

New Wave Technologies: their Emergence, Diffusion and Impact

**The Case of Hydrogen Fuel Cell Technology
and the Developing World**

Colofon

Basisontwerp en realisatie: Unigraphic, Universiteit Maastricht

ISBN 90-5681-177-0

Alle rechten voorbehouden. Niets uit deze uitgave mag worden verveelvoudigd, opgeslagen in een geautomatiseerd gegevensbestand of openbaar gemaakt, zonder voorafgaande schriftelijke toestemming van de auteur of uitgever.

New Wave Technologies: their Emergence, Diffusion and Impact

**The Case of Hydrogen Fuel Cell Technology
and the Developing World**

Rede

Uitgesproken bij de aanvaarding van het ambt van
honoraire hoogleraar Development Economics
op 27 juni 2003 te Maastricht

by

Lynn K. Mytelka¹



Universiteit Maastricht

¹ Lynn K. Mytelka is Director of the United Nations University Institute for New Technologies (UNU/INTECH), Distinguished Research Professor at Carleton University (Ottawa, Canada) and Honorary Professor of Development Economics at Universiteit Maastricht.

Introduction

The last quarter of the twentieth century may well go down in history as the spawning ground for new waves of technological change. Information and communications technologies (ICTs) were the first of these. With the advent of the semi-conductor, waves of technological change transformed traditional telecommunications processes, led to the creation of knowledge-based products in a wide variety of different industries and launched a new era in information processing. The internet opened still newer vistas in the generation, storage and exchange of knowledge.

Information and communication technologies have generated many benefits, but their distribution around the globe has not been even. Alongside the literature on the ICT revolution, there thus came its sequel, that of the digital divide. In the search for a manageable solution, infrastructure was identified as the prime factor in a pattern of international exclusion that had begun to emerge. Hidden from view was the knowledge dimension and the way in which scarce knowledge resources affect the use and diffusion of new technologies. Also largely absent were systemic considerations which might have brought earlier into focus, the associated problems of content, cost and ancillary manufacturing and service activities; all of which are yet to be resolved.

Despite their generic and transformatory nature, ICTs, in many respects, were a transitional technology and thus only a foretaste of what may be in store. They emerged within the paradigm of earlier mechanically based industrial revolutions and only now are beginning to incorporate the nano-level technologies and products that are central to new wave technologies. Their introduction has been incremental thus opening opportunities for those developing countries with financial, organizational and knowledge resources to begin a process of catching up.

In the second wave of technological change, that growing out of biotechnology and its application to pharmaceuticals and agriculture, the knowledge dimension, now focused on a strong science base and intensive patenting activity, is unavoidably evident. The belief that development pathways of the past will be those trodden in the future

must thus be tempered by this new reality. In a knowledge-based economy, the locus of knowledge creation and the forms through which knowledge is appropriated will increasingly shape opportunities for learning, for innovation and thus for growth and development.

A third wave of technological change, involving nano-materials and hydrogen as an energy source, will soon be upon us. Just how soon is a matter of conjecture since the extensive systems embeddedness of these new wave technologies, in social, economic and technological terms, have until recently, slowed their application, particularly in the transport sector. But that is changing rapidly and it is in this context that the role of the South as a 'technology user' is becoming increasingly problematic. Looking back to the impact of ICTs and Biotechnology, it raises the specter of a cumulative and path dependent growth in **inequalities** between North and South in the future.

The objective of the present paper is to explore this larger issue in relation to the development of one particular technology, the proton exchange membrane (PEM) fuel cell and its diffusion within the automotive industry and to assess its potential consequences for countries in the South. Fuel cells, which can convert hydrogen directly into electricity without combustion or moving parts, will, as one author put it, bring "energy conversion out of the "age of fire" into the "age of electrochemistry" (Williams: 1994,22).

Section one of the paper sets out a framework for the analysis of the technological change process in new wave technologies. Section two applies it to explore the development of the internal combustion engine (ICE) and the subsequent evolution of automobile technology based on this motive force. Section 3 analyzes the emergence and development of PEM fuel cells and identifies those factors most likely to affect the speed of their commercial establishment in the automobile sector. The concluding section will sum up these findings and provide an overall assessment of how far we have come towards the establishment of a hydrogen fuel cell vehicle as the dominant design of the future. It will then broadly sketch out some of the consequences that this may have for developing countries drawing upon the experience of the past several decades marked by the rapid diffusion of new wave technologies and the widening of technological and knowledge divides.

1. Understanding New Wave Technologies

Models of broad-based technological change frequently referred to in the literature as technological revolutions (Utterback: 1994; Freeman & Perez: 1988; Perez: 2002), traditionally distinguish three phases in the emergence and development of a technology. The first is the period in which the new technology emerges, product innovation is intense and product variety widens. This is followed by a transitional phase during which competition in the marketplace or performance standards set by law lead to the establishment of a dominant product design (Utterback & Abernathy: 1975) and open opportunities for standardization and mass production.² The third phase is that of the mature technology. Innovation continues to take place but incrementally along the established technological trajectory. The history of the internal combustion engine follows this path, as did many other mechanically based technologies of the past. New wave technologies, however, have three defining features that differentiate them from these earlier industrial technologies: their science-base, patent-intensity and systemic embeddedness. These differences suggest that the forces and factors shaping the pattern of technological change are also likely to differ. In what follows we explore these characteristics and their implications for the pace at which a dominant design is established, costs are reduced and systemic constraints are removed.

(i) A broad knowledge base increasingly anchored in the sciences

New wave technologies are anchored in the sciences and their knowledge base has developed less as the result of incremental change along a single technological trajectory, than through a combination of several distinct trajectories with significantly different scientific roots. These diverse roots, however, increasingly share a common platform – that of working at the nano-level of photons and genes.³ As a result, the

² Carlota Perez (2002,30) divides this phase into two: the full constellation of new industries, technology systems and infrastructure followed by the full expansion of innovation and market potential deriving from the technological revolution.

³ Michael Best has distinguished four technological periods characterized by diminishing critical size dimensions: the mechanical, electrical, electronic and nano-levels (ranging from 10 to 10^{-12} meters, mega to terahertz/sec or in photons 10^{-12} bits/sec) (Best:2001,133).

research laboratory has become central in the discovery and development of new products and processes based on these technologies; so much so that the revolution in molecular biology is said to have blurred the boundary between research and production (Henderson et al.: 1999, 267; Eliasson & Eliasson:1997,140):

Whereas models of technological change have traditionally distinguished between innovation in products and in production technologies and generally regarded these as sequential processes (Utterback & Abernathy:1975), new wave technologies tend to fuse product and process innovation at the experimental stage, that is, in the laboratory. Though accidental discoveries continue to occur, working at the nano- level, leaves less space for the individual 'inventor – tinkerer/ entrepreneur' who filled the pages of technological change in the past (Landes: 1969) and whose virtues were sung by many (Schumpeter: 1939:1942).

The products of new wave technologies are similarly combinatorial. On the input side, the ability to develop such products and to establish a 'dominant design' in industries growing out of new wave technologies has depended upon innovations from across a wide range of scientific and industrial domains. On the output side, these are rarely stand-alone products. Systems integration is so common a feature of new wave technologies that they have often been described as 'generic' technologies.

The combinatorial nature of new wave technologies requires both a wide range of knowledge inputs and a strong science and engineering base. Yet much of the literature on catching up in developing countries takes as its model, the slow, incremental process of change that characterized the mechanically based industries of earlier technological revolutions. From the perspective of the textile industry, for example, a "literate and numerate labor force is the important requisite" (Pack: 2000,79). But if we look more carefully at the catch-up strategies pursued in the Korean automobile and electronics industries, it was already evident that ".... imitative reverse engineering was possible only because Korea had a good stock of well-trained human resources" especially engineers (Kim and Yi: 1997,168). Most developing countries were ill equipped to follow the Korean path and without a radical rebalancing of current educational practices to strengthen tertiary education and build

networks among centers of research and training excellence, closing the knowledge gaps of the future will be even more difficult.

(ii) New strategies of knowledge generation and appropriation

A number of consequences for the pattern of competition flow from the high costs and risks inherent in science-based innovation, the combinatorial nature of new wave technologies and the systems integrativeness of their products. These add to the difficulties faced by developing countries in catching up.

