radha Jalan (Electrochem), Gary Mook (Acumentrics), Paul Osenar (Protonex), Scott Rackey (CellTech Power), Roger Saillant (Plug Power), Walter (Chip) Schroeder (Proton Energy Systems) for participating in my research and providing inputs without which this research would not have been possible.

CHAPTER 1

INTRODUCTION:

Throughout the history of the US, new enterprises have been important sources of technological innovation and business development. The formation and growth of new enterprises has been studied extensively in various industries. This thesis is focused on investigating enterprises in the emerging area of Fuel Cells.

Unlike in the Clay Christensen book on 'Disruptive Technologies' where he describes that almost all disruptive technologies start with a product which is inferior in performance and low cost compared to the technology it is going to displace, Fuel Cells may not strictly fall under this definition because, to start with, Fuel Cells are more expensive and in certain performance metrics better than the existing distributed energy sources or grid electricity. Under these circumstances can the industry still evolve and take off? If so, does it need new business models which are different from the traditional industry structure that exists now? Is there something unique to this industry that will aid or prevent it from taking off?

The present research involves identification of a sample of eight Fuel Cell manufacturing firms and conduct interviews with the top management to understand the growth of their company and the issues facing the industry. A questionnaire, which is the focus of each interview, has been adapted from a similar study done earlier on a different industry by Prof. Elicia Maine of Simon Fraser University. It elicits information on the formation and growth of the enterprise in the following categories: the Entrepreneur's background, local influence on growth, growth models for these new technology based firms, firm's growth history, Intellectual property protection and supplementary section dealing with the future trends. The results of the questionnaire are analyzed in an effort to discover success factors in the growth of the Fuel Cell industry.

MOTIVATION:

There are few examples of successful technological innovations that do not build on some predecessor market and technology – although the source market and technology are often quite distinct from one another. The automobile built on the steam engine and the horse and buggy, the telephone built on the telegraph, which built on the postal service. The personal computer replaced the word processor, which replaced the typewriter. The Edison light emulated and replaced gas lamps and candles. New technologies are typically brought to market emulating existing products and services in order to capture the imagination and attention of consumers. The emulated market or industry may see its absolute demise only if the new technology can best the old in most every salient performance metric at a better price, and if it is truly innovative it can eventually replace the old paradigm with an entirely new, hopefully more expansive, one. For example, many of us first used a PC primarily to do word processing, which it does better than its predecessors, but the PC would hardly be described as just a word processor today. It was this dynamic that had motivated me to take on this topic for my thesis, to further understand the technology, which I was quite familiar with, in the broader context of history and the present industry wide dynamics, with which I was not.

My curiosity also stems from the need to understand how the new technologies get adapted and how the early stages of evolution of a new industry is shaped by the players in the industry. This study will shed some light on the different possibilities in the industry direction and an understanding of some of the challenges facing Fuel Cell manufacturing companies.

OBJECTIVES

There are several objectives to be met in the course of this research. The primary objective is to expose the author to a series of enterprises and entrepreneurs that deal routinely with the business and management issues that have been raised in the course of study at the MIT-Sloan School. The comprehensive nature of the questionnaire allows the interviewer to review most of the major business issues that each entrepreneur has faced.

The study is focused on the Fuel Cell industry in an effort to expand on the author's experience in this industry and to investigate the role of new enterprises in relation to other efforts (by government, by established industry for complementary innovations, and by customers) in this emerging technology.

There is a great opportunity for innovation within this changing industry; thus, it provides a good framework for analyzing the sources and diffusion patterns of innovations developed by these new enterprises. I would start with describing the major trends affecting the energy industry in general and a brief outline about the distributed generation before analyzing the growth of Fuel Cell firms.

CHAPTER 2

INTRODUCTION:

I would like to start with the fact that the lack of access to electricity is a key factor in perpetuating poverty around the world. Conversely, access to energy means more economic opportunity. In South Africa, for example, for every 100 households electrified, 10 to 20 new businesses are created[1]. Electricity frees human labor from day-to-day survival tasks.

MAJOR TRENDS AFFECTING THE ENERGY INDUSTRY:

Ever since Colonel Drake drilled the first true oil well in the state of Pennsylvania in 1859, the ability of oil and natural gas to power electric generation plants, transportation and industry has created both immense economic advances and significant controversy. Many times it has been assumed that the world would quickly run out of oil. In 1939, and again in 1951, the U.S. Department of the Interior warned that all the world's oil reserves totaled only enough to fuel the Earth's nations for about 13 years. In fact, rather than becoming scarcer over time, energy has become much more plentiful. Throughout the history of the energy industry, prices have become lower and lower on an inflation-adjusted basis, while a combination of advancing technologies, determined scientists, exploration firms and utility companies have exponentially expanded the total amount of energy and reserves available for consumption.

In 1892, Thomas Alva Edison established the Pearl Street Station in New York City – the world's first central electric power station. Today, America is the world's great energy hog. During 2000 alone, energy consumers in the U.S. spent over $300 billion on electricity and natural gas bills, about one-half of which was for commercial and industrial use. Hundreds of billions more was spent on fuel used by automobiles, trucks, trains and aircraft. There is no end in sight to the appetite for power and fuel. In contrast, as much as one-third of the world's population either has no access to, or cannot afford, a steady supply of electricity.

Among the major trends shaping the energy industry today are the following:
1) Deregulation of the electric power industry.
2) Continuing global dominance of multi-national oil companies
3) Rapid advances in technology, leading to declining costs for oil and natural gas exploration and production.
4) While energy research & development is lagging, venture capital is slowly nurturing new technologies.
5) Extension of offshore drilling into extreme water depths.
6) Mergers and consolidation.
7) OPEC vs. the global low commodity price environment.
8) Rising demand, new methods and natural gas power growth at electric utilities.
9) In the U.S., a rapidly growing reliance on imported oil to serve growing consumption.
10) Conservation and alternative energy sources are back.
11) Tight energy markets and high demand for investments.
12) Exponential growth in energy trading via e-commerce.

[1] Jeremy Rifkin.; "Thinking Big: The forever fuel"; Boston Sunday Globe; D12 February 23, 2003.

13) Superconductivity comes of age.
14) The industry takes a second look at nuclear power.
The present study is focused on alternative energy sources in the distributed generation. More narrowly the study will be focused on Fuel Cell industry, its growth and trends.

DISTRIBUTED GENERATION OVERVIEW:

As the electric utility industry continues to restructure, driven both by rapidly evolving regulatory environments and by market forces, the emergence of a number of new generation technologies also profoundly influences the industry's outlook. While it is certainly true that government public policies and regulations have played a major role in the rapidly growing rate at which distributed generation is penetrating the market, it is also the case that a number of technologies have reached a development stage allowing for large-scale implementation within existing electric utility systems.

Since the beginning of the twentieth century, the backbone of the electric power industry structure has been large utilities operating within well-defined geographic territories and within local market monopolies under the scrutiny of various regulatory bodies. Traditionally, these utilities own the generation, transmission and distribution facilities within their assigned service territories; they finance the construction of these facilities and then incorporate the related capital costs in their rate structure which is subsequently approved by the relevant regulatory bodies. The technologies deployed and the siting of the new facilities is generally also subject to regulatory approval.

Three major types of power plants have been constructed primarily:
1) Hydro, either run-of-the-river facilities or various types of dams.
2) Thermal, using fossil fuel either coal, oil, or gas.
3) Nuclear (Thermal using nuclear fuel).
Until the end of the twentieth century, other generation technologies only had an incidental impact. The table below shows the installed capacities on a worldwide basis at the end of the twentieth century.

Table 1: Worldwide installed capacity (GW) by 1 January 2000.

(Source: Energy Information Administration)

Region	Thermal	Hydro	Nuclear	Other/Renew	Total
North America	642	176	109	18	945
Central & South America	64	112	2	3	181
Western Europe	353	142	128	10	633
Eastern Europe & Former USSR	298	80	48	0	426
Middle East	94	4	0	0	98
Africa	73	20	2	0	95
Asia and Oceania	651	160	69	4	884
Total	2,175	694	358	35	3,262
Percentage	66.6	21.3	11.0	1.1	100

As we look into the future, all three technologies mentioned above have their own set of problems associated with them.

Hydro: Given their friendly (though many might argue against it) environmental impact, hydro power plants are most often the preferred generation technology wherever and whenever feasible. However, the identification of feasible new sites in highly industrialized countries is becoming increasingly difficult. In highly developed countries, where the cost-attractive traditional hydro facility sites have been almost entirely built, some power plants could be, and are, reconfigured to become pumped-storage facilities. On the other hand, while hydro electric power production is saturating within industrialized countries, it represents very significant development opportunities in several developing regions of the world. While hydro power plants do not create any pollution related to their daily operation, they do bring significant environmental and often societal upheaval when they are constructed. Recently completed facilities or on-going construction projects in South America and Asia have been, and remain, at the center of controversies that go far beyond the national boundaries of their home nations.

Thermal: Even though several pollution-abatement technologies are being successfully implemented, often at significant capital and operational costs, fossil fuel thermal power plants bring operating pollution problems that are becoming increasingly difficult to ignore. The emergence of a broad array of "green power" marketing initiatives provides yet another indication of the growing concern regarding air pollution. While some parts of the world have significant coal reserves, a growing concern is the depletion of the world's increasingly scarce oil and gas reserves for the purpose of electricity production. Future generations will most probably need our remaining carbon resources to fulfill materials production requirements as opposed to as raw energy source.

Nuclear: Except for a few economically emerging regions of the world, it is safe to observe that nuclear power production, using existing technologies, will decrease during the coming decades as old plants are retired and are not being replaced. Several European countries, such as Germany and Sweden, have enacted laws to accelerate the decommissioning of existing nuclear power plants. However, emerging technologies, such as the pebble bed technology, which allow for a highly standardized manufacturing of the power plants with modular installed capacities, may revive the nuclear power industry as will most probably be required within any generation mix that is free of fossil fuels.

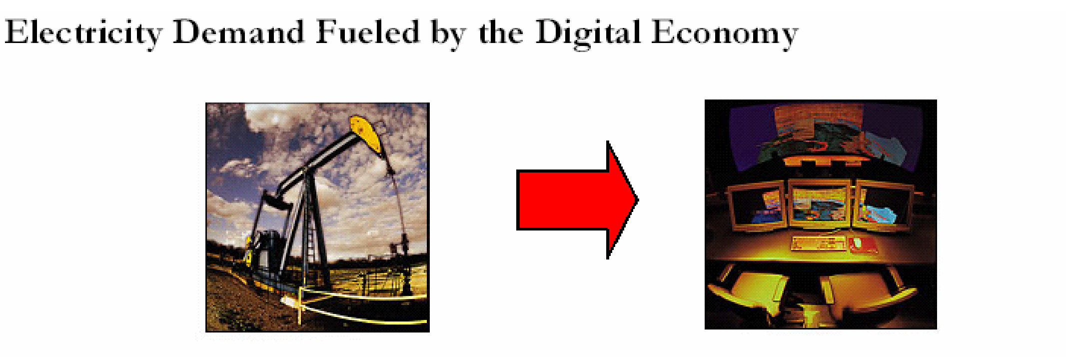
MOTIVATION FOR DISTRIBUTED GENERATION:

As the technologies evolved, ever larger power production units were constructed allowing their operators to take full advantage of construction-cost economies of scale to provide a more cost-attractive generation mix to their customers. However, siting these ever larger facilities has become increasingly difficult. Hydro facilities must be sited as dictated by geography, even if this means displacing very large population centers and /or permanently and seriously affection the local ecology. Since it is more convenient to transport energy in its electric form, fossil thermal plants are generally sited either close to raw fuel sources or to fuel conversion/treatment facilities. The pollution concerns mentioned earlier dictate their siting far away from the population centers. A broad range of environmental concerns mandate that nuclear power plants be located far away from population centers.

These siting issues, as well as the need to share these large power production facilities within a formalized market structure, have required the construction of large, complex, and capital-intensive electric power transmission networks. These transmission networks have become an increasing source of concern as their sustained development becomes a problem from a right-of-way point of view, and as their economic operation comes in limbo under a deregulated electric utility industry. Ecological and environmental protection concerns, as well as political pressure, also often mandate that new transmission facilities be constructed underground, which even further compounds the issue by imposing often unbearable construction cost impediments.

As the industry enters the competitive arena, fewer and fewer corporations are capable of taking on the financing of the construction of large electric power plants at costs far exceeding a billion dollars. Under the present economic and investment climate, with its almost exclusive focus on short-term results, the justification of a multibillion dollar investment with a pay-back period measured in decades has become virtually impossible. In several industrialized countries, aggressive public policies backed by strict regulatory mandates are such that electric power production within the confines of vertically integrated utilities has most probably been relegated to the past, while a true highly diversified electric power production industry is the future.

Figure 1 : Electricity Fueled by digital economy



Industrial economy	Digital Economy
Driven by manufacturing	Driven by Information
Steel mills, automobile, manufacturers, shipyards, factories	Data Centers, Server Farms, Semiconductor Fabs, ISPs, Electronic Marketplaces
99.9% reliability adequate	99.9% reliability Inadequate
"Thin" power demand 40 to 70 W / square foot	"Dense" Power Demand 150 W / Square Foot
Centralized grid model	Distributed Grid Model
Fueled by hydrocarbons	Fueled by Electricity

The increase market penetration of distributed generation has also been the advent of an electric power production industry. Many, if not most, of the players in this industry are not traditional electric utilities; in fact, several of these new players actually are spin-offs of the traditional utilities. Electric power production facilities that do not belong to electric utilities are referred to as non utility generators (NUGs). The rapid emergence of NUGs is illustrated by the fact that, starting during the early 1990s, more generation capacity is added each year in the United States by NUGs than by traditional utilities. NUGs represented 5% of the installed generation capabilities in the United States at the beginning of the 1990s; by the end of the decade, the proportion had grown to 20% as it grew from less than 40 GW to more than 150 GW. These statistics also take into account the fact that several large electric utilities have actually spun off their generation capabilities within separate corporate entities, while they have remained as what has now been referred to as "wire companies".

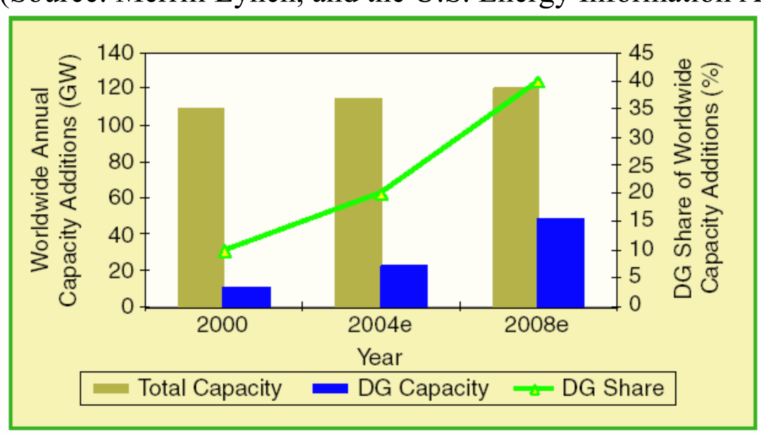
I believe that the acceleration in the broader adoption of distributed power sources would be mainly due to the robust growth in the power consumption (driven by the emergence of the digital economy as illustrated in figure 1), heightened reliability requirements, deregulation, environmental legislation and increasingly stringent government regulation of vehicle and their emissions.

DISTRIBUTED GENERATION:

The transformation of the U.S. electricity market has created an opportunity for distributed generation (DG), or sub-5MW power production, near the point of need. DG applications include powering remote locations, resource recovery, backup generation and grid-parallel power production. The market drivers for the growth of DG market are the digital economy, transmission and distribution issues, deregulation, reliability, and air quality. Figure 2 below shows the anticipated growth in this sector.

Figure 2 : Distributed generation market growth.

(Source: Merrill Lynch, and the U.S. Energy Information Agency (EIA), January 2001.)



Digital Economy: Electricity demand, fueled by the power-hungry digital economy, has dramatically outstripped supply. Traditional power plants take years to site and build; DG technologies can immediately address this imbalance through rapid deployment at the point of need.

Transmission and Distribution: A congested and aging grid further constraints supply and makes it difficult to deliver power to the final consumer. Siting power lines can be almost as troublesome as building new plants. Finally, losses during transmission add to the cost of centralized distribution and reduce efficiency. DG technologies offer the potential to circumvent the troublesome grid entirely.

Deregulation: Much of the underinvestment in both generation and distribution infrastructure grew out of the uncertain market environment spawned by deregulation. Deregulation has also supported growth of DG by allowing for "peak shaving," or the employment of onsite generation assets during times of peak energy demand, and "net metering," which is the selling excess energy back into the grid for a credit.

Reliability: High-quality, reliable power with essentially no downtime has become a necessity for many commercial and industrial enterprises. The unreliable nature of grid-delivered power has caused many consumers to look at distributed generation as a primary power source while simultaneously stimulating investments in backup power generation.