Size and scale, for example, remain critical in the manufacture of products based on new wave technologies and these are radically changing the nature of competition in industries in which these technologies are applied. Historically, incremental changes that enhance the manufacturability of products and economies of scale in production have been critical in reducing costs and speeding technological diffusion and they remain important despite the greater role that science plays in new wave technologies. It would be misleading, therefore, to assume that technological knowledge, "...acquired and accumulated in crude empirical ways, with no reliance upon science" would not continue to play a role (Rosenberg: 1982,143) as it has in the refinement of products and manufacturing processes in earlier waves of technological change.⁴ Once again, however, new wave technologies exhibit a variation on this theme in several ways.

The combinatorial nature of products based on new wave technologies and their integration into the products and processes of other technological systems opens the way for larger firms to play a more prominent role in shaping the technological trajectory and the speed with which new wave technologies are incorporated into the production process than in the past. The cascade of products flowing from the application of microprocessors and lasers to audio/visual equipment, for example, has been shaped by only a handful of large firms and their

⁴ Indeed, "...we routinely fly in airplanes the optimal designs of which are achieved by fairly ad hoc, trail-and-error processes because there are no theories of turbulence or compressibility adequate to determine optimal configurations in advance. Extensive testing and modification based upon test results are still required."(Rosenberg:1982,143).

partners (Delapierre & Mytelka:2003). The application of biotechnology in the pharmaceutical sector has followed this pattern and we would expect something similar to emerge in the development of fuel cell technology.

Strategies of knowledge generation and appropriation that privilege larger firms are also playing a more significant role in new wave technologies than in earlier mechanical technologies. In this, they resemble those few science-based industries of the past -- chemicals, petrochemicals and later pharmaceuticals ⁵ -- whose relatively high research and development (R&D) costs were partly amortized through patenting. Though patenting might, under other circumstances, strengthen the role of small innovative firms, new wave technologies do not exhibit the traditional Schumpeterian pattern of industrial dynamics in which innovation gives rise to a high rate of new firm entry in a variety of new industrial segments and the gradual replacement of incumbents by newcomers.

Size has also been an important element in the appropriation of knowledge that enabled established firms to remain dominant. In the application of biotechnology to pharmaceuticals, for example, ever larger pharmaceutical firms have been able to appropriate new knowledge through in-house R&D, a high level of patenting activity, mergers and acquisitions and partnerships of various sorts including the development of knowledge-based networked oligopolies (Mytelka:2001). For developing countries, the success of efforts to develop uniform intellectual property rules at the global level ⁶ has broadened the scope of

⁵ *The chemically-based pharmaceutical industry was a latecomer in this process and much of the attention of biochemists and microbiologists in the 1920s and 30s was, in fact, focused on hydrocarbon chemistry in the petroleum sector and it was there that most innovations took place. Catalytic cracking in a fully continuous flow process, for example, drew together five of the major oil companies, two process technology firms and the set of German chemical companies which formed the IG Farben cartel into a collaborative R&D project that Chris Freeman describes as "...one of the largest single programmes before the atom bomb" (Freeman:1982,62).*

⁶ *All countries that are members of the World Trade Organization (WTO) are obliged to implement its Trade Related Intellectual Property (TRIPs) agreement with only a few years grace for developing countries.*

patents inevitably narrowing the path around an invention and limiting opportunities for innovation locally. Extending the duration of patent lives under such agreements add to this problem by significantly reducing the commercial incentives to engage in reverse engineering –the classic form of knowledge spillover that contributed so significantly to rapid development in Asia in the last decades of the 20th century. This, too, has disadvantaged developing countries in their ability to catch up and keep up with a moving frontier.

Moving an innovation from laboratory to the market, moreover, increasingly requires partners and a pattern of precocious partnering for research and development as well as standard setting has developed in industries based on ICTs (Mytelka:2001) and biotechnology (Mytelka: 2003). This, in turn, has given rise to changes in the nature of competition in the emergent and transitional phases of these technologies. In contrast to the arms-length firm-to-firm competition characteristic of earlier waves of technological change, in industries based on new wave technologies competition takes place among networks of firms bound to each other through a variety of alliances. Few firms from the developing world are partners in these knowledge networks.

The emergence of knowledge-based networks that extend across borders and industries has stimulated a pattern of oligopolistic market competition on a global scale. Unlike traditional oligopolies based on the statics of cross licensing and market sharing, however, knowledge-based networked oligopolies involve collaboration in the creation of new knowledge and in control over its evolution. They are dynamic, seeking to shape future technological trajectories as opposed to merely rigidifying the status quo. Through mutual forbearance and attention to the market strategies of rivals, oligopolistic competition among these knowledge-based networks may accelerate the process of technological diffusion at the same time as it structures the form and direction that technological change takes. This was evident in a variety of segments within the ICT sector, and how such competitive processes unfold will undoubtedly affect the speed with which fuel cell technologies are applied in automotive sector.

(iii) Systems embeddedness in the establishment of a dominant design

The third characteristic that new wave technologies share is their systems embeddedness. This has a bearing on both the speed and the direction of technological change. The combinatorial nature of their products and their embeddedness in complementary technological systems, for example, requires a high level of systems integration as a prerequisite to the establishment of a dominant design. The further development and diffusion of these technologies, however, are shaped by two other sets of constraints, those emanating from their embeddedness in economic and social systems. Of these, coordination in the development of the necessary infrastructure and change in a variety of habits and practices of both consumers and producers are of particular importance in shaping the pace of change in new wave technologies (Freeman & Perez:1988).

The incremental nature of earlier waves of technological change, made it possible to correct the failings of initial product models and resolve bottlenecks in emergent systems by progressively incorporating new technological inputs. The industrialization of spinning, for example, created a bottleneck in the weaving sector giving a push to innovation there. But investment in the textile industry was not lumpy and did not depend upon the immediate presence of a wholly integrated set of activities, from changes in the characteristics of cotton or wool, to the application of new technology in spinning, weaving, dyeing & finishing. Innovations could be introduced at different moments in the evolution of the industry and in different parts of the innovation system as these were evolving. As the innovation system could be built up incrementally and the knowledge intensity of production in different parts of the production process varied, many points of entry from a low skill base created opportunities for catching up by developing countries.

Overtime, the industries founded on these earlier waves of technological change, developed standardized components whose manufacture could be distributed among firms at a distance and subsequently assembled. New opportunities were thus created for technological upgrading in developing countries that could progress incrementally, as the knowledge, skill and production base expanded and deepened. This process of technological capability building has been well studied in the textile and clothing, automobile and auto parts and consumer electron-

ics industries of the 1960s, 1970s and 1980s (Amsden:1989; Lall:1990; Hobday:1995; Kim:1997; Ernst, Ganiatsos & Mytelka: 1998; Humphrey: 1998, Wong:2001).

In other instances, an existing system benefited from a new technology that could be incorporated. Early numerically controlled machine tools built upon an existing base in the custom machine tool industry. So, too, did fixed-line telecommunications systems move from manual switching, to mechanical cross-bar and then digital switches, each time incorporating a technology developed elsewhere into an already existing system. Although the investment costs of introducing these new innovations were high, the technology system in its broad outlines was already in place and in each case some developing countries moved in behind the front-runners putting the infrastructure in place and building the knowledge base needed to compete. (Desai et al:1999; Mytelka:1999).

In the genesis and emergence of radical technological changes, however, there is always some degree of discontinuity in infrastructure and institutions and a need, therefore, to learn new ways of doing things and unlearn habits and practices of the past.

Each technological revolution, originally received as a bright new set of opportunities, is soon recognized as a threat to the established way of doing things in firms, institutions and society at large... while competitive forces, profit seeking and survival pressures help diffuse the changes in the economy, the wider social and institutional spheres where change is also needed are held back by strong inertia stemming from routine, ideology and vested interests. It is this difference in rhythm of change, between the techno-economic and the socio-institutional spheres, that would explain the turbulent period following each big-bang and therefore the lag in taking full social advantage of the new potential (Perez: 2002,26).

The more embedded a technology is in other systems, the higher the risks to enterprises in their development and diffusion and the greater the resistance to change. Market forces alone, therefore, often fail to stimulate and support an innovation process when coordination requirements are high. The relative weight between the different para-

metric considerations that affect the speed and form of technological change, however, can be shifted through a broad range of government policy initiatives, in the absence of which transition periods may be longer, more difficult and more costly.

The basic contours of the approach taken here in analyzing the time horizon available to developing countries before the next wave of technology bursts upon them are graphically represented in **Figure One** and can be summed up in the following terms. The pace and direction of technological change is largely a function of the speed with which a dominant design emerges, costs are reduced and systemic constraints are removed. Each of these broader variables can be further decomposed. For example, the speed with which a dominant design emerges in new wave technologies, will likely depend upon the availability of finance for research and of technological integration. Both the speed at which a dominant design emerges and there is movement down the cost curve in industries based on these technologies will also depend on the formation of alliances through which standards can be set and the closer coordination needed for technological integration takes place. This will permit the development of economics of scale and scope which are prerequisites to cost reduction. Policy can play a major role in removing the constraints flowing from systemic embeddedness by altering the trade offs between the relative costs and risks of 'preservation vs. innovation' for the enterprise and for the consumer.⁷ In the following two sections this framework is applied to analyze the pace and direction of technological change in the adoption of the internal combustion engine and hydrogen fuel cell vehicles.

2. The Development Path of the Internal Combustion Engines

The internal combustion engine (ICE) was known since the late 17th century and its first commercial application took place in the 18th century in pumping water from coalmines. These engines used powdered coal as a fuel since liquid fuels, such as those derived from petroleum or even

⁷ Eventually it might be possible to develop a formal model of this approach. For the moment, however, it is used heuristically as the analytical framework with which to analyze the factors and forces affecting the pace at which technological change is taking place in the development and diffusion of fuel cell technology in the automotive industry.

alcohol were not yet available. Two centuries later, in 1862, Alphonse Beau de Rochas formalized the two major principals underlying the operation of such engines. The first was the compression of the combustible mixture prior to ignition and the importance of the compression ratio, that is, the lowest attainable ratio of surface to volume in the engine, to 'engine efficiency'. The second, the four stroke cycle in the reciprocating inward and outward movement of the pistons, was applied a decade later by Nicolaus August Otto to the development of an internal combustion engine and this cycle has since been called the Otto Cycle.

The emergence of the modern automobile can be dated to 1885 when the first vehicle propulsion by an internal combustion engine was developed in Germany simultaneously by Karl Benz and Gottlieb Daimler and patented by the latter (Graedel & Allenby:1998). By the turn of the century, the internal combustion engine had become solidly established as the dominant design, replacing earlier experiments with steam and electric powered vehicles, though the latter remained an alternative in small niche markets.⁸ The hand crafted automobiles of this period, however, were luxury products "...the playthings of the wealthy few" (Utterback:1994,127). In 1906, more than two decades after the first automobiles had appeared in Europe, the total number of such vehicles being produced across the whole of Western Europe each year came only to 50,000. (Hoffman & Kaplinsky: 1988,74). By that time, however, a dominant design had emerged.

The transitional period was marked by changes in production processes and organizational structures. In production, the major innovation was the adoption of automatic materials transfer in the manufacture of the Ford Model T. This speeded up the flow of parts and their assembly making mass production a reality (Best;1990). By 1914, the Ford Assembly line alone was capable of producing 300,000 vehicles per year and the price of cars dropped dramatically (Hoffman & Kaplinsky; 1988,74). Techniques of mass production were subsequently adopted elsewhere. Daimler Benz, for example, was in the forefront among European producers.

⁸ Postal service delivery vans, for example.

Organizationally, the corporate model came to dominate the industry, beginning with the incorporation of General Motors in 1908 and a few months later its acquisition of Buick.⁹ Other companies soon followed suit.

The further development and widespread use of the automobile powered by an internal combustion engine, however, was constrained by a number of systems within which it was embedded. One of these was the technological system involved in the production of fuel, including the development of catalytic cracking processes (Freeman: 1982,62) improvements in the antiknock quality of the fuel, expressed as its octane number and higher extraction of gasoline from the same quantity of petroleum through the use of heat, pressure and catalysts to rearrange the molecules of economically less important distilled fractions.

The second was the infrastructure upon which the automobile depended, notably, a distribution network for gasoline and a system of paved roads and highways. The Standard Oil Company, which had been founded in the United States in 1865, was innovative in locating its refineries near railroad lines and planning oil shipments so that railroad companies could make up daily oil trains. Investments in pipelines to link oil fields with refineries and railroads were undertaken later. Some usable infrastructure was thus in place when the sale of automobiles began in earnest. Roads were another matter, since the competition with railroads for long distance travel had favored the latter during the 19th century. Public financing of roads and highways was an important factor in the widespread development of a road network after World War I.¹⁰

Between 1908 and 1927 some 15 million Model T Fords were sold. The transition period drew to a close when the Model A was introduced in

9 Over the next decade, the General Motors Corporation (GM) took over other the Olds Motor Company, Oakland Motor Company, Cadillac and the Chevrolet Motor Company. It integrated backwards with the acquisition of Fischer Body and created an in-house research group.

10 This was done through the US Policy of Federal aid to the States, initiated in 1916 and through annual registration fees and taxes on motor vehicles and motor fuel.

1928, followed shortly by the V.8 engine series. Thereafter progress was slow and took place along an incremental technological trajectory marked by tradeoffs between power, efficiency and fuel economy. These are often attributed to consumer preferences. In the decades before the oil crisis in 1973, an overall reduction in mechanical novelty and variety resulted, although options proliferated (Abernathy:1978). Changes that did occur in production processes, moreover, led to such dedicated systems that opportunities for further innovation were significantly reduced.¹¹ As the problem of emissions were slowly recognized, their solution was reconceptualized within this nexus and strategies of preservation rather than innovation resulted. "It is not that automotive technologies haven't improved; it's that the improvements have been geared toward delivering power, not efficiency" (Fischetti:2002,42). The choice of an incremental path that favored preservation over innovation can be illustrated in the evolution of carburetion and fuel injection systems and by the adoption of the catalytic converter.

Efficient operation of gasoline spark-ignition engines, for example, depends on the air-fuel mixture. Ensuring that the mixture is delivered to the combustion chamber well atomized and at exactly the right ratio of air to fuel can be carried out by a carburetor or by a fuel injection system.¹² The camshaft, a century old mechanism that opens and closes the engine valves which let a fuel and air mixture into the combustion chambers and release exhaust gases is still the dominant design. "A spinning shaft, it moves levers that open and close valves approximately 100 times per second in a fixed pattern" (Fischetti:2002, 46). This wastes fuel. Electronic controls have been introduced that allow some valve control, for example, to open valves only partway when little power is needed, but a real breakthrough would be to substitute electromechanical activators for the camshaft. These would provide software-driven control for each valve. Unfortunately current technology is not yet able to do this without excessive wear, engine noise and

¹¹ *The impact of this on the ability of the Big Three US firms to compete with the flexible production systems introduced by the Japanese, became the subject of considerable attention in the 1980s and led to the establishment of the CAMI (GM-Suzuki) and NUMMI (GM-Toyota) plants and the link between Ford and Mazda (Womak, Jones & Roos:1990)*

¹² *Most of these systems were first innovated in the late 1920s in mechanical form and later updated electronically.*

vibration (Fischetti: 2002,46). Gasoline direct injection and digital micro-processors to control fuel and injection systems and spark advance are only the latest such improvements designed to preserve the mechanical base of this aging system.

The problem of emissions was recognized as early as the 1940s. By the mid-1960s motor vehicles were creating 86 million tons of pollutants per year most of which was carbon monoxide. Unburned fuel, nitrogen oxides, sulfur oxides, particles and lead compounds made up the rest. In 1965 the State of California adopted the first legislation to control exhaust products. The US Federal Government adopted identical laws two years later.