Air Quality: Increasing stringent air-quality standards have stalled new central power plant construction and limited installation of diesel generators, or "gensets," for backup power. Clean alternative energy solutions have emerged as environmentally friendly alternative and opened new market opportunities. Chart below shows the additional external or social cost of electricity due to environmental effects.

Table 2: Cost of electricity

(Sources: International Atomic Energy Agency, ExternE, and Wind Power Monthly, The Wall Street Journal, 27 Aug. 2002)

Resource	Generation Cost (c/kWh)	External Cost of Generation (c/kWh)*
Coal	3.11-3.41	1.94-14.6
Gas turbine	2.53-3.41	0.97-3.89
Nuclear	3.31-5.74	0.19-0.58
Good wind site	5.84	0.05-0.24
Optimal wind site	3.89	0.05-0.24

* The estimated costs to society and the environment due to their operation, not including nuclear waste and decommissioning costs

Various distributed generation technologies & summary of cost and performance

Some of the distributed generation technologies, its costs, performance and its capabilities are listed in the two charts below. Distributed generation places electricity generation close to the point of need and bypasses the expensive and unreliable transmission and distribution network. Distributed generation consists of relatively small power generation, usually less than 5MW. Cambridge Energy Research Associates (CERA) sizes the global distributed generation market, excluding backup power, at more than 13,000 MW and projects it to grow at approximately 5% annually. The DOE estimates that distributed generation could account for more than 20% of domestic capacity additions by 2020, or between 36-78GW.

Table 3: Distributed energy capabilities and system interfaces		
Technology	**Typical Capability Ranges**	**Utility Interface**
Solar, photovoltaic	A few W to several hundred kW	dc to ac converter
Wind	A few hundred W to a few MW	Asynchronous generator
Geothermal	A few hundred kW to few MW	Synchronous generator
Ocean	A few hundred kW to few MW	Four-quadr. Synchronous machine
ICE	A few hundred kW to tens of MW	Synchr. Generator or ac to ac converter
Combined cycle	A few tens of MW to several hundred MW	Synchronous generator
Combustion turbine	A few MW to hundreds of MW	Synchronous generator
Microturbines	A few tens of kW to a few MW	ac to ac converter
Fuel cells	A few tens of kW to a few tens of MW	dc to ac converter

Table 4: Summary of Cost and Performance Parameters for Distributed Generation Technologies

Technology	Size Range (kW)	Installed Cost ($/kW) (2)	Heat Rate (Btu/kWh_e)	Approx. Efficiency (%)	Variable O&M ($/kWh)	Emissions (1) (lb/kWh)	
						NO_x	CO_2
Diesel Engine	1–10,000	350–800	7,800	45	0.025	0.017	1.7
Natural Gas Engine	1–5,000	450–1,100	9,700	35	0.025	0.0059	0.97
Natural Gas Engine w/CHP (3)	1–5,000	575–1,225	9,700	35	0.027	0.0059	0.97
Dual-Fuel Engine	1–10,000	625–1,000	9,200	37	0.023	0.01	1.2
Microturbine	15–60	950–1,700	12,200	28	0.014	0.00049	1.19
Microturbine w/CHP (3)	15–60	1,100–1,850	12,200	28	0.014	0.00049	1.19
Combustion Turbine	300–10,000	550–1,700	11,000	31	0.024	0.0012	1.15
Combustion Turbine w/CHP (3)	300–10,000	700–2,100	11,000	31	0.024	0.0012	1.15
Fuel Cell	100–250	5,500+	6,850	50	0.01–0.05	0.000015	0.85
Photovoltaics	0.01–8	8,000–13,000	--	N/A	0.002	0.0	0.0
Wind Turbine	0.2–5,000	1,000–3,000	--	N/A	0.010	0.0	0.0
Battery	1–1,000	1,100–1,300	--	70	0.010	(4)	(4)
Flywheel	2–1,600	400	--	70	0.004	(4)	(4)
SMES	750–5,000	600	--	70	0.020	(4)	(4)
Hybrid Systems	1–10,000	(6)	(5)	(5)	(5)	(5)	(5)

(1) Nationwide utility averages for emissions from generating plants are 0.0035 lb/kWh of NO_x and 1.32 lb/kWh of CO_2.
(2) The high end of the range indicates costs with NO_x controls for the most severe emissions limits (internal combustion technologies only).
(3) Although the electric conversion efficiency of the prime mover does not change, CHP significantly improves the fuel utilization efficiency of a DER system.
(4) Storage devices have virtually no emissions at the point of use. However, the emissions associated with the production of the stored energy will be those from the generation source.
(5) Same as generation technology selected.
(6) Add cost of component technologies.

DER – Distributed Energy Resources

CRITERIA FOR SUCCESS OF DISTRIBUTED GENERATION

Despite the many advantages of distributed power generation, its success depends largely on a number of factors. In addition to government policies, these factors include capital costs, ease of installation and reliability concerns. The following points explore the more critical requirements:

Generators With Very High Reliability

The use of numerous engines raises the concern of higher maintenance costs. Many small engines scattered over a large neighborhood are more troublesome to service than a large engine found at a single point. Moreover, private companies (Non DG) that own distributed generators are unlikely to have the skill and expertise required for service and repair. This makes very high reliability one of the main requirements for distributed power generation.

Low Introductory and Installation Costs

Investment costs determine the rate at which distributed generation is able to gain in acceptance and market share. Due to concerns over funding and quick profitability, privately owned power generators must have low introductory and installation costs.

Interconnect Installation and Operation Costs

A network of wires is used to link power stations and their customers. This is known as the electrical grid. The connection between this grid and distributed power generators is a significant barrier to distributed power generation. Engineers refer to such connections as the *distributed generation technology interface* [DGTI]. The installation and operation costs of these connections need to be lowered.

Sociological Factors

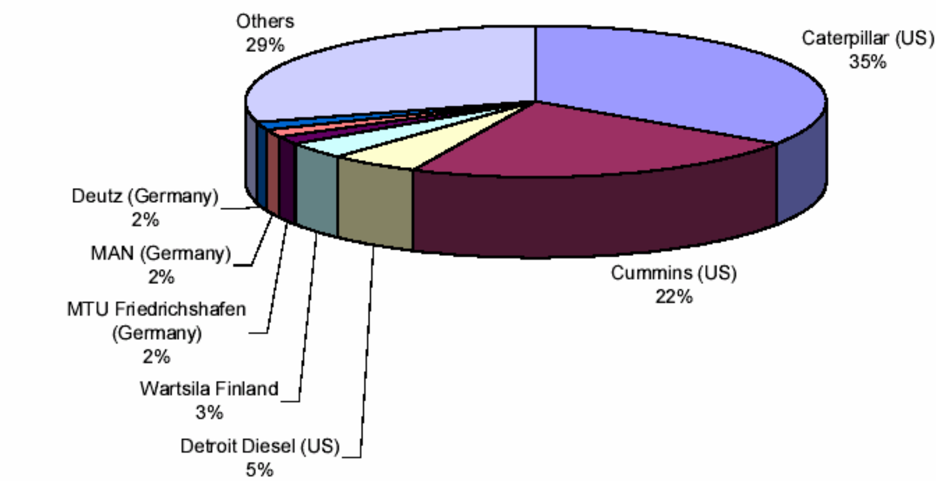
For distributed power systems to become popular, the public needs to be comfortable with having power generators sited in their homes and work places. The common notion of a noisy and heavily polluting power station has to be addressed. In the past, construction of overhead transmission lines has been shown to trigger public outcries. This highlights the significance of sociological issues

COMPANIES CURRENTLY DOMINATING THE DG MARKET:

If we look at the present market share among distributed generation system manufacturers, Caterpillar and Cummins together have about 60 % market share. This is important because some respondents to the questionnaire felt that there will be a distributed generation industry rather than a fuel cell industry. It remains to be seen if Caterpillar and Cummins will remain the leaders and capitalize on their market dominance when Fuel Cells enter the commercialization phase or whether another company is going to emerge, taking Fuel Cells as the lead source of distributed generation.

Figure 3: Distributed generation Market Share (Revenues)

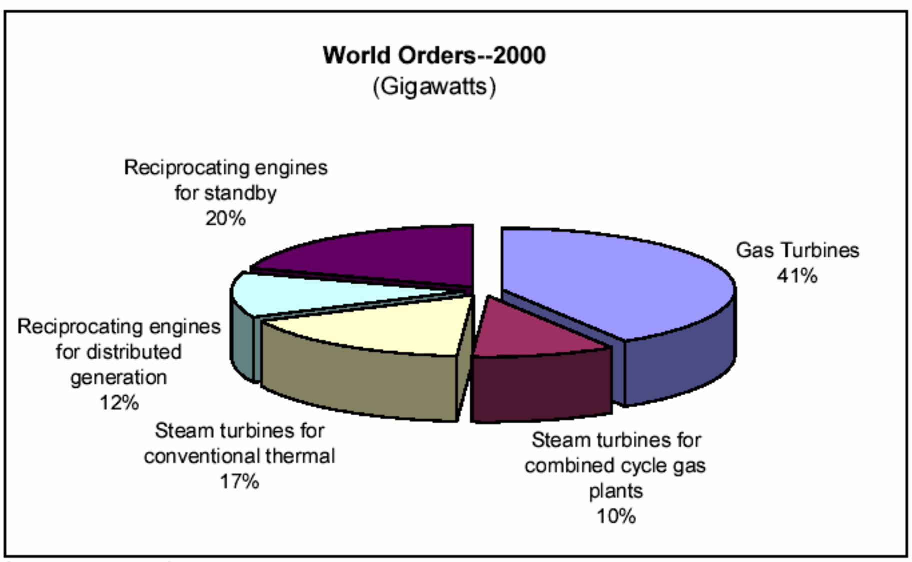
Distributed Generation Market Share



Source: Datamonitor

Figure 4 : World Order for Generation Equipment

2000 World Orders for Generation



Source: Datamonitor

CHAPTER 3

BASICS OF FUEL CELL TECHNOLOGY

A fuel cell is an electrochemical device that produces electricity by separating the fuel (generally hydrogen gas) via a catalyst. The protons flow through a membrane and combine with oxygen to form water – again with the help of a catalyst. The electrons flow from the anode to the cathode to create electricity. As long as the reactants – pure hydrogen and oxygen – are supplied to the fuel cell, it will produce electrical energy.

A single fuel cell is basically a piece of plastic between a couple of pieces of carbon plates that are sandwiched between two end plates acting as electrodes. These plates have channels that distribute the fuel and oxygen.

A factor that draws interest to the fuel cell stack is that it can operate at efficiencies two to three times that of the internal combustion engine, and it requires no moving parts. Since it converts the fuel, hydrogen, and oxygen directly to electrical energy, the only by-products are heat and water. Without combustion, hydrogen fuel cell systems are virtually pollution free.

Although hydrogen is the most common fuel used to power a fuel cell, research is being done on a new type of fuel cell that operates using methanol (without using a reformer to convert it to hydrogen) and oxygen. However, this type of fuel cell remains in the early stages of development.

HISTORY OF FUEL CELLS:

As early as 1839, Sir William Grove (often referred to as the "Father of the Fuel Cell") discovered that it may be possible to generate electricity by reversing the electrolysis of water. It was not until 1889 that two researchers, Charles Langer and Ludwig Mond, coined the term “fuel cell” as they were trying to engineer the first practical fuel cell using air and coal gas. While further attempts were made in the early 1900s to develop fuel cells that could convert coal or carbon into electricity, the advent of the internal combustion engine temporarily quashed any hopes of further development of the fledgling technology.

Francis Bacon developed what was perhaps the first successful fuel cell device in 1932, with a hydrogen-oxygen cell using alkaline electrolytes and nickel electrodes – inexpensive alternatives to the catalysts used by Mond and Langer. Due to a substantial number of technical hurdles, it was not until 1959 that Bacon and company first demonstrated a practical five-kilowatt fuel cell system. Harry Karl Ihrig presented his now-famous 20-horsepower fuel cell-powered tractor that same year.

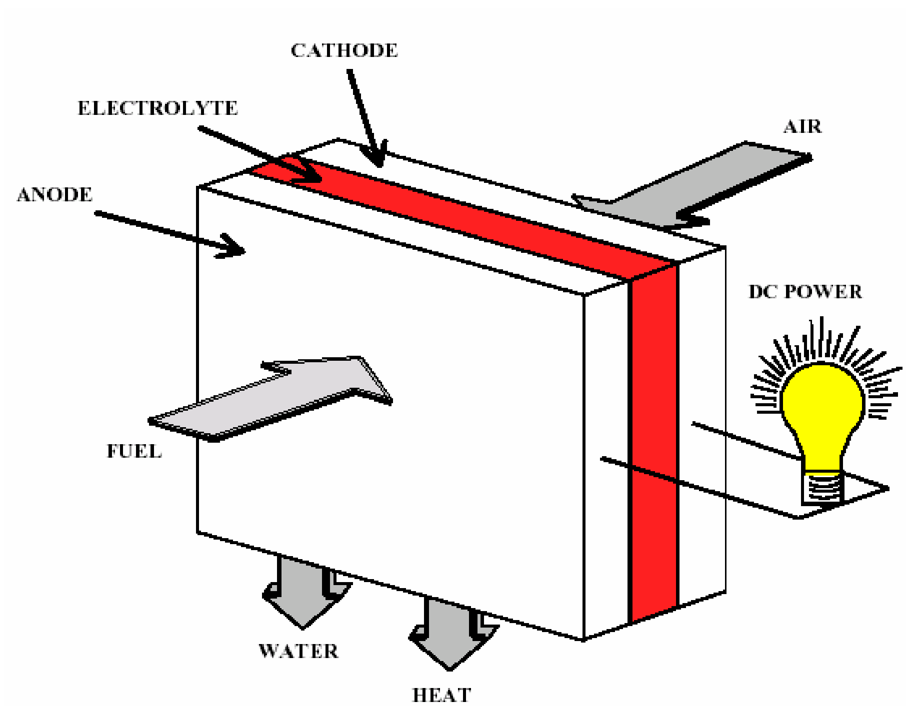
Also in the late 1950s, NASA began to build a compact electricity generator for use on space missions. NASA soon came to fund hundreds of research contracts involving fuel cell technology. Fuel cells now have a proven role in the space program, after supplying electricity to several space missions. Appendix E show the pictorial representation of the history of Fuel cells.

FUEL CELL TECHNOLOGY

Unlike electrochemical batteries, which use chemical reactions to both store and discharge electricity, fuel cells generate electricity from hydrogen fuel. Haul around enough fuel, and the fuel cell will power an electric vehicle as far as the motorist wants to drive or power a home as long as needed.

A fuel cell consists of two electrodes: a positive electrode called an anode and a negative electrode called a cathode. Pure hydrogen gas - or hydrogen extracted (or reformed) from a hydrocarbon fuel such as methanol or gasoline - together with oxygen is fed into the cell. A catalyst at the anode (usually based on a platinum-family element) causes hydrogen atoms to give up their negatively charged electrons, leaving positively charged protons. Negatively charged oxygen ions (from ionized oxygen gas) at the cathode side attract the hydrogen protons. As the protons pass selectively through a semi permeable solid electrolyte membrane (in the most common fuel-cell type), the remaining electrons are redirected to the cathode by way of an external circuit, thus producing current that powers an electric motor. The electrons combine with the hydrogen protons and oxygen ions at the cathode forming the fuel cell's major byproduct, water. The other principal end-product is heat, which can be captured and reused, or released. Because a single cell generally produces only a few volts, fuel cells are typically piled into "stacks" to generate more useful voltage. The exhaust emissions of a pure hydrogen fuel cell are clean, but the extraction of hydrogen from hydrocarbon fuels in reformer systems does release some atmospheric and other pollutants.

Figure 5 : Fuel Cell basic configuration



TYPES OF FUEL CELLS

Alkaline fuel cells - AFC
1. Alkaline fuel cells were first used in the Gemini-Apollo space program to produce drinking water and electrical energy.
2. Operate on compressed hydrogen.
3. Alkaline fuel cells generally use a solution of potassium hydroxide (chemically, KOH) in water as their electrolyte.
4. Output of alkaline fuel cell ranges from 300 watts (W) to 5 kilowatts (kW).

Direct methanol fuel cells - DMFC
1. Direct methanol fuel cells use methanol instead of hydrogen.
2. Operating temperatures of direct methanol fuel cells are in the same range as PEM fuel cells – 50 to 100°C (122 to 212°F).
3. Direct methanol fuel cells are being considered for use in the transportation industry.

Molten carbonate fuel cells - MCFC
1. Molten carbonate fuel cells use a liquid solution of lithium, sodium, and/or potassium carbonates soaked in a matrix.
2. Units with output up to 2 megawatts (MW) have been constructed, and designs exist for units up to 100 MW.
3. The nickel electrode-catalysts of molten carbonate fuel cells are inexpensive compared to those used in other cells, but the high temperature also limits the materials and safe uses of MCFCs.

Phosphoric acid fuel cells - PAFC
1. Phosphoric acid fuel cells use phosphoric acid as the electrolyte to make electricity.
2. Efficiency ranges from 40 to 80 percent and operating temperature is 150 to 200° C (about 300 to 400° F).
3. Existing phosphoric acid cells have outputs up to 200 kW, and 11 MW units have been tested.

Proton exchange membrane fuel cells - PEM
1. PEM fuel cells are the most common type of fuel cell being developed for transportation use.
2. They operate at the one kW per liter of volumetric powered level at a temperature under 100°C (212 °F)
4. PEM fuel cells react quickly to changes in electrical demand and will not leak or corrode.
5. PEM fuel cells use relatively inexpensive manufacturing materials (plastic membrane).

Regenerative fuel cells – RFC
1. Regenerative fuel cells separate water into hydrogen and oxygen by a solar-powered electrolyser.
2. Hydrogen and oxygen are fed into regenerative fuel cells, generating electricity, heat and water.
3. Water is then re-circulated back to the electrolyser of the regenerative fuel cell and the process repeats.

Solid oxide fuel cells - SOFC

1. Solid oxide fuel cells use a hard, ceramic compound of metal (like calcium or zirconium) oxides (chemically, O2) as electrolyte.
2. Output for solid oxide fuel cells is up to 100 kW.
3. Reformer is not required to extract hydrogen from the fuel due to high temperature.

Figure 6 : Fuel Cell comparisons based on applications

Target Applications				Polymer Electrolyte Membrane Fuel Cell (PEMFC)	Alkaline Fuel Cell (AFC)	Phosphoric Acid Fuel Cell (PAFC)	Molten Carbonate Fuel Cell (MCFC)	Solid Oxide Fuel Cell (SOFC)
	Stationary-Distributed	Grid Sited	Central	Unlikely	Unlikely	Unlikely	Likely	Likely
			Distributed	Unlikely	Unlikely	Unlikely	Likely	Likely
			Re Powering	Unlikely	Unlikely	Likely	Likely	Likely
		Customer Sited Cogeneration	Residential	Likely	Under consideration	Unlikely	Under consideration	Likely
			Commercial	Likely	Under consideration	Likely	Likely	Likely
			Light Industrial	Under consideration	Under consideration	Likely	Likely	Likely
			Heavy Industrial	Unlikely	Unlikely	Likely	Likely	Likely
	Transportation	Propulsion	Light Duty	Likely	Unlikely	Unlikely	Unlikely	Unlikely
			Heavy Duty	Likely	Unlikely	Under consideration	Under consideration	Under consideration
		Auxiliary Power Unit	Light & Heavy Duty	Likely	Unlikely	Unlikely	Unlikely	Likely
	Portable	Premium	Recreational, Military	Likely	Unlikely	Unlikely	Unlikely	Likely
		Micro	Electronics, Military	Likely	Unlikely	Unlikely	Unlikely	Unlikely

● Likely
◐ Under consideration
○ Unlikely

FUEL CELL VALUE CHAIN:

PEM Fuel Cell value chain[2] shown in the diagram below depicts the fuel cell industry as a whole where significant value can be added in the various segments in the chain.

2 PWC Report.

Figure 7 : Fuel Cell Value Chain

Basic Material & component supply	Fuel cell Manufacture	Fuel cell Stack Assembly	Power Plant Assembly	Repairs and Maintenance	Recycling
1. Research & Product development 2. Aluminum 3. Steel 4. Plastics 5. Platinum 6. Wiring 7. Membranes 8. Electrodes	1. Research & Product development 2. MEA's 3. Electrolyte 4. Catalysts 5. Bi-Polar plates 6. Testing Equipment	1. Research & Product development 2. Fuel Cells 3. Trays 4. Testing Equipment	1. Research & Product development 2. Fuel cell stacks 3. Air delivery systems 4. Fuel storage units 5. Fuel delivery systems 6. Cooling systems 7. Electrical systems 8. Control systems 9. Drivetrains (Vehicles) 10. Testing equipment.	1. Research & Product development 2. Diagnostics 3. Equipment 4. Shop supplies 5. Replacement parts 6. Refurbished parts	1. Research & Product development 2. Collection depots 3. Dismantling 4. Facilities 5. Resell 6. Infrastructure

FUEL CELL VERSUS CARNOT EFFICIENCY

The theoretical thermodynamic derivation of Carnot Cycle shows that under ideal conditions, a heat engine cannot convert all the heat energy supplied to it into mechanical energy; some of the heat energy is rejected. In an internal combustion engine, the engine accepts heat from a *source* at a high temperature (T_h), converts part of the energy into mechanical work and rejects the remainder into a *heat sink* at a low temperature (T_c). The greater the temperature difference between source and sink, the greater the efficiency.

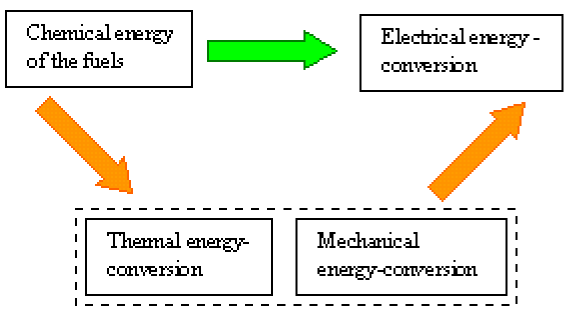
Maximum efficiency (Carnot), $\eta_{carnot} = \frac{T_h - T_c}{T_h}$

Note: the temperatures T_h and T_c are in degrees Kelvin.

Because fuel cells convert chemical energy directly to electrical energy, this process does not involve conversion of heat to mechanical energy. Therefore, fuel cell efficiencies can exceed the Carnot limit even when operating at relatively low temperature, for example, 80ºC.

The diagram below is a graphical illustration of energy conversion processes from chemical energy in fuels to electrical energy:

Figure 8 : Energy Conversion of Fuels



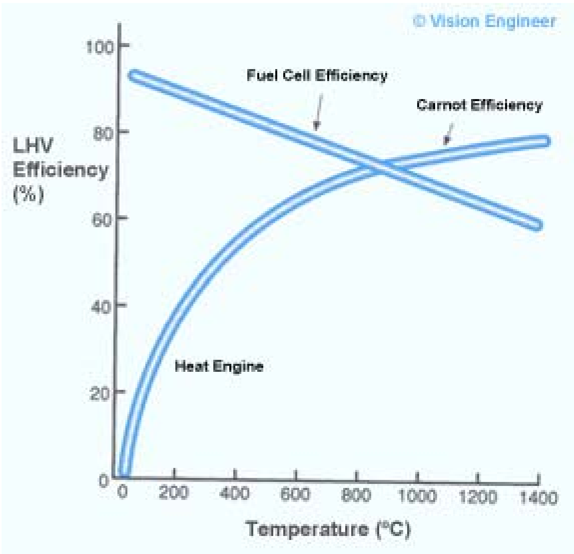
There are 2 ways in converting chemical energy to electrical energy: green route and orange route.
The orange route is a general route for combustion process plus electricity generation in vehicles and power stations that use fossil fuels. The green route is for fuel cells. Fuel cell generates electricity by electrochemical reactions. It bypasses the thermal and mechanical energies conversions, hence are more efficient.

The theoretical efficiency of a fuel cell is related to the ratio of two thermodynamic properties, namely the chemical energy or Gibbs energy (dG^0) and the total heat energy or Enthalpy (dH^0) of the fuel.

Fuel cell efficiency, $\eta_{fc} = \frac{\Delta G^{\circ}}{\Delta H^{\circ}}$

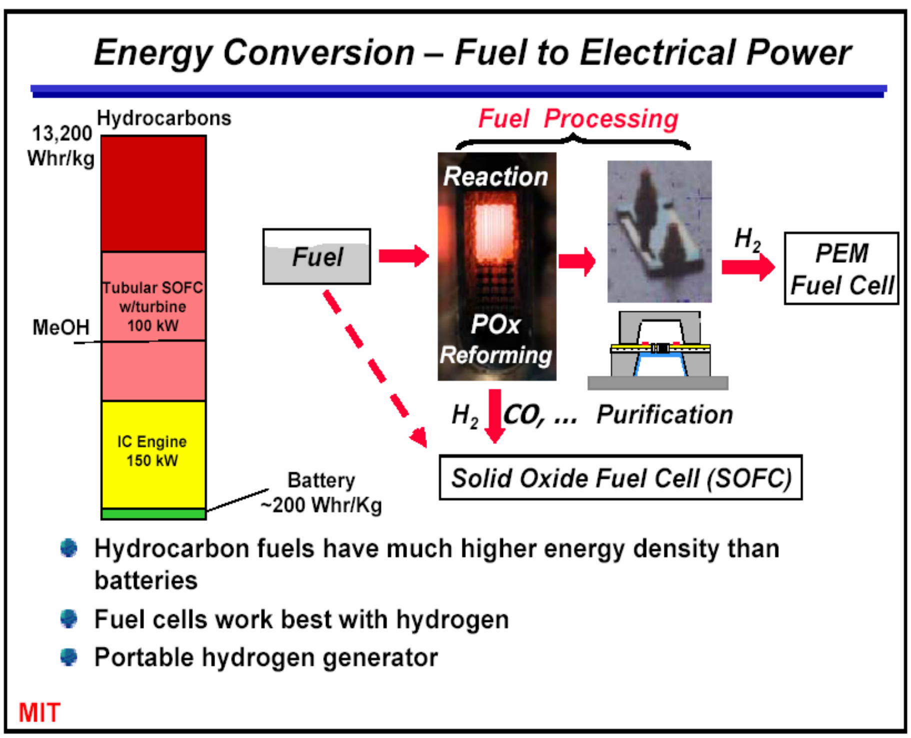
The variation of hydrogen fuel cell theoretical efficiency versus Carnot efficiency is shown in the figure 9 below:

Figure 9 : Relative theoretical efficiency change with temperature of a fuel cell and heat engine



The hydrocarbon fuels have much higher energy density than batteries which is shown in the diagram below.

Figure 10 : Energy conversion comparison (Batteries, IC Engines, SOFC)



FUEL CELL SYSTEMS FOR DISTRIBUTED POWER GENERATION:

Fuel cell technology holds the promise to produce electricity at local sites from a wide range of fuels, and with high efficiency. Most types of fuel cells operate on hydrogen fuel, but this hydrogen can be produced from natural gas, liquid hydrocarbon fuels including biomass fuels, landfill gases, water and electricity (via the process of electrolysis), biological processes including those involving algae, and even from coal. Fuel cells are being proposed for use in powering electric vehicles, providing remote power for buildings and communication facilities, providing power as distributed generation (DG) in grid-connected applications (as either primary power or backup power), and for small electronic devices such as laptop computers and cell phones.

One principal attraction of fuel cell technology, as evidenced by this diverse array of potential applications, is that fuel cells can produce power with high efficiency in a wide range of system sizes. This feature is a function of the modular design of fuel cell systems (where individual cells are compiled into "stacks" to achieve higher voltage and power levels), as well as the fuel cell operating principle that allows electricity to be produced without combustion. There are several potential operating methods for using both stationary fuel cells and fuel cell vehicles (FCVs) as distributed generation resources. These systems could be used to:

1. Produce power to meet the demands of local loads;
2. Provide additional power to the grid in a net-metered or electricity buy-back scenario, helping to meet demands in times of capacity constraints;
3. Provide emergency backup power to residences, offices, hospitals, and municipal facilities;
4. Provide "peak shaving" for commercial sites, reducing demand charges;
5. Provide ancillary services to the grid, such as spinning reserves, grid frequency regulation, power quality support, reactive power, and possibly other services;
6. Provide buffering and additional power for grid-independent systems that rely on intermittent renewables.

Net Metering of Fuel Cell Systems:

There are two basic means by which commercial fuel cell systems could be net metered. First, they could be net-metered in a manner analogous to current net-metering programs, whereby overall billing would be assessed on a monthly or annual basis and the customer could have a zero balance, a negative balance, or in the case where credit is awarded to net excess generation, even a positive balance. One argument against including fuel cell systems in these traditional net metering programs is that while PV and wind systems tend to have peak availability in the daytime and afternoon periods, coincident with the gird peak, much excess fuel cell power may be available off-peak, when the grid is running mainly from base load power plants. However, net metering policies could be designed to work in conjunction with "real time" electricity meters that are currently being installed at many commercial sites to allow excess generation to only be credited at peak hours of the day when the grid is employing peak power plants. In theory, use of fuel cell systems in this way could reduce the need to operate peak power plants and to construct new ones to meet peak demand growth. For this reason, the excess fuel cell power added to the grid is only credited for net metering during hours that coincide with the overall grid peak power demand, rather than at any time during the day or night.

A second type of net metering is “short term” net metering, where the fuel cell system is connected in parallel with the utility grid and relies on grid power to take up the transients in the commercial or residential load. If the fuel cell system does not need to fully “load follow,” for example, a residential load that averages only 1 or 2 kW but can spike to 12-15 kW, then it can likely achieve higher efficiency. In addition, system components can be sized more optimally, backup battery systems would not be needed, and hydrogen “buffer” storage may also not be needed. This use of the utility grid to load-level the fuel cell system, whereby energy that is “borrowed” from the grid to take up transients is then “repaid” with gradual fluctuations in fuel cell power over a 15-30 minute period of time, could significantly improve the economics of fuel cell system operation.

At certain settings net metering may improve the economics of using small fuel cells for distributed generation because it would allow fuel cell operation to be better optimized for high efficiency that is possible with load-following operation. This may be particularly true for the case of FCVs being used to generate power while they are parked at residential settings, due to the fact that the fuel cell systems in the vehicles have been optimized for use as vehicle power, and may not be particularly well suited to powering small building electrical loads. Net metering of these systems may therefore play an important role in allowing the systems to be used in a manner where higher efficiency operation is possible that in the absence of a net-metered operational strategy.

Fuel Cell Benefits:

Fuel cell power offers many benefits like;

1. Cleaner, quieter and more efficient power production than conventional internal combustion engines (ICEs)
2. Operating efficiencies at part load and in all size configurations
3. Few moving parts and thus an anticipated high degree of reliability, lower maintenance and long operating life
4. Modular design, offering flexibility in size and efficiencies in manufacturing
5. Use of multiple fuels, such as hydrogen, natural gas, methanol and gasoline
6. Zero or low emissions, depending on the fuel used.
7. Use in combined heat and power purposes, further increasing the efficiency of energy production.

Table 5: The list of current and potential applications for fuel cell[3]		
Stationary Uses	Portable Uses (Including micro)	Transportation Uses
1. Distributed power 2. Off-grid power (uninterruptible) 3. Back-up generator power 4. Co-generation power and heating 5. Cellular telephone towers 6. Data centers 7. Emergency standby • Hospitals • Fire Stations • Airports 8. Building self-generation 9. Residential • Individual homes • Subdivisions 10. Remote industrial operations • Mines • Portable mills 11. Peaking application for grid	1. Small generators • Military • Cottages • Worksites 2. Camping 3. Film industry 4. Off-grid power (uninterruptible) 5. Power tools 6. Laptop computers 7. Cellular phones 8. Personal digital assistant 9. Camera equipment 10. Toys 11. Road signs 12. Wheelchairs 13. Lawnmowers 14. Watches 15. Medical devices • Hearing aids • Neurological 16. Embedded power for miniature devices	1. Buses • School • Transit • Fleet 2. Automobiles • Fleets (taxi, municipal, military) • Personal Auxiliary Power units 3. Trucks (light, medium, and heavy) 4. Motorcycles and scooters 5. Locomotives 6. Marine craft • Commercial • Personal 7. Recreation vehicles • ATVs • Snowmobiles 8. Golf Carts 9. Fork lifts 10. Underground mining and tunneling vehicles

Fuel cells will likely be used in certain applications sooner than others. Initial uses will be in markets requiring reliable and secure forms of power where users are prepared to pay a premium, or where the cost of alternatives is already high. As production costs drop and miniaturization technology improves, fuel cells will power an increasing number of consumer applications.

[3] PricewaterhouseCoopers report.

CHAPTER 4

INNOVATION AND DIFFUSION:

In order for society to capture the benefits of technological innovation the new technology must be transferred or diffused to the marketplace. This diffusion phenomenon has been studied elsewhere in an effort to determine the characteristics of an innovation that affect its rate of diffusions. One key characteristic for innovations in the energy industry is the depth of the innovation, or the amount of change to the status quo caused by the innovation. In the energy industry the depth of innovation is measured in relation to existing markets. For example, in 1973 no market existed for terrestrial solar photovoltaic (PV) systems. This innovation required the development of new applications and new markets and can be classified as having great innovation depth. Similarly Fuel Cells have a potential for having great innovation depth.

The performance of new business ventures will be affected by the magnitude of the innovation that it seeks to diffuse. The decision to serve existing markets or to establish new markets will, therefore, have a significant impact on the performance of the firms. Similarly, other innovation characteristics, such as cost-effectiveness and breadth of the innovations (number of users affected by the innovation) will also be investigated.