The initial reduction in carbon monoxide and unburned fuel emissions was done by modifying carburetion, using a leaner mixture and modifying ignition timing. This reduced compression ratios but these would increase again with some refinement in combustion-chamber designs to allow faster burning of the fuel (Somerscales & Zagotta 1989). Sulfur oxides and lead compounds were to be eliminated from the fuel. With the reduced in federal hydrocarbon and carbon monoxide emissions standards in 1975, the catalytic converter – an end-of-the-pipe solution – that reduced the need for further innovation, rapidly became the dominant design in dealing with the emissions problem over the next several decades (Somerscales & Zagotta: 1989; Newcomb & Spurr: 1989). **Figure 2** illustrates the incremental development path of the internal combustion engine since its application to transportation.

Consumers have always placed a high value on dependability in choosing a car. But other preferences have loomed large at various moments in time. The oil price shocks of the 1970s seem to have marked the 1981 preference structure with its emphasis on fuel economy (Table 1). Six years later, however, fuel economy was of least importance to the consumer and price had along with dependability become the prime concern. In the latter half of the 1990s, safety had replaced both fuel economy and price as the second most important buying preference. This change in preference was accompanied by a rise in sales of SUVs and other large vehicles.

Table 1. Consumer Automotive Buying Preferences

	Fuel Economy	Dependability	Price	Quality	Safety
1981	43	32	14	4	9
1987	4	44	31	8	14
1996	7	35	11	19	29
2001	11	30	8	22	30

Source: Derived from Office of Technology Policy:2003, Chart 3, p.6.

Despite the brief blip in consumer preferences for fuel economy, in terms of the trade off between efficiency, power and pollution, consumers and producers alike, have joined forces over this 20-year period in the pursuit of power. This is reflected in data from the US Environmental Protection Agency which shows that since the 1980s, horse power has increased by 84 percent "allowing vehicles to accelerate faster even though they have gotten heavier" at the expense of fuel efficiency. (Fischetti: 2002,41-42). Emissions have thus remained a problem and as automobile sales rose in the developing world and Eastern Europe, the internal combustion engine came increasingly under fire in international milieu as a significant and growing source of environmental damage.

Rather than engine efficiency, emissions and energy concerns are thus driving the move away from the gasoline powered internal combustion engine. Through regulatory policies, tax incentives and financial support for research and development (R&D) attention was directed primarily in two directions neither of which have produced the required magnitude of change. The electric vehicle floundered on the continued technological problems of battery storage and the consumer preference for rapid acceleration and refueling (Neufville et al.:1996). Its successor, hybrid cars such as the Toyota Prius and Honda Insight have only recently been commercialized and others will not appear until this year. Despite their newness, they are clearly an intermediary solution based on incremental improvements to the old model. Alternative fuels such as ethanol, when based on grains, still require heavy subsidies and make only a small dent in the overall pollution problem when they provide only 10 percent of the fuel.

We have thus reached a classic period in the evolution of technological trajectories -- the exhaustion of the current technological paradigm. Is the next wave of technological change upon us?

3. Moving Towards a Dominant Design in PEM Fuel Cells

Fuel cells are now touted as the wave of the future. Barely ten years ago this was not the case and certainly not in the transport sector where its first application to vehicle propulsion did not take place until 1993.

The fuel cell reverses the long known process of electrolysis, which uses energy to split water into its components. Instead it uses a fuel supply to combine hydrogen and oxygen thus generating an electric current. A first working fuel cell was demonstrated by Welsh Scientist, Sir William Grove in 1839, but not applied for over a century. The genesis of modern fuel cell technology then took about 100 years, somewhat less than in the case of the internal combustion engine. But the emergence of this new technology has taken much longer and this phase is still not complete.

During the 1950s, Allis-Chambers and General Electric of the United States worked on fuel cells of various sorts, but not until 1959 did N.T. Grubb build the first fuel cell with an ion exchange polystyrene resin membrane as a the electrolyte. L.W. Niedrach with whom he worked at GE, then turned the electrodes into fine metal mesh on which a platinum catalyst could be deposited. Patents were granted for the elements of this first proton exchange membrane (PEM) Fuel cell.

The PEM fuel cell was developed for the US space programme and provided electrical power on board the Gemini Space craft in the 1960s. Thereafter, however, GE sold its PEM fuel cell business and concentrated its work during the 1970s and 1980s on fuel cells with a phosphoric acid electrolyte, oriented towards stationary power. Phosphoric acid fuel cells were the preferred area for research on fuel cell technology throughout this period although some work on PEM fuel cells did continue based initially on a Nafion® membrane developed and patented by Dupont and applied mainly in a variety of chemical manufacturing processes.

Partly because of their potential for miniaturization and thus use in mobile equipment, the military maintained a residual interest in the PEM fuel cell. In the early 1980s, the Canadian Department of National Defense (DND), put out a research tender to produce a 'low cost' PEM fuel cell that could run on impure hydrogen produced by reforming a liquid fuel like methanol (Koppel:1999,63-64). Ballard, a small, Vancouver-based company founded in 1979 and doing research on lithium batteries, won this three-year contract. The first Ballard cell was based on the old GE fuel cell but used a Nafion[®] 13 membrane and replaced the GE flow field plates made of niobium by sheets of graphite with carefully machined fine grooves on the electrode side of each plate (Koppel: 1999,77). Both this innovation and the development of a special manifold to distribute the gases (Koppel:1999,80) were then patented. In two years, Ballard succeeded in developing an eight-cell stack that produced 130 watts, considerably higher than the 50-100 watts specified in the DND contract (Koppel:1999,86). By mid-1986 they had succeeded in creating a 12-stack version capable of producing 280 watts. DND awarded Ballard a second contract for further development. If changing the flow field design had quadrupled the performance in the first phase of its development, finding a new membrane 14 would result in yet another steep jump and the growing awareness at Ballard that "these power densities and overload capabilities could make the electric automobile happen" (Savage:1987,16).

For Ballard to play a role in further developing the PEM fuel cell for the automobile industry, a change in organizational model and in financing would be necessary. (Koppel:1999,126). In 1988 Geoffrey Ballard, co-founded of Ballard as a contract research and development organization, moved to the position of Board Chairman and a young executive, Firoz Rasul, became Ballard Power System's new President and CEO and research contracts were replaced by venture capital as the main source of finance. Over the next five years Ballard built ever more powerful and smaller PEM fuel cell stacks.

13 Nafion[®] was a polymer developed by Dupont and used in chemical processes such as industrial scale electrolysis of sodium chloride to produce chlorine, chlor-alkali ...Yarime (2003).

14 Initially this involved working with Dow Chemicals on a membrane that they were developing and in the 1990s creating an in-house team to develop a proprietary membrane of their own.

By 1993 the first Ballard Fuel Cell bus was plying the streets of Vancouver and Daimler-Benz and Ballard had agreed to a joint venture to which Daimler committed \$35 million over four years. In 1994 Daimler-Benz had the first of its New Electric Cars (NECAR I) on the road, a boxy cargo van whose passenger space was largely taken up by 12 stacks, collectively generating 50 kilowatts (kW) and producing 60 HP, and tanks holding compressed hydrogen. But technological progress was accelerating (**Figure 3**). Two years later, NECAR 2, had smaller, lighter stacks and could go 110 MPH and by November 2000 DaimlerChrysler's NECAR V was a five passenger, Mercedes Benz A class vehicle with a powerful 75 kW-engine and an on-board methanol reformer. It produces no exhaust emissions.

The year 1996 was a major turning point in the emergence of the PEM fuel cell as the prime contender to replace the Internal Combustion Engine. Over the next few years every major automobile company built alliances and/or created the in-house capability to develop fuel cell powered cars. In 1997, Daimler-Benz took a 25 percent stake in Ballard and was later joined by Ford, with a 13.5 % share and by Shell working to develop the fuel for new generations of fuel cell cars. General Motors and Toyota, partners in electric car development, began working on a fuel cell cars in 1999, Honda and Renault-Nissan, working initially with Ballard Fuel Cell Stacks and Hyundai and BMW using stacks produced by International Fuel Cells also joined the race.