LIFE CYCLES FOR INNOVATION AND PRODUCT DEVELOPMENT:

The time required to transform new technical information into a well diffused innovation is an important factor for new technical ventures. The ability of the new firm to survive is tied to its ability to generate revenue within a short period. Fuel cell industry is unique in the energy industry in the sense that it has taken a very long time for the innovation to diffuse. This is because of various reasons. The innovation studies have found that a substantial lag (from 8 to 15 years) exists between the generation of new technical information and its use as an innovation[4]. This period includes an active research and development phase on the basic technology, a product development stage, followed by product introduction and diffusion through market.

After several years of government and private sector involvement, the diffusion of Fuel Cells remains in its earliest stages. This market appears to be developing agonizingly slow because of difficulties with the technology and bringing the overall cost down. Several studies indicate that innovative firms seeking to develop new markets for their technical innovation must commit to a long term development and diffusion process before they expect to capture the benefits resulting from their efforts. "If we can put a man on the moon then surely we can …" attitude may not work always. The new ventures that sought to develop the Fuel Cell technology and market with one or two year of government or private funding is not true anymore.

[4] Utterback, James M.; "Innovation in Industry and the Diffusion of Technology"; Science; Volume 183; pp 620-626.

Energy is a commodity today (unless we come up with ideas to de-commoditize). The essential attribute of a commodity is price. Thus, the diffusion of energy innovations is dependent on the cost-effectiveness of the innovation in relation to other available energy options. For most energy innovations life cycle costs which incorporate the first costs and operating costs (or savings) are the only true measure of cost-effectiveness. This greatly complicates the energy innovation pricing and leads to consideration of product life estimates and consumer discount rates.

RESEARCH METHODOLOGY:

The research methodology employed in this work closely follows the paper by Gransey[5] on the theory of the early growth of the firms. In particular, the interview and questionnaire technique were adapted to incorporate the ideas in the above paper.

SAMPLE SELECTION:

The initial task faced in this analysis was to develop a list of Fuel Cell Manufactures and experts in New York, Connecticut and Massachusetts. Company names were collected from a number of sources and personal contacts. Since there were not many companies (less than about 20) involved in the manufacturing of Fuel Cells in the above mentioned states, most of the information was available online. Ten companies were short listed from the information gathered earlier.

The ten companies consisted of firms that were involved in the manufacture of stationary fuel cells in the range of 1kW to 50 kW and in one case higher than 50kW. These firms were contacted with an introductory email explaining the nature of the study and subsequently a personal interview was arranged with the Founders, President & CEO or CTO of the companies.

INTERVIEW AND QUESTIONNAIRE:

The interview, which normally ran for one to two hours, were structured in such a way as to insure completion of the questionnaire (Appendix A) and informal enough to allow the interviewee to relate all aspects of the venture formation and growth. The entrepreneurs were a fascinating group, quite willing to relate their experience in this format. Their thoughts ranged from the present and past issues of the company and thoughts about the future of this technology and their predictions. The questionnaire has various sections related to company background information, local industry & research labs influence on company's growth, various growth phases of the company and critical events during their growth, founder's experience, financing, firms growth history and intellectual property

GEOGRAPHIC LOCATION:

The Landmark publication of Krugman (1991) and Porter (1990) focused debates in economic geography and business policy on the factors affecting industrial agglomeration and the productivity of national industries and provided critical frameworks for thinking about these issues. Porter's analysis of national industrial clusters (1990, 1998) has formed the cornerstone of strategy research on the role of the location. In this view, highly competitive local conditions

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[5] "A Theory of the Early Growth of the Firm," ***Industrial and Corporate Change***, vol 7 (3) 523-555, 1998 (a).

and policies that support continuous upgrading promotes competitive advantages among the set of firms within a cluster.

RESEARCH FINDINGS:

Interviews were conducted with the nine firms highlighted in the list of Potential Respondents in Appendix G. The interview sample contained both new enterprises and new internal ventures initiated within a large organization to serve newly developing markets.The interviewed firms were all Fuel Cell manufacturing companies in the three states of Massachusetts, New York and Connecticut. There is diversity in terms of different fuel cell technologies adopted by these firms in the study.

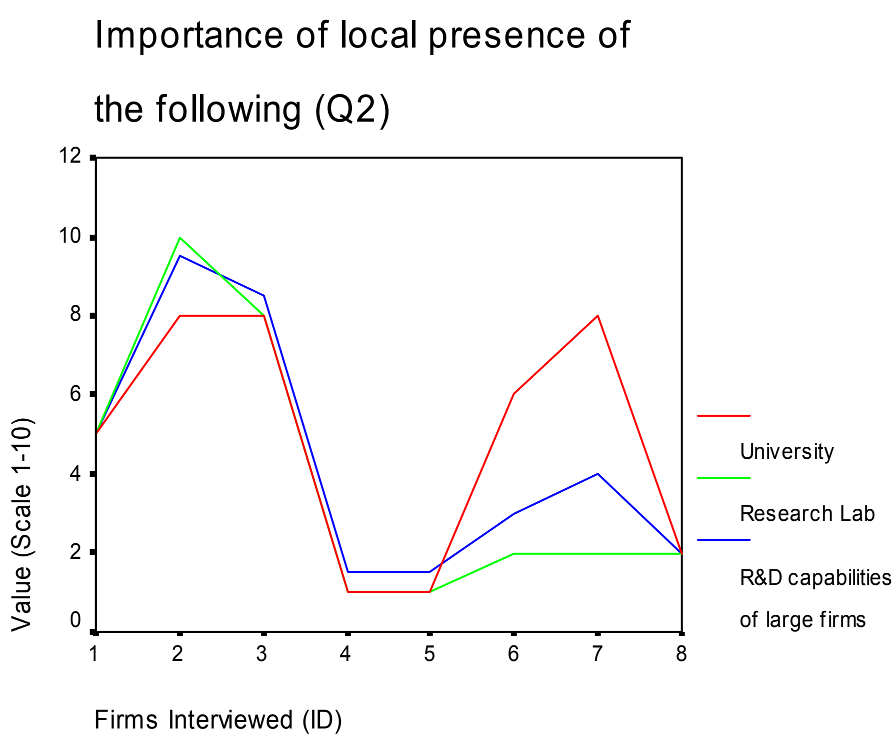
SECTION 1: Company and Entrepreneur's Background

Eight new enterprises were interviewed during the course of this study and backgrounds of these entrepreneurs were investigated. The most significant element of these entrepreneur's background is the technical expertise that they bring to their new ventures. This is not totally unexpected considering the highly technical nature of the businesses. The length of the time these people were with the company range from 1 year to 19 years.

SECTION 2: Local Influence on Growth

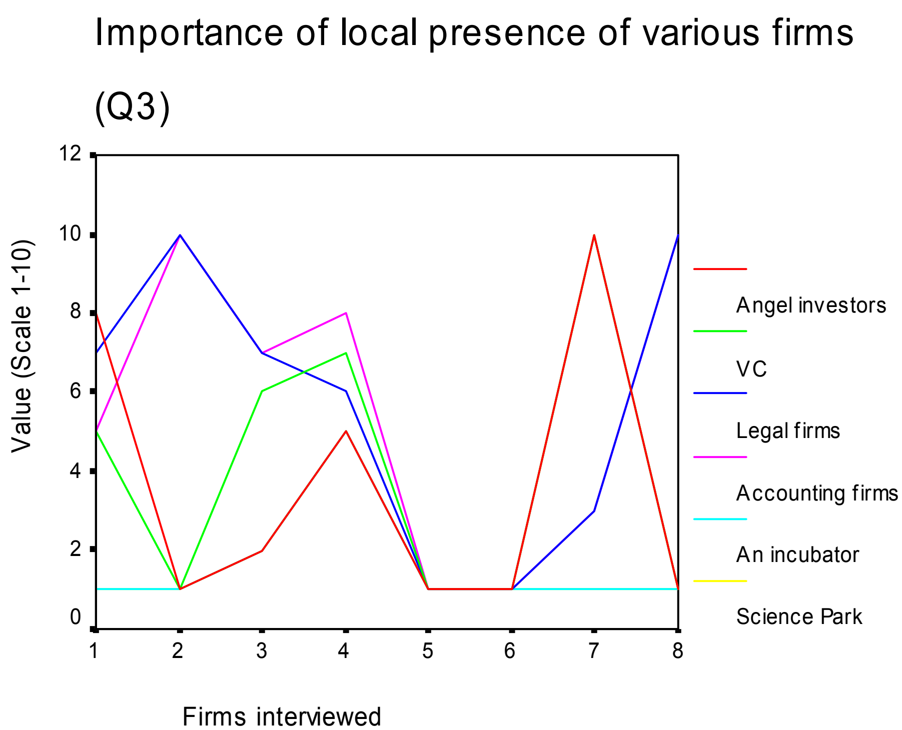
This section dealt with the questions related to the local influence (facilities & infrastructure) on the growth of these firms. It was found that the involvement of these companies with the industry associations activities locally were very minimal and also the presence of the local universities and research labs was not perceived as very important to their growth.

Chart 1:



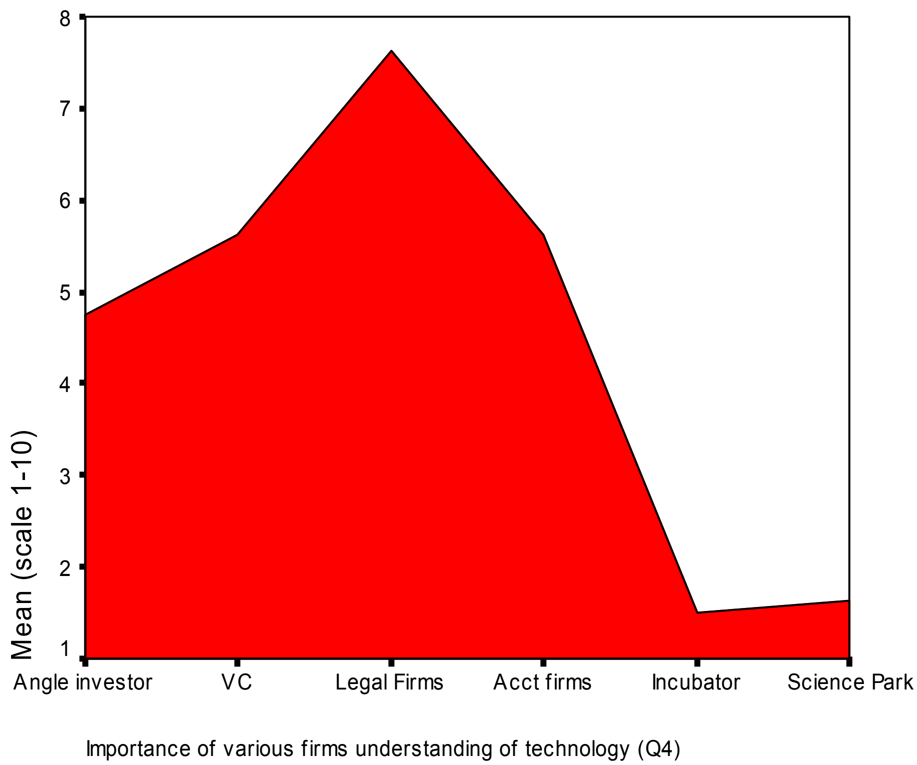
To the question of the importance of the local presence of the supporting organizations & establishments like the venture capitalist, legal firms, accounting firms etc, it was found that the Angel investors, legal firms and accounting firms presence locally was important to most firms. This is shown in the graph below. Legal firms were important for patent filing and writing good contracts. Some firms outsourced the accounting function and therefore the local presence was important to them. Apart form the list mentioned in the question 3 in the questionnaire some companies felt that there is a need for the presence of other High-Tech firms locally to outsource components and do the technology transfer where ever appropriate.

Chart 2:



The importance of these local entrepreneurial service firms to have some knowledge of Fuel Cell industry is critical for the legal firms and to a lesser extent the VC's and the accounting firms as shown in the chart 3 below.

Chart 3:

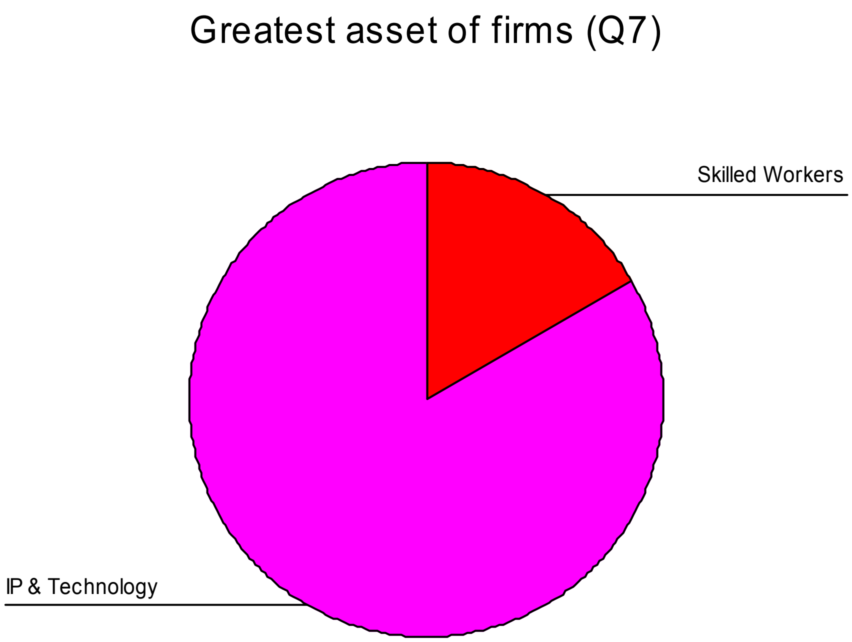


To the question (Q5), if the founders of the firm lived in a remote city which did not have direct access to various resources or had a limited access would the firm have been started there, the majority of them said they would not have started. They sited various reasons such as.

1. Availability of qualified people gets limited if the location is not right.
2. It also becomes easy to find and attract talent from other high tech industries where the firms are currently located.
3. Some of them felt that the access to the financial resources would become limited if the location is a remote city.
4. Some of the companies, due to historical reasons, were located where they are currently and since they were a spin off or a division of a major company; it would not have made sense to move their location to another city which has limited access to resources.
5. Also typically the chances of founders with specific talents meeting in a city with high access to various resources including educational institution are very high compared to a remote location.

The greatest positive impact on the growth of their firms (Q6) has been strong intellectual property and an important technological innovation. The only impact other than IP that was mentioned was getting Government grants & industry partnerships. In one instance a key management individual had a greatest positive impact because the person rescued the company from going bankrupt. To a related question (Q7) of the greatest asset of their firms currently, predominantly it was intellectual property and technology as shown in the chart 4 below.

Chart 4:



Apart from the above one company mentioned that its strong cash position was the firms greatest asset currently in this poor economic environment. One other company mentioned that their strong asset was their leaders with strong technical knowledge, program management skills, relationship building skills, product to market skills and an extended enterprise view.

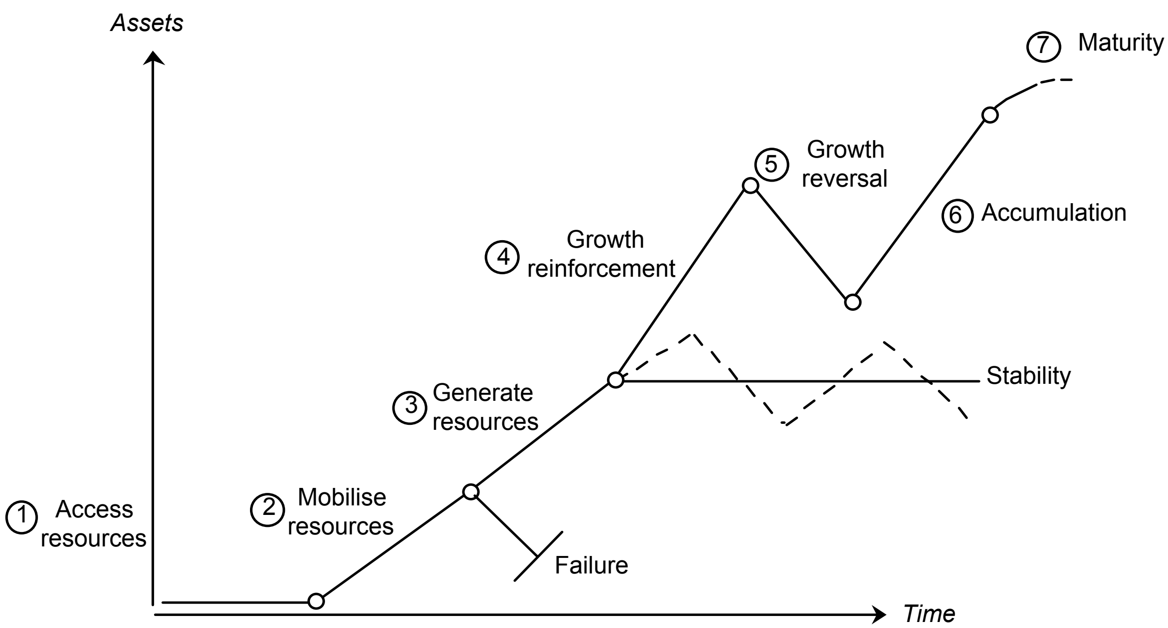
To the question of the greatest management challenge faced by these firms to date had varied responses such as

- Fundraising
- Focus and reality based thinking
- Being sustained visionary
- Making products that work (Going from concept to profits)
- Transition from R&D mentality to product development mentality with customers in mind.
- Serial production (move to mass production Vs a single unit production for R&D or demonstration)
- Growing and managing an R&D team from scratch.
- Selling the organization to venture capitalist because these people are making decisions based on incomplete information (which happens most of the time irrespective of the industry).
- Managing people – it's always people who are the cause of either problems or successes.

SECTION 3: Growth model for NTBF's

This section uses Gransey's[6] model of the growth of NTBFs (New Technology Based Firms). This mode is used here to see similarities and differences of management focus at various phases of an NTBF's growth. Gransey's model represents a firm's growth path as a series of growth processes which can occur sequentially or simultaneously, and which can occur more than once in the life of a firm. For example, a hypothetical firm's growth path, arranged sequentially, could be represented as: phase 1, phase 2, phase 5, phase 2&3, phase 4, phase 3, phase 6, and phase 7. Various phases are shown in the figure 11 below.

Figure 11: Gransey's Growth Model



All the companies interviewed agreed that their firm's experience fits this model. All the firms except two said that they were currently experiencing phase 3. It is also interesting to note that the technology risk and market risk perceived by the firm as it moves into various phase is different. The charts 5 and 6 below depict the technology and market risks during the various phases.

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[6] Garnsey E.; "A theory of the Early Growth of the Firm"; Industrial and Corporate Change, Volume 7 (3) 523-555, 1998 (a).

Chart 5:

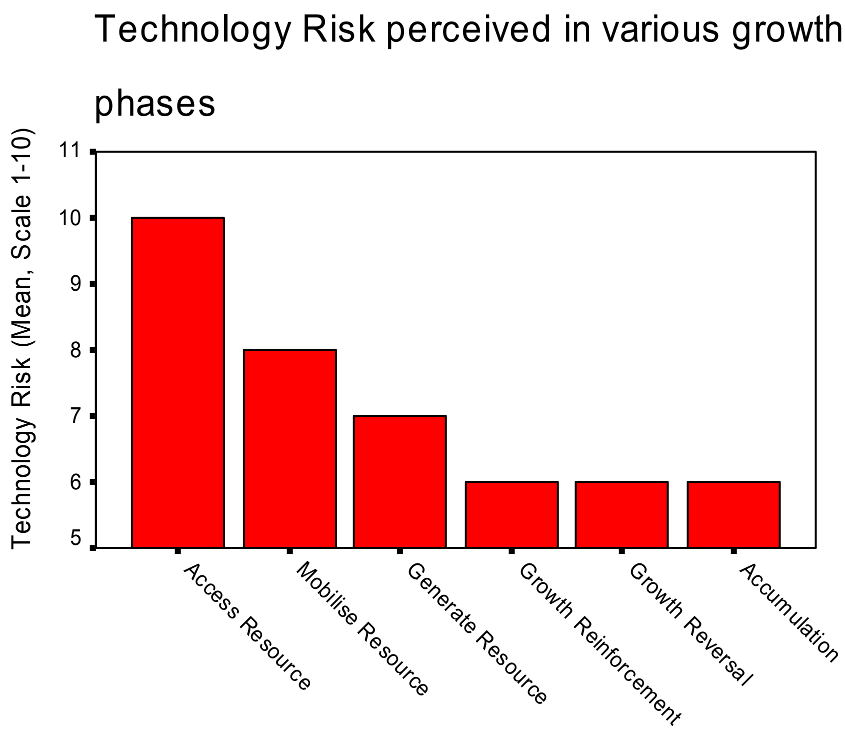
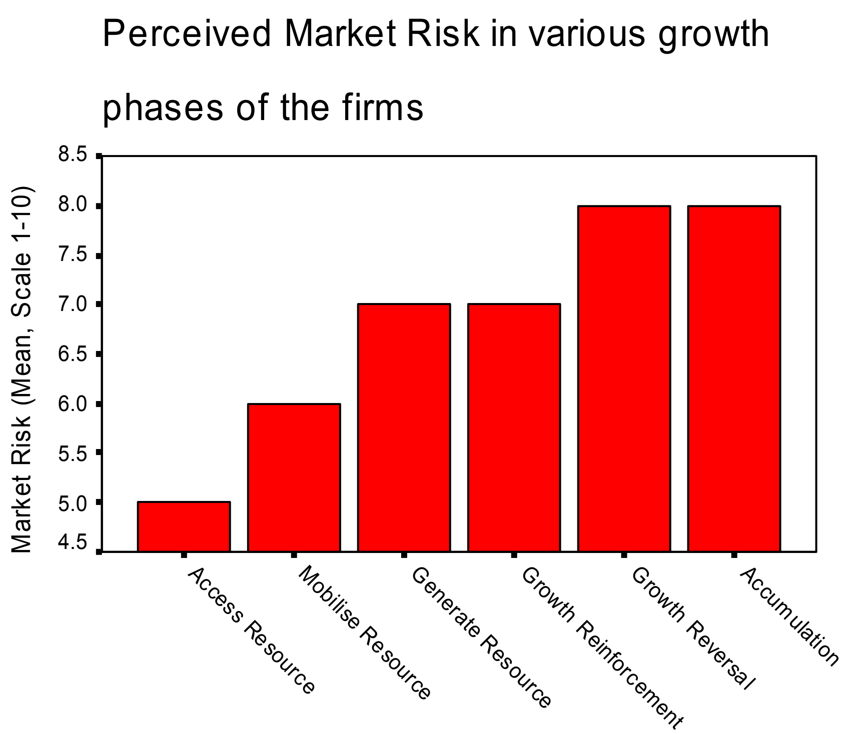


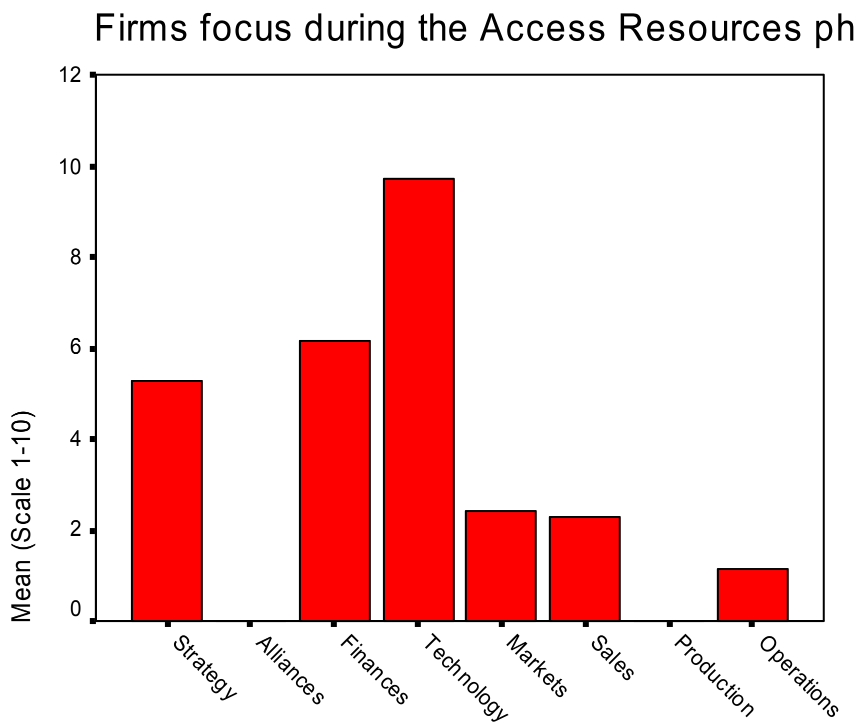
Chart 6:



Technology risk seems to go down as the firms understand the technology and develop core competencies as they traverse through various phases of their growth where as the market risk seems to grow higher which seemed counter intuitive. The theory that ' you build it and they will buy' does not hold here and companies realized that it is getting difficult to market these products because the fuel infrastructure is not in place, balance of plant improvement are not done at a faster pace than the fuel cell firms would like to and one other issue that was mentioned was with the bleeding edge technology the product obsolesce is very fast and since people are looking and wanting the latest technology makes it difficult for fuel cell firms to productize the technology that is already available because of the reason of obsolesce.

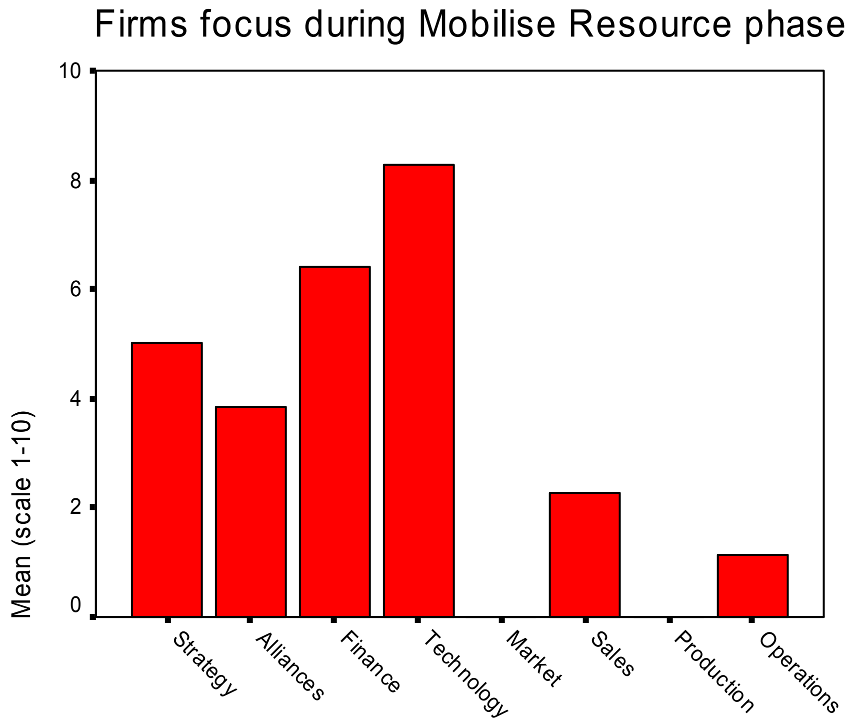
Since most of the firms are in phase 3 (generate resource), the analysis of the managerial expertise focused on during these three phases is described below in the charts.

Chart 7:



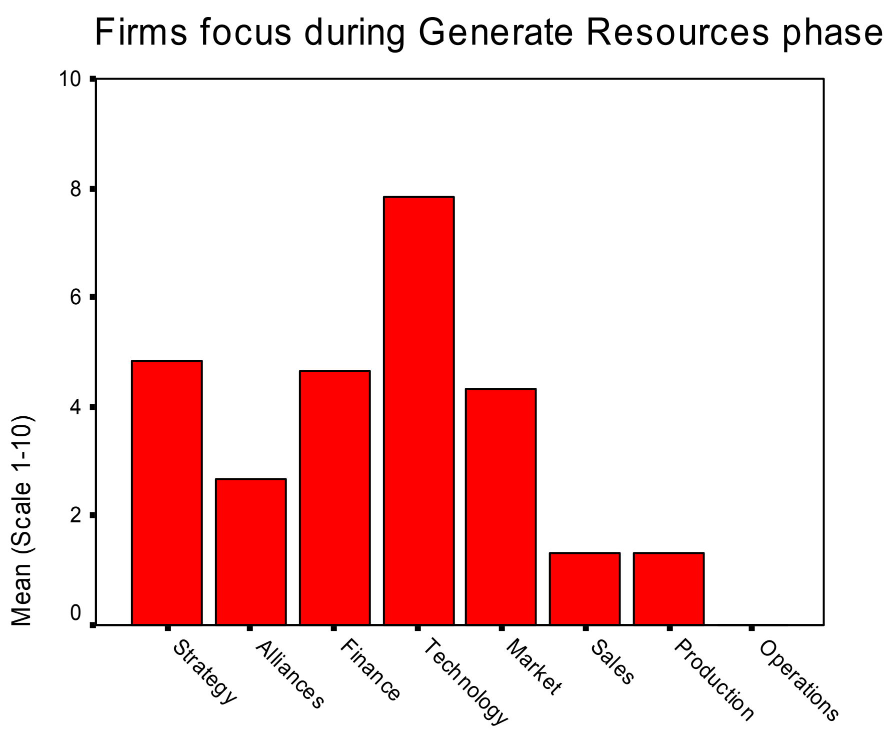
During the Access resources phase (First Phase in the growth) the predominant focus has been on Technology and Finance.

Chart 8:



During the Mobilize resource phase (Phase 2), once again the focus has been on technology and finance. One of the categories that also got attention was alliances as compared to the phase 1. This is explained by the fact that the firms realize that it would need the efforts of other complementary industries to make the fuel cells happen.

Chart 9:



During the Generate resources phase (Phase 3) the predominant focus has been technology, finance and strategy.

SECTION 5: Founders experience

Section 5 dealt with the founder's experience before establishing the company in terms of education and prior work experience. It was found that all the founders had higher education ranging from PhD in material science, Master's in Engineering to a master's degree in Management. The experience range is also pretty broad. One had converted his PhD idea into a fuel cell company where as others had experience in contract R&D, Finance, Engineering, and Operations. It was also found that at least one founder is still active in each of the eight firms that were interviewed. This shows that the industry is pretty much in its early stages. No dominant company has emerged yet.

SECTION 6: Financing

This section dealt with financing issues. Only two of the eight companies that were interviewed were public companies. Others companies are either self-funded or venture backed or Angel backed. Companies are planning to raise public money but right now the window to raise money is pretty much closed because of the downturn in the economy. Unlike just prior to the internet bubble (2000), companies are finding difficult to raise equity because the venture capitalist are looking for companies that already have revenues. This makes it a tough environment for the fuel cell industry and has been pointed out by some companies.

SECTION 7: Firm Growth History

Firm's growth history showed a steady increase in employee and revenues, though not very substantial. There were four companies in the survey which had employees between 90 and 350. Others had substantially lower than 90 employees. As far as annual revenues are concerned none of the companies had ever crossed $20 million. Most of the revenues are from the government contracts and demonstration projects. None of the companies have been profitable because the cost of goods sold (COGS) plus the R&D expense is greater than the revenues by a considerable degree.

SECTION 8: Intellectual Property Protection

All the companies felt that the intellectual property protection is very high in importance. Most of the companies had at least a few Patents (either filed or pending).

ANALYSIS OF THE FUEL CELL INDUSTRY:

Future trends in the fuel cell industry:

Broad opinions of the top management regarding the future of the industry resulted in an interesting range of answers. Some felt that fuel cell integration companies will succeed in the future. They pointed out that the fuel cell companies are already out of the MEA (Membrane Electrode Assembly) business and they will be out of the stack business pretty soon. Component suppliers (material and process innovation companies) and smaller number stack suppliers will survive. Some felt that there will be lot of consolidation in the industry and there will be segmentation of the fuel cell industry based on the applications for which the fuel cell will be used. One response was that there will not be a fuel cell industry in the future but there will be a distributed generation industry where fuel cells will play a dominant role. One of the response felt that the pharmaceutical industry is a reasonable approximation of how things may look like in the future. There will be some big companies that license what they need – in auto the car companies will have products licensed from one or more other companies, but it will be at a small scale of production at this time – late demo phase, early product phase.

Stationary- Probably will have fuel cell companies that have good positions in the Distributed Generation market. Probably some form of partnership or even consolidation will multiple Distributed Generation product type – Fuel cells, Mini turbines, etc. offered by a solution provider. Hybrid Fuel Cell systems (Fuel cells–Microturbines, Fuel Cells-Lead Acid Batteries for example) may prove to be a winner in the early stage of the growth of the industry.

Portable – continue domination by the battery companies- Duracell, Eveready and some strengthening of the Japanese, particularly given their position in the rechargeable segment.

One other opinion regarding the future of the fuel cell industry was that there will be a shake-out and a few companies will remain – each focused in their industry, two or three in portable electronics, a few in stationary generation, one in automotive, one in military, etc. Many of the efforts (but not all) will be in a JV with an existing OEM within that industry.

As with all new technologies, the industry will take off when a fuel cell-based product can offer a dramatically increased performance or a valuable new functionality over the existing means of power generation / storage. To date, none of the technologies have all of the performance and cost characteristics necessary to disrupt the existing technologies. Also one common answer as to what is required for the fuel cell industry to take off is that the product has to be reliable and durable in real world environment (more money has to be invested in product development), cost reduction, simplification of core components (cell stacks), and improved reliability of subsystems beyond cell stacks. Cooperation on DG standards and codes for stationary applications, improved performance for auto and technology improvement for portable will also play a role in the successful take off of fuel cell market. Industry also desperately needs a few successes (some successful products and project) within today's price points which will propel the markets. The early to mid adoption numbers have to increase coupled with stable economy will also boost the fuel cell market assuming that there is no other new technology that is going to be better than fuel cell.