How might we explain this sudden turn around on the part of automobile manufacturers? A proven concept, performance capabilities, the pace of technological change and a shortening time horizon all played a role. By 1996 the concept of a PEM fuel cell engine had been proven and the speed with which the Ballard-DaimlerChrysler-Ford alliance moved down its learning curve was simply remarkable. There was no longer a doubt that fuel cells powered by hydrogen or methanol would be far more energy efficient than gasoline cars and also more environmentally benign (OTP:2003, Ogden et.al:2002). It increasingly became evident, moreover, that they would match the performance of internal combustion engines and with an ultra capacitor to store energy, already commercially available on Honda cars, would provide the extra power for starts and passing that had turned consumers away from traditional electric cars. With fewer moving parts, the fuel cell engine would outlive the internal combustion engine and have the added advantage of an

electric drive train to deliver power to the wheels and software to provide the car with 'drive by wire' control that eliminates the need for mechanical systems traditionally used for steering, power and braking.¹⁵ (Williams:1994; Swoboda:2002,10).

By the late 1990s, the main question was no longer whether the Fuel Cell could supplant the internal combustion engine as the dominant design in the automobile industry but when this would likely occur. Although some articles continued to place the time horizon for commercialization far into the future (Freedman: 2002), most writers in the field had begun to talk of 2020 (OTP: 2003) and as the millennium drew to a close, some were suggesting that PEM fuel cell vehicles (FCVs) would be commercialized as early as 2010. That allowed very little time for automakers to learn, innovate, design and mass manufacture such a radically new product. Alliances were one solution.

Much as the pace of technological change had accelerated in the latter half of the 1960s, so, too, had the speed with which alliances were consolidated and systems integration was pursued. Two broad alliances emerged in this process.¹⁶ Fundamentally different in construction, the first, centered on Ballard, is modeled on a structure existing in the information and technology sector where networks form around rival component solutions and their producers such as INTEL in microprocessors or Microsoft in software (**Figure 4**). The second, centered on General Motors (Truett: 2001), adopted a design typical of the biopharmaceutical sector where large, final assembly firms are at the core of networks composed of smaller, vertically integrated companies (**Figure 5**). Rival networks such as these characterized the emergence of a dominant design in the development of the VCR, but the time frame, infrastructure investments and costs to the consumer and society more generally were far fewer than they are likely to be in the development of a fuel cell vehicle.

¹⁵ 'The Autonomy' GMs concept car presented in Detroit in 2002 was highly innovative in its design and showed the large number of new possibilities if 'form follows function'. see "Fuel Cells and Cars The Turning-Point?" *The Economist*, Jan. 12, 2002, pp. 70-71.

¹⁶ Other alliances such as that between Hyundai (**Figure 6**) and its partners are too small to affect this process and have tended to ally with one or the other of these two broad alliances in dealing with these major choices.

Currently, each of these alliances is pushing forward its own set of standards with regard to the choice of fuel, as this is linked to fuel cell design, and the need for either an on-board reformer or an on-board fuel storage system. Costs, technological complexity and time to market will affect tradeoffs here. But the choice of fuel is also system embedded and the availability of infrastructure and social acceptance can be expected to shape the parameters within which a decision about fuel will be taken. As Daimler Chrysler's Vice President for Research and Development thus argued, "[t]he most important unresolved issue with fuel cell vehicles is not the fuel cell, it's the fuel" (Financial Post, Dec. 12, 2001, p.4).

The choice of fuel is mainly focused on three alternatives, gasoline, hydrogen and methanol, although there are others such as the Hydrogen-on-Demand Natrium[®] Fuel Cell Vehicle developed by DaimlerChrysler using Borax. Curiously the initial choice of fuel by core members of these two broad alliances has changed overtime. Chrysler, began with gasoline as its preferred fuel but following its merger with Daimler-Benz, switched to methanol and in parallel the development of a more innovative technology based on sodium borohydride better known in its laundry powder version as borax.¹⁷ General Motors, which began with hydrogen and a radically new car concept, is today the major proponent of gasoline powered fuel cell vehicles. At issue are the interests and preferences of both producers and consumers, the systems embeddedness of the technology and the role of public policies in shaping the parameters within which these decisions will be made. These are summed up in **Figure 7** and related to the establishment of a dominant design.

If the primary goal is speed to market, then a gasoline powered fuel cell car appears to be a rational choice in the short term. Appearances,

¹⁷ *Step on the throttle and a 20 percent solution of sodium borohydride "is pumped past a catalyst made of ruthenium. This strips the hydrogen out of the compound and feeds it to the vehicle's fuel cell stack. The used slurry is then stored until it is time to refuel, when it is pumped out while a fresh batch is loaded" (Economist:2002,71). The reformer was built by Millennium cell. The Hydrogen-on-Demand[®] process eliminates on-board hydrogen storage and reduces dependency on fossil fuels. To the extent that it is widely available, it improves fuel security.*

however, might be deceiving. Developing a small on-board gasoline reformer for GM cars may yet take years. However, by minimizing the problems of both systemic embeddedness in an existing fuel distribution network and social embeddedness in the preference of both oil companies and consumers to preserve the old, that is preserve older products and existing infrastructure in the case of oil companies and maintain traditional habits and practices with respect to rapid refueling at a multitude of existing fueling stations, gasoline is the least disruptive of the choices. Once Toyota joined GM in a partnership to develop gasoline powered FCVs¹⁸, Nissan and Renault announced that they, too, would move in this direction as it now appeared that a gasoline powered fuel cell car would likely become the American standard.¹⁹ But the life cycle of gasoline does not make it an optimal technology from the environmental perspective, nor does it increase fuel security in the medium-term. By continuing to rely on gasoline, we reinforce existing habits and practices and reduce incentives to undertake the needed investments in longer term, more comprehensive change.

Methanol, derived from natural gas, represents a middle road. It has a higher octane number allowing for higher compression ratios and hence greater thermal efficiency compared to gasoline engines. Its well-to-wheel energy consumption is also lower than that for gasoline although tiny amounts of carbon monoxide and oxides of nitrogen are produced by the operation of the reformer and small amounts of evaporative emission may come from the fuel tank (IEA:1999,23-27; Williams: 1994,24). Many of the complementary technologies, such as processes for the production of methanol from natural gas and for the distribution of natural gas already exist and a number of countries with important

18 *In December 24, 2002 the Wall St. Journal reported that GM and Toyota had decided to "gar up to produce hybrid gasoline-and-electric versions of sport utility vehicles and pick up trucks" Clearly GM is still running scared after earlier efforts to produce and sell electric vehicles. The company now announces that its "goal is to be ready to build as many U.S. hybrids as U.S. consumers will buy, but not to be saddled with so many that it has to sell them at a loss..." EV World "GM, Toyota to make Vehicles that use Hybrid Energy".*

<http://www.evworld.com/databases/printit.cfm?Pageid-news>.

19 *<http://media.tbo.com/fhc> "Nissan-Renault to Develop Fuel Cell Cars that Run on Gasoline" AP June 4, 2001.*

automotive markets have significant natural-gas vehicle fleets.²⁰ Thus, countries that "... have natural gas distribution grids can introduce it as a vehicle fuel relatively easily, but nations without such infrastructures will find them very costly to establish" (IEA: 1999,23). In using methanol to power fuel cells, considerable progress has also been made. Small on-board methanol reformers are already installed in test vehicles and high compression canisters for on-board storage have been developed and tested. Methanol is also a close substitute for gasoline in the pattern of refueling and the distance between refueling stops.²¹ The choice of methanol, however, will lead to heavy investment costs in countries where natural gas is not readily available; the installed methanol production capacity is weak and the distribution network limited or non-existent. A methanol consortium was formed in September 2000 to assess further the relative costs and availability of methanol production, delivery and reforming technologies.²²

In the choice of hydrogen, there is an image problem to overcome as some still emphasize its explosive potential if stored as a gas. But there are a number of solutions to the distribution and on-board storage problems that are already commercially available. These derive from earlier experiences with the liquefaction and compression of natural gas (LNG & CNG) and demonstrate the safety of hydrogen in these two forms. Hydrogen powered fuel cell vehicle prototypes using these solutions are currently on the roads. They store hydrogen on-board under high pressure in canisters made of lightweight, high strength material such as aluminum wrapped with carbon fiber. Hydrogen powered FCVs are environmentally friendly but complementary technologies still need to be developed to ensure sustainable and energy efficient hydrogen production and the infrastructure for delivering hydrogen at the pump or to the home is in its infancy. Several experimental hydrogen fueling

20 Italy, Argentina, New Zealand, the Russian Federation and the United States.(IEA:1999)

21 Although "...the energy content of a unit volume of methanol is half that of gasoline, the fuel-cell car would be more than twice as efficient." (Williams:1994,23)

22 Its members are DaimlerChrysler, Ballard, Xcellis (now a subsidiary of Ballard), Norway's STATOIL Stanvick, BP, Methanex, a Canadian firm with a dominant share of the world Methane market and Basf, a German chemical company.

stations have been set up in Japan, Iceland, the European Union²³ and California as part of programmes to road test hydrogen powered FCVs²⁴ and by the end of 2003 there will be some 60 hydrogen fuel stations operating around the world (Geiger:2003,4), but the infrastructure costs of building a distribution network from scratch are very high.