Sales and distribution channels:

Most companies are using a direct sales force; some have a distributor base as well. There are numerous people/companies around the globe that want to become distributors. Few to none want to help develop the product or take the early risk. They want a lower cost, more reliable product that they can mark up. They all claim to have some connection to important government officials or investors with lots of capital. However, few ever commit to use the technology or purchase a system. There are few companies interested in the installation and service side of the business.

One of the views was that the OEM's will have to develop the sales, installation and service force whether on their own or with a partner. The warranty and product liability return to the OEM and installation and service are critical to early success so they will want control over these aspects, at least in the early years of commercialization. There is always debate regarding an open or closed system architecture using the beta vs. VHS example. Most companies are trying to become the industry standard, it is too early to declare victory for anyone and this is one reason for the limited sharing of ideas between competitors and the promotion of various fuel cell technology types. For smaller companies the route is to have a JV with an existing OEM who already has the sales and distribution network in place or partner with a sales and distribution company that are really hungry to do the business of proactively selling rather that wait for the phone to ring from a customer. It is not realistic for these small companies to build these large and expensive networks from the grass roots. Larger companies could choose direct sales, direct service and additionally services of distributors (sales & service). Some of the fuel cell companies have already established relationships with distribution companies.

Complementary innovations:

Some of the complementary innovations and solutions that the fuel cell companies are waiting for are:

- Fuel source, storage and distribution
- Balance of plant improvements
- Small scale successes are needed to boost market confidence.
- A national distributed generation solution that is accepted by the market
- Small chiller units which convert waste heat for cooling purpose.
- Alternate fuel (pre-processed fuel)
- Low cost, high volume supply of performance ceramics for the SOFC industry
- Low cost, high volume supply of inverters
- Low cost, high volume supply of reformers.
- Lower cost catalyst formulation and deposition.
- Lower cost cell design for assembly
- Simpler system for products.
- High temperature membrane
- Nano-technology electrodes
- Software to control the systems even in remote applications.
- Cell stacks durability.

These also drive cost and reliability. The fuel cell is a great product, but it has limitations. It is impossible at this point to beat the grid in cost or reliability with a single piece of equipment- the grid has multiple redundant generating devices and is virtually free. The value of a fuel cell is the ability to have much higher power quality at your location to increase your grid reliability by an additional 9 times. It is currently expensive to do this, but no other technology has this capability.

Disruptive technology or not:

There are varied answers to this question. Some of them are:

1. No, they are not disruptive technology. It does however disrupt the concept of what is possible as solutions to various problems – GHG (Green House Gases), pollution and grid congestion. It is not disruptive because fuel cells cannot be envisioned to completely replacing the current infrastructure of IC engines, turbine, hydropower etc. These other technologies can operate on hydrogen as well.
2. Yes, because they improve flexibility and allow consumers to move away from grid power, allowing local control at the point of use of electricity.
3. Yes, because the incumbents are low cost and are satisfactory to consumers (IC engines & batteries) but if fuel cells can better these in terms of cost and performance then they will be disruptive. Most of the fuel cell companies exist because they believe this will happen.
4. Yes, they are disruptive given a long time horizon. They will replace the incumbent technologies fully on a very long term. (100 years or more)
5. Yes, absolutely a disruptive technology. Fuel cells have the potential to obsolete batteries in portable electronics markets, IC engines in the automotive markets, and centralized power generation / distribution in the stationary markets. If that is not disruptive, what is?

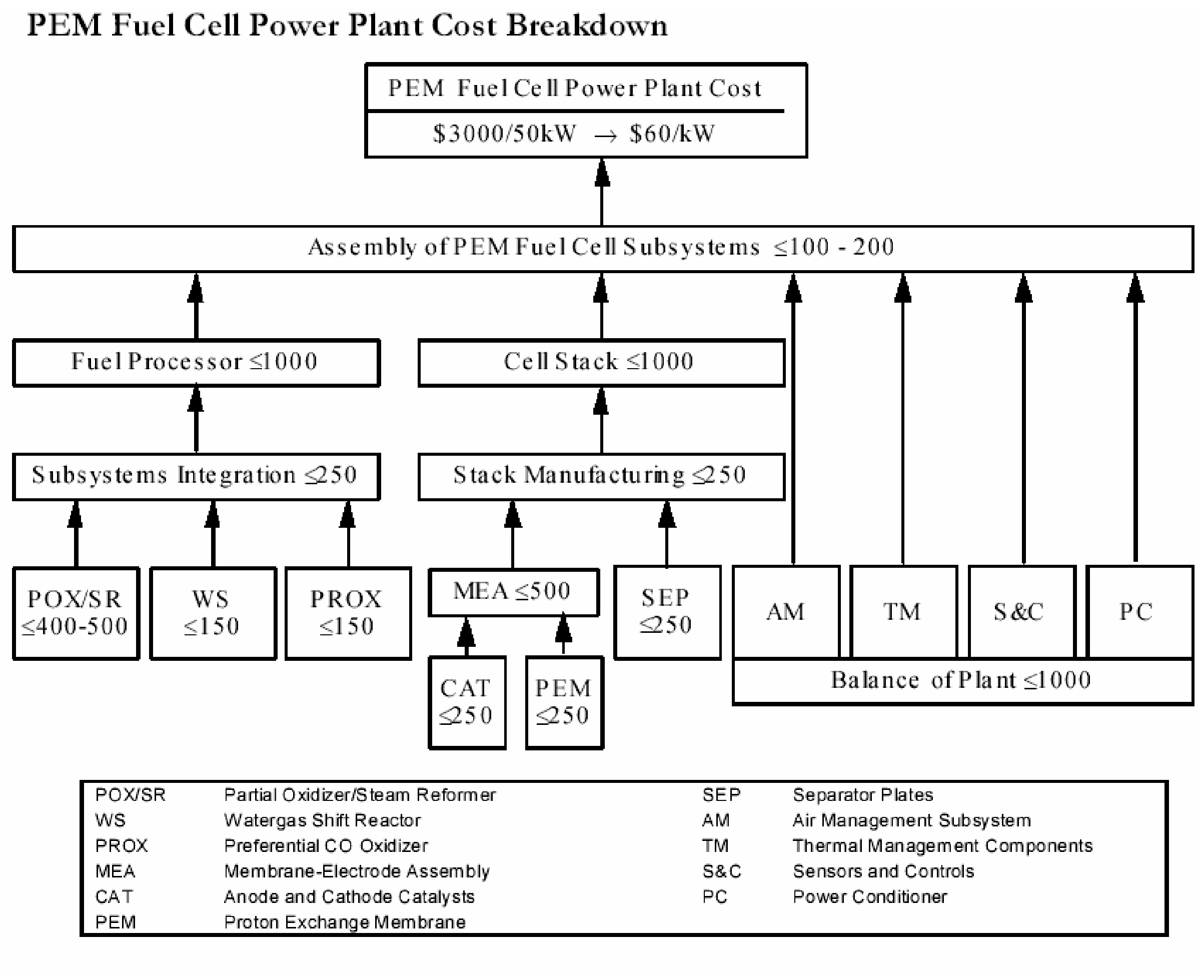
My view is that the fuel cells have the potential to be a disruptive technology however it going to be expensive and fuel cells have better efficiency than the technologies it is going to displace. Therefore it is a slightly different from Clay Christiansen's definition of disruptive technology in his book innovator's dilemma. According to Christiansen, almost all the disruptive technologies initially have poor performance and are expensive compared to the incumbent technology. This is not true in case of fuel cell.

Cost Reduction:

Cost ($/kW) is one of the major issues that is preventing faster diffusion of the fuel cell technology. The parts surrounding the fuel cell stacks should come down. It is can be compared to the packaging cost in a consumer goods for example we pay for the plastic bottle rather than the water when we buy a bottled water or the breakfast cereal may cost less than $0.25 but we pay more than 10 times that cost because of packaging expense. Particularly at this stage of technology where the fuel cell stacks are expensive, the industry cannot afford to have the other components like the inverters and control systems to be too expensive. Cost could come down if there are initial successes in the niche markets and the sales volumes increase. The other factors external to the fuel cell technology that could help large scale acceptance is the heightened environmental concerns and increase fuel cost (gas and petroleum). The argument that fuel cells will dominate because there will be a shortage in the fossil fuels is flawed. With the improved technology in the drilling industry and oil exploration, many oil reserves are found daily around the world. The theory that the oil (gas) will be exhausted is not a strong argument, at least for more than another 150 years. So the fuel cell industry has to find other innovative way to improve market adoption. Also there has to be mandates (maybe by the Government) that cause the big players to have a real stake in the technology on a long term. But more specifically industry has to focus on very integrated designs, system simplification, fewer moving parts, excellent sensors, more use of plastics and improvements in base metal catalyst.

In order to be competitive fuel cell systems must drop to $60/kW particularly for automotive applications to bring the costs inline with existing combustion technologies. The following illustration represents the component cost required to achieve this pricing level. It is noted that the cell stack is only expected to represent 40% of the total cost of the power plant, with the balance of plant and fuel processing comprising the other 60% of costs.

Figure 12: PEM Fuel cell power plant cost breakdown



Source: California Air Resources Board

The first generation of fuel cell products is based on phosphoric acid fuel cell technology and these units have current installed cost of around $5000/kW, too high to make them attractive in any but the most specialized niche markets. Second generation cells based on PEM, molten carbonate and solid oxide technologies will be able to compete at a significantly lower installed cost.

The US Department of Energy (DOE), under its fossil fuel program, is fostering the development of fuel cells for a wide range of power generation applications. A DOE performance target for the next generation of fuel cells envisages an efficiency of 50-60% (LHV) and an installed cost of $1000/kW-$1500/kW. It hopes systems meeting these targets will be available by 2003-04 (see the table below). However the feedback from the interviews point to a longer time frame than 2004.

In comparison, a diesel generator currently costs around $800/kW-$1500/kW and can operate with an efficiency as high as 50% in very large slow-speed applications. Gas turbines can cost as little as $500/kW and with a simple cycle efficiency of 30-45%.

Table 6: Installed cost and efficiency numbers in the past and in the future

	Installed Cost ($/kW)	Efficiency (%)	Year
First Generation	4,000–4,500	30–40	1996
Second Generation	1,000–1,500	50–60	2003
21st Century System	$400	70–80	2015
Diesel Generator	$800–$1,500	25–50	2000
Gas Turbine	$500–$1500	30–45	2000

Source: US Department of Energy — Reuters Business Insight

Industry structure / business model:

Most of the respondents felt that the since the technology is still so new, business model considerations are a bit premature. However a few ideas were expressed. For stationary power generation, a more unified grid interconnection standard would be helpful, fire marshal acceptance on national level to eliminate or reduce the need for town by town permitting, enable the wires companies (deregulated) to own DG assets and recover in rates, equitable stand-by and exit fees for DG. For portable – acceptance of methanol cartridges for air travel, distribution system for canisters. For transportation – hydrogen infrastructure or much simpler, smaller fuel reformers for on board reforming. Fuel infrastructure is critical for transportation industry like we have currently for petrol and diesel. It is also interesting to note that diesel outlet in the US are small in number compared to the petrol outlet and this has a correlation to the number of diesel vehicles sold in the United States. It also helps tremendously to have a closer collaboration between the government and the industry (a consortia approach may be one way to go about it). Larger companies should be given reason to support smaller companies and transfer know-how to support entrepreneurial drive which helps more industry partnerships.

ISSUES FACING THE INDUSTRY:

Fuel Cell firms are facing number of challenges for it to be competitive in a global market. Some the common theses that came out of the survey are the following:

1. Reducing fuel cell material and production costs to make them competitive with conventional energy technologies.
2. Accessing sufficient skilled resources. Companies are competing with other advanced technology sectors for highly specialized workers. There are not enough of these skilled employees to meet growing demand.
3. Working with other jurisdictions to develop universally accepted, consistent codes and standards
4. Demonstrating the economic, environmental and social benefits of fuel cells. The industry believes that the economic, environment and social benefits of fuel cells are not fully appreciated. This is hindering investment and support.
5. Accessing sustained capital to maintain both R&D and begin production. A number of companies are having difficulty securing long-term financing to conduct the R&D needed to resolve technical issues and undertake demonstration projects.
6. Ensuring ready access to fuelling infrastructure for all applications.

Firms felt that some of the issues cannot be solved by the individual firms but needs partnerships, with government and the private sector, to operate competitively on an international scale.

Technical Challenges:

1. Reducing the fuel cell stack and system cost.
2. Increasing durability (i.e., lifetime) and reliability
3. Reducing start-up time of a "cold stack"
4. Increasing power density and energy efficiency.

Global competition will be fierce, with more countries positioning themselves to be both producers and users of fuel cell technology. Strategic alliances, joint ventures, mergers and acquisitions are occurring, with some of the world's largest corporations moving into the industry. Companies that currently have the best technology or highest profile will not necessarily be the ones who would emerge as the dominant players in the long-term.

Cost of Production:

Production costs are potentially the industry's greatest challenge. For many applications, fuel cells need to be competitively priced with conventional energy conversions devices to be accepted in the marketplace. Users in certain segments will pay a premium because of the benefits of fuel cells, such as their reliability.

The Fuel cell industry is placing much of its focus and resources on bringing down production costs through solutions such as use of alternative materials (especially reducing the amount of platinum required in case of PEM fuel cells), developing advanced manufacturing processes and reducing labor inputs. Progress is being made. Costs have dropped significantly (from over $15000/kW to around $ 4000/kW), as innovative technical solutions are found. However, the industry recognizes there is still a considerable distance to go. Transportation fuel cell production will be a highly automated process once full commercialization is reached. This will assist in reducing costs, as economies of scale are achieved in production.

Sustained Access to Capital:

Greater sustained investment is needed in R&D and innovation initiatives, demonstration projects and pilot production. The cost of setting up and running production facilities on a commercial scale will also be significant.

Ongoing significant investment will be required in machinery and equipment for plant production, some of which will quickly become obsolete as technologies improve.

Access to Skilled Resources:

The fuel cell industry requires a knowledge-based, technology-oriented labor force. The fuel cell industry is competing with other sectors for these skilled workers and cannot fill all the jobs available, particularly in engineering. With commercialization this shortage could impede the industry's progress.
Industry clusters would benefit from university and college education programs focused on the fuel cell industry, and applied training at technical schools in areas such as product development, maintenance and continued technology research.

Demonstration of the Benefits:

As an emerging technology, fuel cells are not well understood by many people, either in terms of how they work or their economic, environmental and social benefits. This is hindering support for the technology.

Demonstration projects are one way the benefits can be shown. Government and other businesses can play an important role in this process by being early adopters and by participating in demonstration projects across the country in a variety of applications. Governments can also provide incentives for others in the public and private sectors to adopt the technology.

Codes and Standards:

The lack of understanding of fuel cells and related fuels is reflected in the fact that few government/industry codes, standards or permitting requirements have been developed or finalized to date. This is especially the case in the transportation sector and the distributed power markets where stationary fuel cell will compete. Appendix C list of companies currently active in the organization to define standards.

Transportation Fuelling Infrastructure:

There are conflicting views as to which fuel or fuels will ultimately be most suitable to power various fuel cells. Existing infrastructure provide adequate distribution for some fuels, while some would require relatively simple modification. Yet others would require the development of a significantly new fuelling infrastructure.

The cost of developing the fuelling infrastructure for transportation fuel cells in particular could be substantial, although little data is publicly available to allow reasonable estimates. The cost will also depend upon whether gaseous hydrogen or hydrocarbon fuels are used. Hydrocarbon fuels would required onboard reformers, but would offer more ready access to fuel.
There may be delayed returns on the investment in fuelling infrastructure. This will discourage providers from entering the market until the exact nature and timing of demand is better known. It will also depend on the pricing over time of conventional fuels. This could be influenced not only by supply but also by government taxation.

INDUSTRY DRIVERS:

The key factors driving the development of the fuel cell market include:

Environmental concerns: Air pollution and global warming are leading to more stringent environmental regulations and emission standards to protect our environment and health. Fuel cells have zero or near zero emissions (this may be debatable) and are recycled. Further, the efficiency of fuel cells in energy conversion results in lower levels of fuel being required, and therefore of Carbon-di-oxide and other emissions that occur in the production of the fuel.

Energy Security: This has recently become of even greater strategic importance to the US, Europe, Japan and other countries heavily reliant on imported oil. Fuel cells can use a variety of fuels and are not reliant on oil-based products (depending on the technology employed).

Electricity reliability: This is a growing problem in the US, which has experienced brownouts and blackouts in major population centers (e.g., California) due to electricity demand exceeding supply. Fuel cells provide the potential for an extremely reliable source of power.

User savings: By providing great energy efficiency and reliability, fuel cells can offer significant cost savings to users. For businesses involved in the production and transportation of goods and materials, reduced energy costs could enhance their competitiveness in the market place.

Performance standards: A growing share of the market is seeking energy conversion devices that offer greater reliability and life, especially in the portable devices market. Fuel cells have the potential to be very durable and have the potential for long life as a power unit.