The above review of options, however brief, raises a number of the critical questions that still need to be answered. Should we embark on building hydrogen fueling stations now, or should we wait until new complementary reforming or electrolyzing technologies are available to use the natural gas, water and electricity that already comes into homes and workplaces thus saving considerably on investments in infrastructure? Who will make such decisions and how will they be made? If we do take this giant step forward into a hydrogen economy, what kinds of hydrogen storage systems, especially in vehicles, would be socially acceptable? One possible future scenario involves research currently underway on the absorption of hydrogen into solid compounds such as metal hydrides or in nanotubes.²⁵ But these technologies are not yet proven. Should we thus adopt an intermediary technology and if we do attempt to reduce levels of pollution by using methanol or reformed gasoline, would this slow down the pace of realizing the ultimate goal of a hydrogen economy?

Despite the length of the emergence phase in the development of fuel cell vehicles and the range of issues that are still to be resolved, there is no doubt that considerable progress towards bringing PEM fuel cell vehicles to market has been made since the mid-1990s. A number of indicators support such a conclusion.

All major automobile companies have announced programmes to build fuel cell vehicles and many of these are investing heavily in doing so. According to figures supplied by the US Office for Technology Policy,

²³ *By the end of 2003, hydrogen fueling stations will be set up to deliver fuel to 30 fuel cell buses that will operate in the nine European cities participating in the EU's CUTE (Clean Urban Transport for Europe) project. These include Amsterdam, Barcelona, Hamburg, London, Luxemburg, Madrid, Porto, Stockholm and Stuttgart. DaimlerChrysler will supply the buses.*

²⁴ *These are being carried out by the California Fuel Cell Partnership.*

²⁵ *Based on a discovery by Iijima, a Japanese scientist at NEC and published in Nature in 1991.*

the US automobile industry invested some \$18.4 billion in research and development in 1997, higher than any other manufacturing sector (OTP: 2003,3), while the R&D investments of Japanese vehicle makers rose from an average of US\$11.8 billion in the period 1990-1995 to \$14.7 billion in 1996-2001 (OTP:2003,33).

On an individual company basis, DaimlerChrysler was one of the first to invest heavily in fuel cell research at home and through its alliance with Ballard. Along with Ford, it was also one of the founding members of the California Fuel Cell Partnership (CFCP) in April 1999. But others have since followed suit. General Motors and Toyota joined the CFCP, a year and a half later and as GM's chief executive officer Rick Wagoner stated in 2002, "Fuel cells are very important to GM's future. We've spent hundreds of millions already, and we're going to spend a lot more than that until we get into production vehicles."²⁶

A broad range of strategic partnerships now link all automakers in a set of global knowledge-based networks. In addition to the DaimlerChrysler- (Mitsubishi)-Ford (Volvo, Mazda) alliance with Ballard in which Honda is also involved and the General Motors (Opel, Suzuki)-Toyota (Hino, Daihatsu) alliance; Renault is linked to Nissan and along with Fiat works closely with Nuvera Fuel Cells, VW, BMW, and Hyundai work with International Fuel Cells and Peugeot-Citroen (PSA) works with Millennium Cell to develop their FCVs.

Within these alliances all producers of fuel cells and fuel cell stacks are flexible in the type of fuel cell they produce, tailoring these to their customs. Ballard Power Systems, for example, has focused on methanol fueled PEM fuel cell technology and expects to have a direct methanol PEMFCs that eliminates the need for a reformer, commercially available within a few years. Nonetheless, they have supplied hydrogen fuel cells to their clients on demand.²⁷ Nuvera Fuel Cells, believes that "a hydrogen society will exist within 20 years... Until that time, we must turn to alternative innovations to solve the world's growing energy demand. Hydrocarbon-fueled fuel cell systems offer one such solution."²⁸ Although specialized in gasoline fueled FCs with a metallic stack archi-

²⁶ Cited in *Canadian Driver Communications, Inc.*, www.CanadianDrive.com, March 19, 2002.

²⁷ See the Ballard Power Systems website at www.ballard.com

texture, Nuvera works with its partners and customers to produce other types of fuel cells as well. The absence of a dominant design does not seem to be a serious impediment to realizing a commercializable FCV.

Normally, there is a considerable lag time between research and patenting. But an online search of the US patent office data base reveals that the number of transport related fuel cell patents rose dramatically from 204 in the period 1991-1995 to 732 in the years 1996-2002. Data provided by the US Office of Technology Policy similarly shows a dramatic rise in patenting activity in the 'automotive fuel cell patent family' in the period from 1996 onward and a return to strong patenting activity in the 'hydrogen storage patent family activity' (OTP: 2003,3 & 23). These investments are having a positive impact on the speed with which technological progress is coming about and augurs well for a number of technological solutions to existing problems. One of these is the high cost of the platinum catalyst used in PEMFCs. Recent work on the substitution of cobalt for platinum is showing promise here and has already been transferred from the university laboratory to industry.

In addition to the sharp increase in patenting, there is evidence that, like the DaimlerChrysler experience discussed earlier, other automobile manufacturers are moving rapidly down their learning curves and engaging in systems integration. In a relatively short time, Honda, for example, moved from its first FCV, a hydrogen fueled vehicle with energy stored in metal hydrides, a motor power of 49 kw and the ability to seat only two passengers to its FCV4 in 2000 – a hydrogen fueled car with hydrogen stored under high pressure in tanks at 35 MPa, a motor power of 60kw and the ability to seat four people and still have space for luggage. Both vehicles used Ballard fuel cell stacks. Unlike the prototypes and concept cars of a few years ago, road testing of this new generation of FCVs, as a step towards commercial production, is already underway in many locations around the world²⁹ and Ford has announced that its hydrogen fuel cell "Focus" would enter into limited production at the end of 2003.³⁰

28 Statement by Roberto Cordara, President & CEO on the Nuvera website: www.nuvera.com

29 Fifty cars are also being licensed to organizations and municipalities in the US and Europe for testing in 2003.

Even though full-scale production of FCVs for most companies will not take place much before 2010, dual-purpose usage in stationary power systems and in FCVs is creating economies of scope for companies such as Ballard, International Fuel Cells and General Motors. This should enable these companies to reach their breakeven point of about 300,000 stacks per year without having to produce 300,000 FCVs a year. Economies of scale in the manufacture of automobiles might thus not be as much of a constraint as is currently the view.

"Serious pursuit of the fuel-car option", Williams wrote in 1994, "will require a major redirection of U.S. automotive R&D. So far only modest public resources have been committed to the relevant techniques" (Williams: 1994,28). Since then, governments in the United States, Canada, Japan and Europe have announced substantial programmes of R&D funding for the development of FCVs and are supporters of consortia to work on complementary technological systems. The Ecological City Transport System, ECTOS, began in March 2001 and will end in February 2005 "involves creating a hydrogen infrastructure and demonstrating fuel cell buses in Iceland's capital, Reykjavik, in the first large-scale, real-world trial of converting to a hydrogen infrastructure" (OPT: 2003,53). The US government established its Freedom CAR Partnership between the Department of Energy and the U.S. Council for Automotive Research composed of General Motors, Ford and DaimlerChrysler. Its primary objective is to promote the development of hydrogen as a primary fuel for cars and trucks and similar programmes exist in Japan. There is a need for research into the way in which these programmes are likely to structure the direction of technological change, however, before it is clear whether they are focused on supporting a process of change or on giving a new lease on life to technologies of the past. Though the emergence phase might thus be longer, given that current new ICE engine programmes will end by 2012/2013 (Truett: 2001, 39), and in view of the intensity of the work underway, the transition is likely to be very much shorter.

Conclusion

Is history repeating itself? The development of the international combustion engine began in 1885, when the first vehicle propulsion by an internal combustion engine was developed in Germany simultaneously by Karl Benz and Gottlieb Daimler. The next big landmark came in 1906 when the first flow through process of assembling automobiles led to the mass production of a 4 cylinder 15 horsepower car, the Ford Model N. In the development of the PEM fuel cell for vehicle propulsion Daimler-Benz has similarly played an innovative role when it became the first automobile partner of Ballard Power systems, developer of the PEM Fuel Cell for the transport sector in 1993. Ballard's second partner was Ford. Since then other networks have formed to compete in the establishment of a dominant design for fuel cells, the choice of fuel and for the distribution systems to provide fuel to these cells. This process is not yet complete and the parameters, which shape choices, are still in flux.

Historically, rapid movement down the cost curve through standardization and the creation of economies of scale, moreover, did not take place until a dominant design had emerged. Will the fuel cell car be different? Some of the data presented above, on dual use fuel cell technology, suggests that it will. With respect to fuel cells and the transport sector, however, we have far too little information on costs to evaluate this process.

If the future is 'hydrogen' should we wait until all pieces of the system are in place or do environmental considerations force us to take action now? If the latter, how might we build a path today that does not compromise change in the future? With regard to the transport sector, can two solutions –methanol and hydrogen, for example, coexist without wasteful investment? Would investment in gasoline reforming keep the market for petroleum buoyant and reduce incentives for change?

Among the many tradeoffs to be considered in dealing with the above questions, three are of particular importance:

- (i) The cost and complexity of short term vs. longer term horizons with respect to emissions reduction, fuel security and infrastructure investment,

- (ii) The impact of these choices on industry structure, competition and prices, and
- (iii) The incentives and constraints that present choices will create for innovation in the future.

Policies will clearly have a major impact in shaping the parameters within which the choice between tradeoffs will be made. Given the social, economic and environmental consequences that flow from each of these choices, dialogue between stakeholders would be needed to build awareness of these potential consequences. Here a consensus-conference mechanism that involved oil and gas companies as well as other energy producers and users, automobile and auto parts firms, the range of actors involved in fuel cell and ancillary technologies, researchers, consumers, environmentalists and policy-makers from national and local (urban) levels, would be a particularly effective means to assist government in arriving at socially and economically acceptable tradeoffs.

Support for policies that are oriented towards change, moreover, can only be secured through such a mechanism. Governments in the North will thus have to take a pro-active stance to 'promote the new' by organizing such a process. In parallel, there will be a need to create the kind of 'public knowledge goods' that have largely been missing in the rapid development of alliances and high rate of patenting. A better understanding of costs standardized testing procedures and vetted empirical studies are the foundation upon which serious social reflection and consensus building can be created.

Given the pressures upon governments, North and South, to deal with environmental pollution, can we wait until a consensus process plays itself out in the North before involving the South? Even more critically can the North carry out its own policies in building a hydrogen economy without bringing the South on board? And from a South perspective, should the pace of change in the North set the trajectory there? The latter would be the natural consequence of simply accepting that in developing countries "...the introduction of fuel cell technology certainly will occur significantly later than in the industrialized countries because of cost and infrastructure issues..." (OTP:2003,18). But should it?

There are a number of reasons why developing countries should be brought into the process of planning their transition as quickly as possible and why there will be a need for new sorts of North-South partnerships to help bring this about. From a Northern perspective, perhaps the primary advantage of involving the South now, is environmental.

Pollution reduction in the South is a win-win solution. The number of automobile and truck registrations is expected to increase substantially over the next fifty years, reaching 3.5 billion vehicles on the road by 2050, as compared with a 1996 figure of 670 million. Most of this increase will be in developing countries, in which vehicle registration is estimated to grow from under 100 million at the turn of the millennium to 2.5 billion by 2050 (OTP: 2003,18). It is thus surprising that so little attention is being paid to opportunities for the development and diffusion of fuel cell technology in these countries. Perhaps the only major programme currently underway is the testing of fuel cell buses with the support of the Global Environment Fund (GEF) in five mega cities with serious pollution problems: Shanghai, New Delhi, Sao Paulo, Mexico City and Cairo, located in countries with a strong scientific and engineering base. This is not typical of developing countries as a whole.

From the perspective of the South, how the North deals with environmental pollution has a strong bearing on their own opportunities for growth. These cannot simply be reduced to accommodate lower levels of pollution worldwide. Instead, that growth must be hitched to the development and diffusion of technologies associated with the hydrogen economy. Yet the process of catching-up in these new wave technologies is significantly different from traditional, engineering-based industries of the past. In these earlier waves of technological change, catching up depended more upon deepening production capabilities thereby ensuring that the clones, copies or OEM goods were, at the least, of similar quality and yet initially competitive because they were cheaper. There was thus no need for much domestic R&D in the early phase of a catch up process. Adaptation, modification that led to productivity increases or capital stretching could largely take place within the firm and through the strengthening of engineering capabilities. The process of catching up in these industries was thus an incremental one, in terms of the kinds of knowledge –bases that were needed, the sequential way in which they would be acquired, and the gradual building up of the system that enabled the imported technologies to func-

tion optimally in their new environment.

In science-based, patent intensive and systems embedded new wave technologies, however, the process of catching up differs from this traditional incremental process and its focus on single enterprises and on building basic skills first. Tertiary education and research are needed from the outset as they permit close monitoring of the changing technological frontier, enable the identification of opportunities for entry into new productive activities and provide the base for a more holistic, systems-oriented approach to policymaking for the transition. These new capabilities will have to be developed, as will the awareness, that such a focus is even necessary. The creation of new informal mechanisms for dialogue on these issues, both North-South and South-South, are of potential utility here.

Across the South, needs are different and a standardized approach to the transition would not be appropriate. For oil producers in the South, the hydrogen economy spells a significant drop in oil consumption³¹ and revenues, potentially within 20 years. While this allows for at least a short period of time in which to develop alternative uses for fossil fuels, such alternatives will have to be identified and the research and production capabilities put in place over the next 10 to 15 years. Similarly, for developing countries that have become involved in assembling automobiles and producing parts and components, the car of the future will require new skills and new knowledge. Strengthening the local knowledge base, ensuring its flexibility, engaging more intensively in domestic-demand driven research and creating new sorts of knowledge networks and partnerships will be needed to make a transition happen in these countries.

More broadly still, most developing countries are moving down an older technological path as they continue to build their vehicle-related infrastructure – the auto repair services, fuel distribution networks, fueling stations – around the internal combustion engine and the con-

³⁰ Some estimates have placed this as high as 40 percent and a quick look at oil consumption in the United States, where the transport sector depends on petroleum for 95% of its fuel and transport accounts for 67% of US petroleum use, would support such a dramatic drop in oil consumption if gasoline fueled FCs do not become the dominant design.

sumption of gasoline. This is all the more serious as many developing countries have become major importers of used cars thus creating a stronger incentive to strengthen a fossil fuel-based system. Were this to continue, North and South would find themselves on divergent paths with an ever wider technological divide between them. How should they then proceed? The answer is not intuitively obvious and a period of reflection and dialogue will be needed to arrive at a consensus on a country-by-country basis. In this connections, there is much to be learned from the experience of those countries in the North and the South which have engaged in foresight exercises and have organized stakeholder meetings and consensus conferences to deal with difficult decisions of great public importance.