Fuel stock efficiency: There is a need to generate more power per unit of fossil fuel to extend supply. Fuel cells are highly efficient, with approximately twice the efficiency of internal combustion engines, and allow co-generation through the heat generation of certain types of fuel cells. This increased efficiency also lowers levels of carbon dioxide and other emissions produced per kWh of power produced.

Sustainability: More nations are focused on securing sustainable energy sources that reduce non-renewable resource consumption and associated infrastructure costs. Fuel cells offer an opportunity for countries to move towards greater sustainability in resource consumption.

Off grid power: Access to energy in many remote locations around the world is limited by the reach of power grids. Fuel cells are well suited for use in distributed applications and remote locations, and could successfully replace many of the portable power units currently used to generate electricity. They are also ideal for urban areas where the addition of electricity transmission line is not possible like Tokyo city for example.

Very clearly, fuel cells are entering the market at a time when countries face growing pressure to adopt alternative energy technologies on a large scale. The challenge for the fuel cell industry is to ensure that it can deliver competitively priced, performance-proven products as demand grows.

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APPENDIX A:

QUESTIONNAIRE:

This correspondence is a part of student research work at the MIT Sloan school of management

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QUESTIONNAIRE NOTES

1. In completing this questionnaire, you are being asked to co-operate in research for a Masters Thesis being supervised by Steve Connors, Director, AGREA - Analysis Group for Regional Electricity Alternatives, MIT Laboratory for ENERGY and the ENVIRONMENT (LFEE). This research aims to study the growth of Fuel Cell firms and deduce some hypothesis based on this study.

2. The answers and opinions expressed in this questionnaire and any follow-up interviews are completely confidential. Any information would be used only by myself and would not be available to company, MIT, or any other outside people. No situations, personalities or even participating companies would be identified and all information will be aggregated into a final report eliminating all possibility of identification.

3. In answering the various questions please be as frank and as honest as possible for the success of this study depends on the completeness of the information you provide.

4. If a personal interview is not feasible then please answer the questions in the questionnaire in the blank space provided and email it back to me.

5. A final report summarizing the results of this study will be made available to all participants.

Survey questionnaire

Section 1: Company Background Information

Company name: ____

Company location: ____

Name of interviewee: ____

Position of interviewee: ____

Length of time at firm: ____

Year of company formation (current form): _________ (original company) ________

Categorize your firm as one or more of the following:

SME (Small or Medium Sized Enterprise)	
NTBF (New Technology Based Firm)	
Spinoff from large company	
Large company division or R&D lab	
Research consortium	
University lab	
Other (please specify)	

Section 2: Local Influence on Growth

1. How involved is your company with industry associations' activities locally?
   Rate from 1 to 10 (1 = no importance, 10 = high importance)

	1	2	3	4	5	6	7	8	9	10
No importance										High importance

2. How important to your firm was / is the presence of a local:

	Past	*Current*
university,	_______	________
research lab,	_______	________
or the R&D capabilities of a large firm?	_______	________

	1	2	3	4	5	6	7	8	9	10
No importance										High importance

3. How important to your firm was the local presence of:

	Actual History	*Desired*
angel investors,	_________	________
venture capitalists,	_________	________
legal firms,	_________	________
accounting firms	_________	________
an incubator	_________	________
science park	_________	________
other (please specify)	_________	________

	1	2	3	4	5	6	7	8	9	10
No importance										High importance

4. How important is it that these local entrepreneurial service firms have some knowledge of your industry or technology?

angel investors, __________

venture capitalists, __________

legal firms, __________

accounting firms _________

an incubator _________

science park _________

other (please specify) __________

1	2	3	4	5	6	7	8	9	10
No importance									High importance

5. a) If one or more of the founders of your firm lived in Winnipeg / Kansas City / Newcastle, could your firm have been started there?
(yes/no) ________________

b) Why or why not? ____

6. What had the greatest positive impact on the growth of your firm?
Please choose one only

Local technical infrastructure / partner _______

Incubator ________

Key management individuals (please specify) ________

Strong IP and an important technological innovation _________

Venture capital ________

Angel investment ________

Government grant _________

Other (please specify) _________

7. What is the greatest asset of your firm currently?
   Please choose one only

Skilled knowledge workers ________

Senior management _________

Visionary CEO / dealmaker __________

IP and technology ________

Market reputation ________

Distribution agreement ________

Other (please specify) _________

8. What was your greatest management challenge to date with this firm?
   ____

   ____

9. What is constraining your growth currently?
   Please rate each from 1 to 10 (1 = no importance, , 10 = high importance)

Management time _______

Waiting for complementary innovations _______

Financial resources _______

Competition / competitive products _______

Demand for your product _______

Other (please specify) _______

10. Please categorise your firm's past, current, and future strategy as one of the following:

(Check one only)	Past	Current	Future Plan
Licensing of IP			
In-house manufacturing strategy			
Manufacturing with outsourcing			
Service firm			
Other (please specify)			

Section 3: Growth Model for NTBFs

For the purposes of this study, we are using Garnsey's model of the growth of NTBFs. We would like to use this model to see similarities and differences of management focus at various phases of an NTBF's growth. Garnsey's model represents a firm's growth path as a series of growth processes which can occur sequentially or simultaneously, and which can occur more than once in the life of a firm. For example, a hypothetical firm's growth path, arranged sequentially, could be represented as: phase 1, phase 2, phase 5, phase 2&3, phase 4, phase 3, phase 6, and phase 7 (see **Figure 1**).

11. a) Can you envision your firm's experience fitting within this model? *(It is not important that your firm has experienced all phases, just that they have experienced some of the phases and can see the others as possible futures.)*
(yes/no) ______

b) If so, which phase(s) are you experiencing currently?

____

c) If not, in what ways does your firm's experience not fit into this model?

____

____

12. For each growth process that your firm has experienced, please indicate:

the approximate years that the phase began and ended,

a critical event that occurred during that phase,

the degree of technological and market risk,

and which types of managerial expertise were top priority in your firm during that phase. **(strategy, alliances, finance, technology, market, sales, production, operations)**

Note that some phases may not have occurred in your firm's history, and that some may be simultaneously present.

For the purpose of this study, we are defining:

Technology Risk - as the risk that the technological targets will not be met
multiplied by
the likelihood that the company will fail if the current (in each phase) technological targets are not met

*Technology risk = risk of achieving targets * company reliance on targets*

Market Risk - as the risk that the market will not accept / prefer
your product features
multiplied by
the likelihood that the company will fail if market does not accept/prefer the product features of your main product line

*Market Risk = risk of non-acceptance * company reliance on market acceptance*

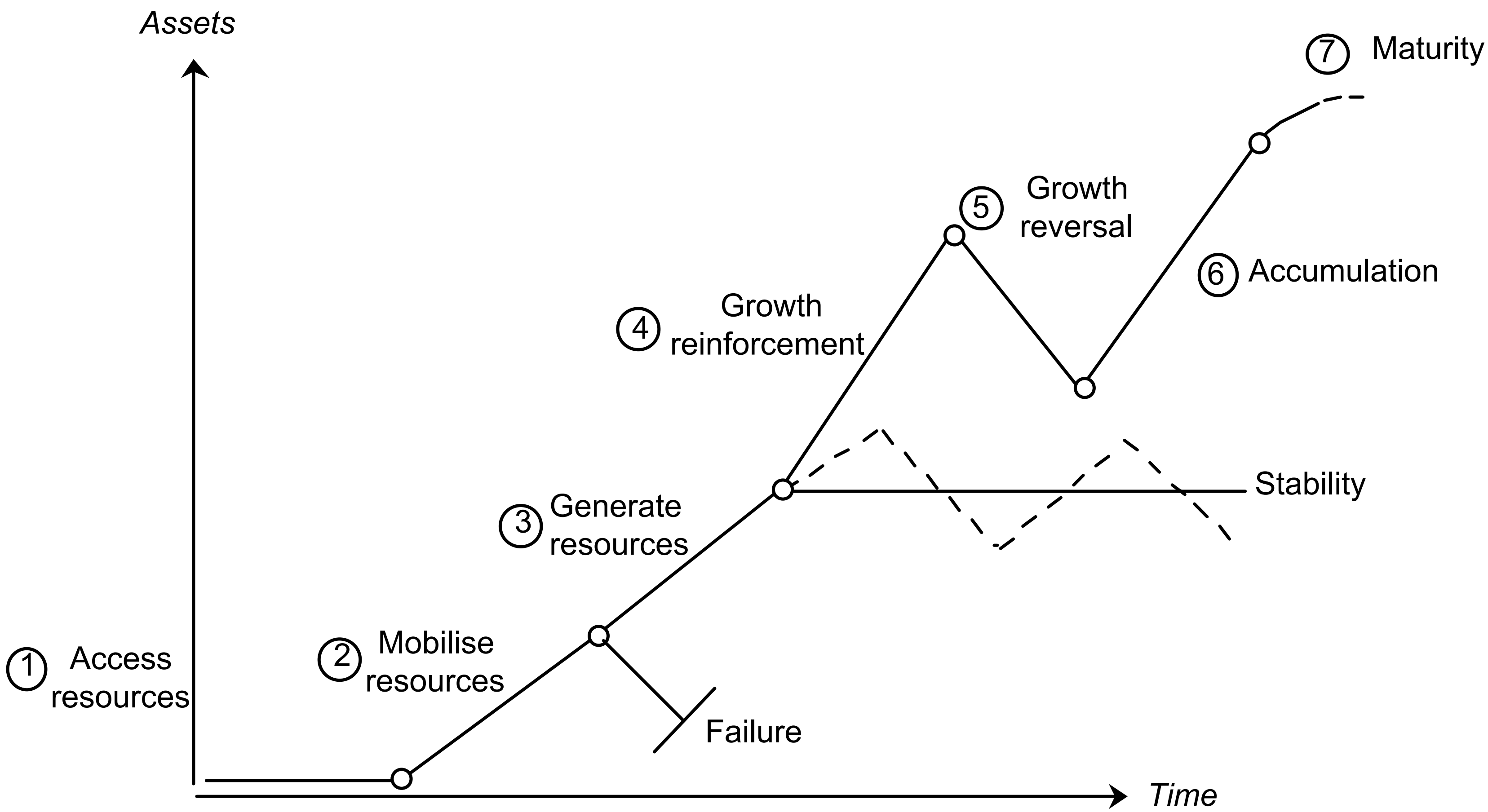


Figure 1: Firms' growth paths, comprised of growth phases and the transition points (marked by hollow circles) between these phases (Garnsey, 1998a)

	Year(s) Phase Begins	Year(s) Phase Ends	Critical Event(s) During Phase	Technolog y Risk (1=no risk, 10= high risk)	Market Risk (1=no risk, 10= high risk)	Managerial Expertise Focused on Which Area(s) (3 areas maximum, in order of priority)	Importance of local technological infrastructure (1=not important, 10= very important)	Importanc e of local angel investors (1=not important, 10= very important)
Phase 1: **Access Resources**								
Phase 2: **Mobilise Resources**								
Phase 3: **Generate Resources**								
Phase 4: **Growth Reinforcemen t**								
Phase 5: **Growth Reversal**								
Phase 6: **Accumulation**								
Phase 7: **Maturity**								

Section 5: Founders' Experience

13. What were the founders' educations before establishing the company?

i ____________________________

ii ____________________________

iii ____________________________

iv ____________________________

14. What were the founders' work experiences before establishing the company?

i ____________________________

ii ____________________________

iii ____________________________

iv. ____________________________

15. Are the founders still active in the company today?

i ____________________________

ii ____________________________

iii ____________________________

iv. ____________________________

Section 6: Financing

16. If you have venture financing, is it: Private ☐ self-funded
☐ angel backed
☐ venture backed
or
Public ☐ Small Cap (< 50)
☐ Mid Cap (50-500)
☐ Large Cap (500+)

17. Do you plan an IPO or outside venture financing in the future? __________

Section 7: Firm Growth History

18. Employee History

Year	Number of Employees	Year	Number of Employees
1983		1993	
1984		1994	
1985		1995	
1986		1996	
1987		1997	
1988		1998	
1989		1999	
1990		2000	
1991		2001	
1992		2002	

19. Revenue History

Year	Total Revenue	Year	Total Revenue
1983		1993	
1984		1994	
1985		1995	
1986		1996	
1987		1997	
1988		1998	
1989		1999	
1990		2000	
1991		2001	
1992		2002	

20. During your growth thus far, have there been periods of time when profitability has changed substantially? What events do you feel were linked to any such changes?

Section 8: Intellectual Property Protection

21. How important to your firm is the protection of your Intellectual Property?
(1 = no importance, 10 = high importance)

____

22. Which of the following methods do you use to protect your IP? (check all that apply)

☐ Patents
☐ Trade secrets
☐ Lead time
☐ Other (please specify) ______________________

23. Patents/ Intellectual Property growth

Year	Total # of Patents	Year	Total # of Patents
1983		1993	
1984		1994	
1985		1995	
1986		1996	
1987		1997	
1988		1998	
1989		1999	
1990		2000	
1991		2001	
1992		2002	

24. If you file for patent protection, at which stage do you file?

☐ As soon as an innovation is discovered in the lab or the production facility
☐ After commercial viability has been proved
☐ After full scale production has been proved
☐ Before you look for outside financing

25. List your main product offerings and the technologies on which they are based:

Year of Introduction	Product	Technologies

26. Indicate which of the above technologies could be considered materials innovations.

____

27. Percentage of Company (by revenue) involved with this materials innovation (0% to 100%) ________________ %

SUPPLEMENTARY QUESTIONNAIRE

RESEARCH INTO THE FUTURE TRENDS IN THE FUEL CELL INDUSTRY

1) What will the fuel cell industry look like in ten years?

2) What will it take for the fuel cell industry to really take off?

3) Who do you view as your three main competitors or there major players in the fuel cell industry in the future (from the information and knowledge available today)?

i)

ii)

iii)

4) What in your opinion should be sales, distribution and services network to support a fuel cell product effectively and what is your company's current position on these networks?

5) What are the complementary innovations (technology, services and products) that you are not currently working on in-house (or may be working on in-house) that are needed for large scale deployment (acceptance) of your fuel cells in the market place?

6) What technological advancement will be required in the next 2-3 years? What are some of the critical problems Fuel Cell industry in general is working on that may have impact on your company?

7) Do you consider Fuel Cells to be a disruptive technology? Why or Why not?

8) What will be required to bring down the cost of Fuel Cells to be competitive with other technologies, such as internal combustion engine, diesel engines, and the grid?

9) What industry structures or business models are needed to scale-up the fuel cell business from an infant industry to a large sustainable, growth industry?

10) What production methods for hydrogen make economic and environmental sense? (Consider the total energy balance, direct use of fuels, environmental costs to produce and ship hydrogen)

THANK YOU FOR YOUR CO-OPERATION

APPENDIX B:

COMPARISON OF POWER GENERATION TECHNOLOGIES

Comparison of Power Generation Technologies

	Diesel Engines	Natural Gas Engine	Steam Turbine	Combined Cycle Gas Turbine	Microturbine	PEM Fuel Cells
Electrical Efficiency (LHV)	30-50%	25-45%	30-42%	40-60% (combined)	20-30%	up to 50%
Size (MW)	0.05-5	.05-5	Any	3-200	0.025-0.25	0.01-0.5
Footprint (sf/kW)	0.22	0.22-0.31	<0.1	0.02-0.61	0.15-1.5	0.6-4
CHP Installed Cost ($/kW)	800-1500	800-1500	800-1000	700-900	500-1300	4,000
O&M Cost ($/kW)	0.005-0.008	0.007-0.015	0.004	0.002-0.008	0.002-0.01	0.003-0.015
Availability	90-95%	92-97%	Near 100%	90-98%	90-98%	>95%
Hours between overhauls	25,000-30,000	24,000-60,000	>50,000	30,000-50,000	5,000-40,000	10,000-40,000
Start-up Time	10 sec	10 sec	1 hr - 1 day	10 min - 1 hr	60 sec	5-20 sec
Fuel Pressure (psi)	<5	Jan-45	n/a	120-500	40-100	na
Noise	moderate to high	moderate to high	moderate to high	moderate	moderate	low
NO_x Emissions (lb/MWhr)	3-33	2.2-28	1.8	0.3-4	0.4-2.2	<0.02
Useable Temp for CHP (F)	180-900	300-500	na	500-1,100	400-650	80-120

Source: Onsite Sycom and Thomas Weisel Partners LLC estimates

APPENDIX C:

Organizations involved in the fuel cell codes and standards:

Vehicle Manufacturers

- Ford
- Toyota
- General Motors
- Nissan
- Peugeot
- Honda
- DaimlerChrysler
- Freightliner
- Renault

Fuel Cell Manufacturers

- Ballard Power
- International Fuel Cells
- Gore
- DHX
- McDermott Technology
- Gore
- Millennium Cell
- Plug Power LLC
- DMC2

Suppliers

- Air Products and Chemicals
- XCELLSIS
- Johnson Controls
- Freudenberg-NOK
- Eaton Corporation
- Motorola
- Vairex Corporation
- Eadie Consultants
- Liquid Filtration
- Curtis Instruments
- Donaldson Company
- Unifrax
- Zeon Chemicals
- Edgcumbe Technologies
- Mark IV Automotive
- Methanex

Collaborative Organizations

- American Petroleum Institute
- National Hydrogen Association
- Underwriters Laboratory
- US Fuel Cell Council
- Argonne National Laboratory
- Naval Surface Warfare Center
- ISO/TC22/SC21
- Japan Electric Vehicle Association (JEVA)
- IEC/TC105
- US Air Force
- US Department of Energy

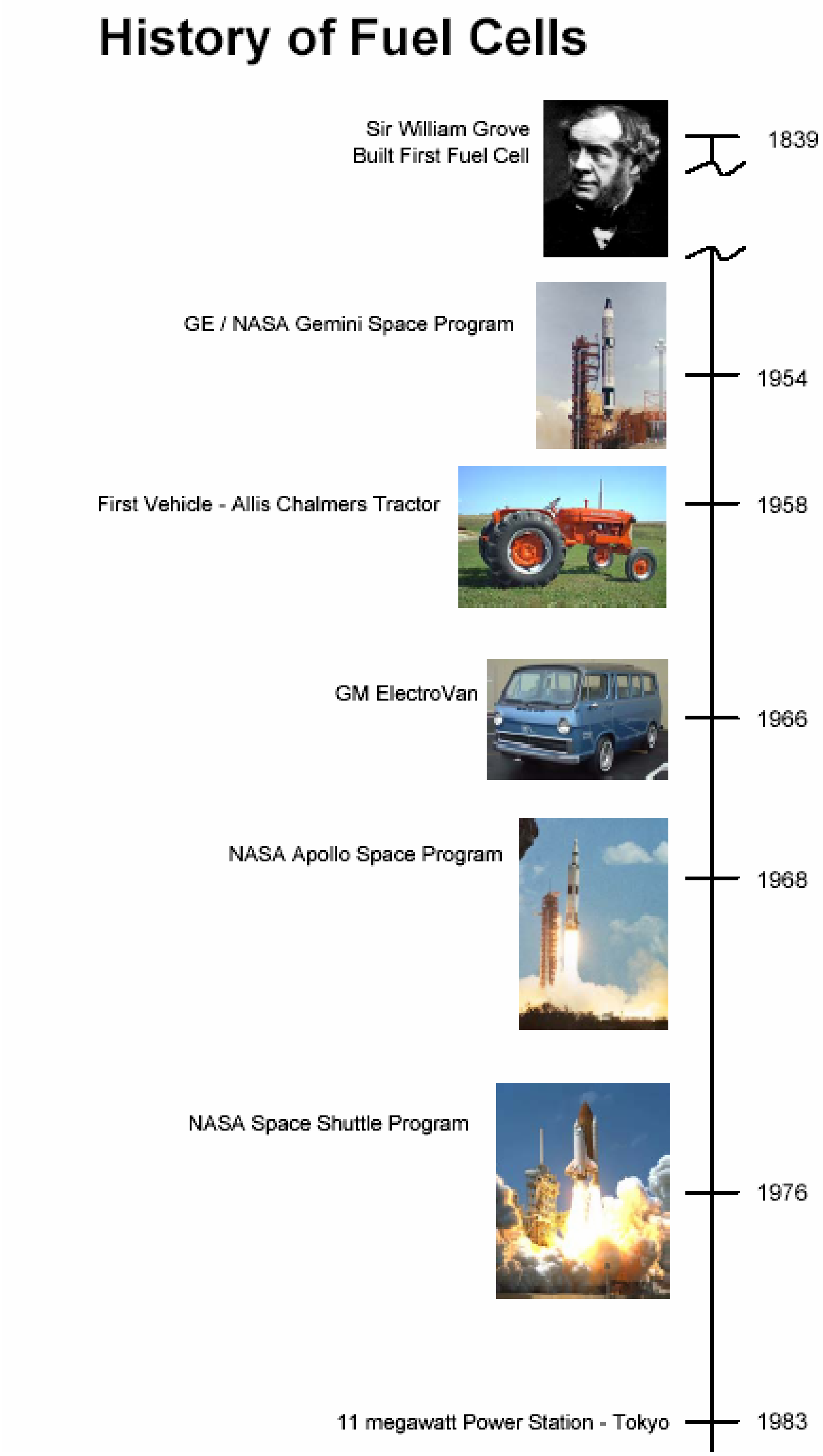
APPENDIX D:

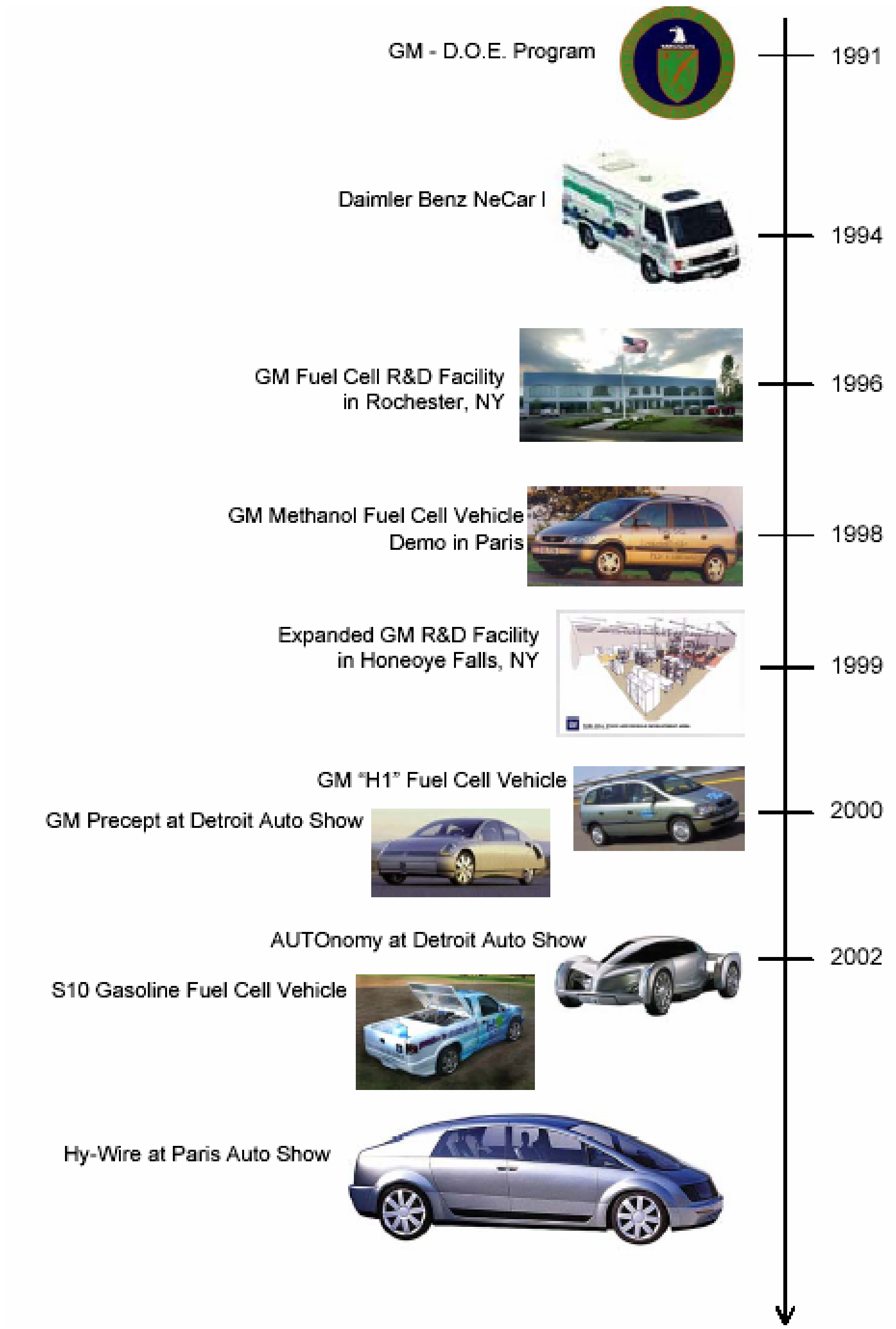
Companies involved in fuel cell that exist in 2003:

- Acumentrics Corporation
- Adelan
- Advanced Measurements Inc.
- Air Products and Chemicals
- Aluminum-Power
- Ansaldo CLC
- Anuvu Incorporated
- Apollo Energy Systems
- Astris
- Avista Laboratories
- Ballard Power Systems
- BCS Fuel Cells
- Catalytica Energy Systems
- Ceramic Fuel Cells Limited (CFCL)
- ChevronTexaco
- Coleman Powermate AirGen Fuel Cell
- Coval H2 Partners LLC
- Daimler-Chrysler's Fuel Cell Powered Vehicle
- Delphi Automotive Systems
- Dias Analytic Corporation
- DTI Energy, Inc.
- EcoSoul
- Electric Auto Corporation
- ElectroChem, Inc.
- Electro-Chem-Technic
- Element 1 Power Systems Inc.
- Energy Conversion Devices
- Engelhard Corporation
- eVionyx
- Evonyx
- Fuel Cell Materials
- Fuel Cell Technologies Corporation
- FuelCell Energy, Inc.
- FuelCellStore.com
- GE Power Systems
- General Hydrogen
- Giner Electrochemical Inc.
- Global Thermoelectric
- Graftech Inc.
- Greenlight Power Technologies, Inc.
- GreenVolt Power
- H Power
- Haldor Topsøe A/S
- Hamilton Sunstrand
- Heliocentris Energiesysteme
- Hydro Environmental Resources Inc.
- Hydrogenics
- IdaTech
- Johnson Matthey - UK
- Lynntech, Inc.
- Manhattan Scientifics
- McDermott Technology, Inc.
- Medisel Technology
- MesoFuel
- Metallic Power
- Methanex
- Millennium Cell
- Modine Manufacturing Company
- Mosaic Energy
- MTI Micro Fuel Cells
- Neah Power Systems
- Nuvera Fuel Cells
- Ocean Power
- Palcan Fuel Cells Ltd.
- Plug Power, LLC
- PolyFuel Inc.
- Powerball Technologies
- PowerNova Technologies
- Porvair Fuel Cell Technology
- Proton Energy Systems
- QUANTUM Technologies Inc.
- Shell Hydrogen
- Siemens Power Generation
- Smart Fuel Cell GmbH
- Solar Hydrogen Energy Corporation
- StarTech
- Stuart Energy Systems
- Sulzer Ltd.
- Sunline
- Superior MicroPowders
- Sure Power
- Technology Transition Corp.
- Teledyne Energy Systems, Inc.
- TH!NK Mobility
- Toyota Motor Co.'s Fuel Cell section
- Trimol Group Inc.
- UTC Fuel Cells
- Virent Energy Systems LLC
- W.L. Gore
- Xogen Power Inc.
- ZOXY Energy Systems

APPENDIX E:

History of Fuel Cells:




GM - D.O.E. Program
1991
Daimler Benz NeCar I
1994
GM Fuel Cell R&D Facility
in Rochester, NY
1996
GM Methanol Fuel Cell Vehicle
Demo in Paris
1998
Expanded GM R&D Facility
in Honeoye Falls, NY
1999
GM "H1" Fuel Cell Vehicle
GM Precept at Detroit Auto Show
2000
AUTOnomy at Detroit Auto Show
S10 Gasoline Fuel Cell Vehicle
2002
Hy-Wire at Paris Auto Show

APPENDIX F:

STATE SUPPORT FOR THE FUEL CELL INDUSTRY:

There are three primary methods by which states have sought to support early fuel cell development and deployment – mandates, direct customer incentives, and indirect incentives. Renewable Portfolio Standards (RPS) requires that Retail Electric Providers (REPs) purchase a minimum percentage of renewable energy to deliver to customers. A state or institution might also simply set a goal of purchasing clean energy, as the Governor of New York did for state buildings in his state, or California's new Power Authority has done for fuel cells there. Direct incentive programs provide customers, or the installing contractor or other third party, rebates or incentive payments, generally linked in some way to the value or the cost of the installed technology. The California PUC's Self-Generation Funding program is the most significant direct incentive program in the country that specifically includes fuel cells. Indirect incentive programs as used here, refer to tax incentive provisions, which allow customers to reduce their tax liability associated with a particular purchase or installation. Several states have adopted a variety of clean energy tax incentives.

Financial incentives have historically been used by states to encourage the purchase and installation of efficiency and renewable energy technologies. Traditionally, state programs can be classified as direct incentives, and indirect incentives, or a combination of these.

Direct Incentives Programs:

A. Rebates and Buy-down Programs:
Rebates and Buy-down Programs typically require a cost sharing arrangement whereby the customer shares a portion of the cost with the entity providing the funds. These programs usually cap the amount of monies available per project and may require additional criteria for entities receiving the monies, such as monitoring and verification. Rebates are offered at the state, local and utility levels to residential and business sectors. At times, rebates are coupled with low-interest loans.

Rebates and Buy-down Programs offer administrative ease; however, the rebate needs to be set a level high enough to offset the cost sufficiently to motivate customers to participate in the program. Rhode Island resorted to raising their rebate program to $3 per Watt in 2001 after very little response.

B. Grants:
Grants are usually made available to business, industry, government, utilities and schools. The programs vary in the amount of funds available, though typically entities can receive between $500 and $1,000,000 per project. The projects can focus on research and development or the commercialization of an emerging technology. Grants are usually provided to parties that respond to Request for Proposals for projects that meet program objectives.

C. Loans:
Existing loan programs offer zero to low-interest financing arrangements to residential, commercial, industrial, transportation, public and nonprofit entities purchasing fuel cells. Repayment of these loans may be determined on a project-by-project basis. These programs generally work best where the primary market barrier is not the cost effectiveness of new technology, but rather its initial capital cost. Because it is early in the development of fuel cell technology, the prices are still relatively high, capital costs are a potential barrier. However, a loan program alone might be expected to motivate customer adoption only in relatively select niche market until costs and prices come down further. A loan program coupled with other direct or indirect incentives could be expected to have broader impact.

Indirect or Tax Incentives:

A. Personal Income Tax Incentives:
Personal income tax incentives are tax credits or deductions extended to individuals to offset the cost associated with purchasing and installing clean energy technologies. Tax credits are often capped at a certain percentage or have a defined number of years in which they may be used. Oregon homeowners and businesses can take up to $1500 off their taxes for purchase of a fuel cell. Texas does not currently have a personal or corporate income tax, and so this is not an option for Texas.

B. Corporate Tax Exemptions:
Like tax incentives for individuals, corporate tax incentives allow corporations to receive credits or deductions ranging from 10% to 35% against the cost of equipment or installation to promote adoption of clean energy equipment. Arkansas offers a business income tax credit for companies that develop or manufacture fuel cells, of up to 50% of the funds invested. Texas currently offers a franchise Tax exemption for renewable energy investments by companies, although it does not apply to fuel cells currently.

C. Sales Tax Exemption:
Several states offer a sales tax exemption for the purchase of renewable energy technology, and a few have begun to include fuel cells under their definition of renewable energy technology. Maryland provides a sales tax exemption for fuel cells of 2kW or more. Maine exempts from sales tax the extra cost of a fuel cell vehicle over a normal version of a vehicle (up to half the price of the vehicle if no comparable vehicle). Texas previously exempted renewable energy form sales tax, but the exemption has since lapsed. Typically this tax credit or deduction does not have a cap. Some states, however, have a credit that decreases over time or make the tax credit contingent on the amount of money a corporation pays for fuel cell technology.

D. Property Tax Exemptions.
Where fuel cells would be considered part of a property, and therefore taxable, exempting the value of the improvement from property tax is a common method to avoid making a new technology more costly that it already is. Twenty-three states, including Texas, enacted property tax exemptions for renewable energy devices.

APPENDIX G:

Companies and People Interviewed:

Person Contacted	Position	Company	Location
Gary Mook	President & CEO	Acumentrics Corp	Westwood, MA
Scott Rackey	CEO	CellTech Power	Westborough, MA
Radha Jalan	President & CEO	Electrochem	Woburn, MA
Jerry Leitman*	President & CEO	Fuel Cell Energy	Danbury, CT
Roberto Cordaro	President & CEO	Nuvera Fuel Cells	Cambridge, MA
Roger Saillant	President & CEO	Plug Power	Latham, NY
Walter (Chip) Schroeder	President & CEO	Proton Energy Systems, Inc	Wallingford, CT
Paul Osenar	CTO	Protonex Technology Corp	Marlborough, MA
Thomas Voigt*	President & CEO	Siemens-Westinghouse	Pittsburgh, PA
Jan Van Dokkum*	President	UTC Power	South Windsor, CT
Michael Hsu	President & CEO	ZTek corp	Woburn, MA

* Unable to participate within the time constraint of the author's thesis, though initial contact was made and some of them have agreed to participate if time permitted.