Even then, there are a number of steps that can be envisaged and that begin to create a knowledge base on how to manage a transition in developing countries. One of the most important is the opportunity to study the outcomes and experiences of current experiments in the introduction of fuel cell buses in urban environments in the five countries in which this is currently underway and to immediately extend this experiment to a number of poorer developing countries to better assess the needs in their environments. Attacking urban environments first is potential a strong candidate for beginning the transition in a developing country context since much of the CO₂ pollution is concentrated there. It provides an excellent learning environment with minimal costs since focusing upon the use of fuel cell buses in large cities requires a relatively limited investment in new infrastructure. It also avoids the need for an onboard reformer, which adds to the high cost of fuel cell driven vehicles, as there is space available for hydrogen storage tanks on the roof. Technology of this sort has already been tested for other alternative fuels in both bus and taxi fleets, but its widespread adoption will require new policy initiatives and new financial resources, to speed-up the conversion process.

As this third wave of technological change approaches, we have an opportunity to learn from the past. By putting in place the structures and processes needed to deal with transition in the South now, it may be possible to avoid a cumulative growth in knowledge divides and global inequalities.

Figure 1

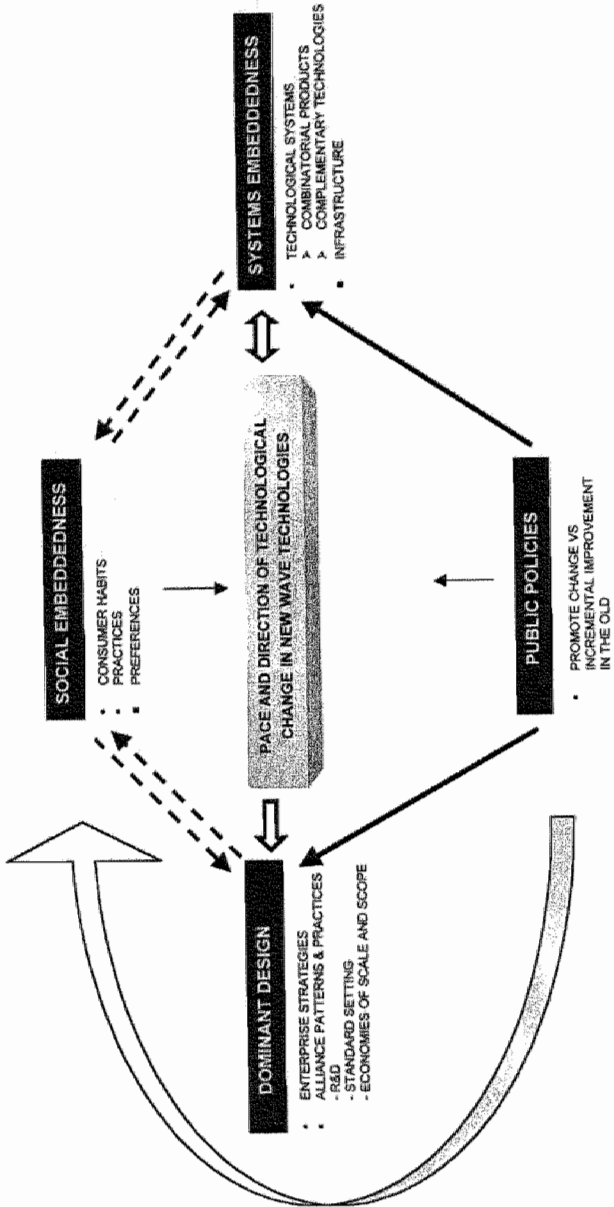
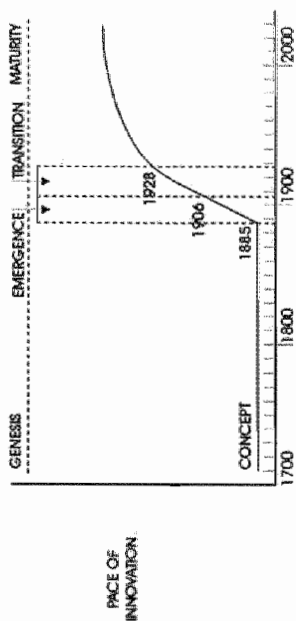


Figure 2

DEVELOPMENT OF THE INTERNAL COMBUSTION ENGINE



NOTES:

- 1885 DAIMLER and BENZ SIMULTANEOUSLY DEVELOP THE FIRST VEHICLE PROPULSION BY INTERNAL COMBUSTION ENGINE (ICE)
- 1890 DAIMLER MOTOR COMPANY WAS FOUNDED
- 1900 DOMINANT DESIGN ESTABLISHED
- 1906 FORD MOTOR COMPANY PRODUCES FIRST CAR DEVELOPED FOR MASS PRODUCTION (MODEL N)
- 1907 GENERAL MOTORS INCORPORATED AND BEGINS PROCESS OF ACQUISITION
- 1914 FORD MODEL T PRODUCTION REACHES 300,000 PER YEAR
- 1928 MODEL A REPLACES THE MODEL T

Figure 3

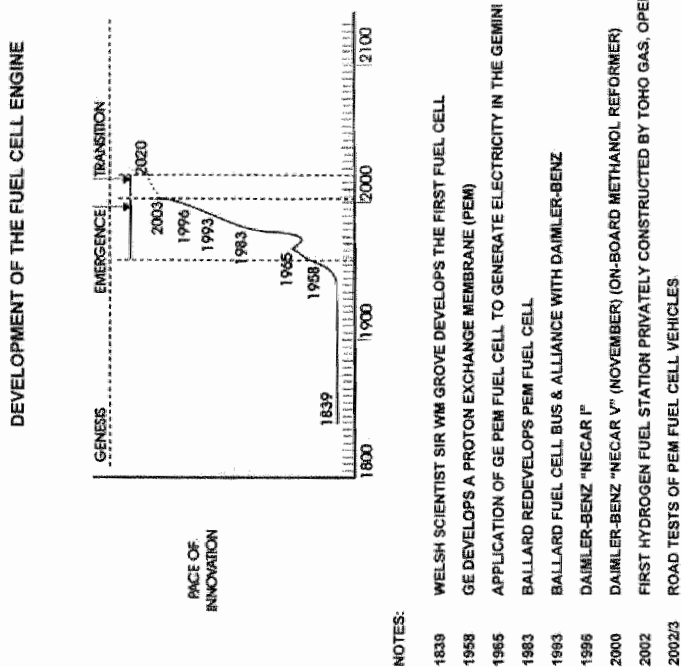
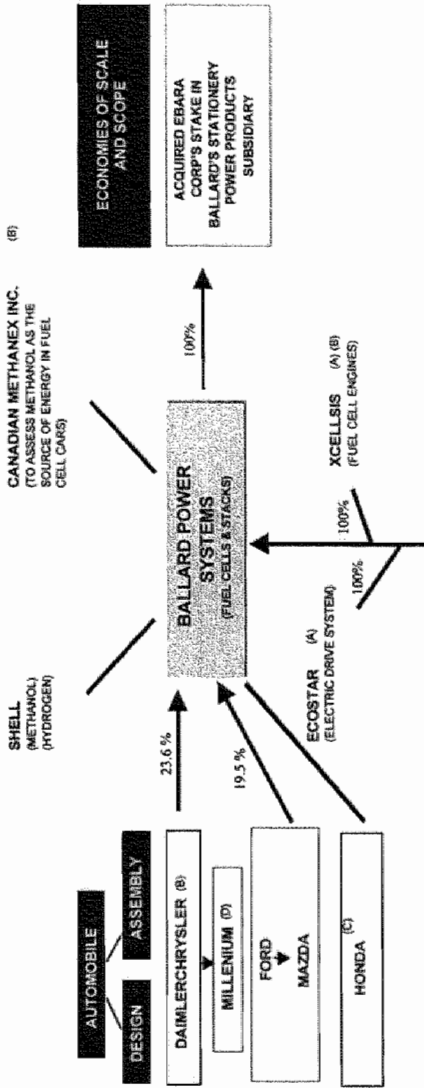


Figure 4

BALLARD: ALLIANCE STRUCTURE 2003



(A) PREVIOUSLY JOINT VENTURES WITH DAIMLER CHRYSLER & FORD CONSOLIDATION IN OCTOBER 2001
 (B) MEMBER OF THE METHANOL CONSORTIUM
 (C) MEMBER OF THE CALIFORNIA FUEL CELL PARTNERSHIP
 (D) MAKER OF THE NATRILUM® REFORMER

Figure 5

GENERAL MOTORS: ALLIANCE STRUCTURE 2003

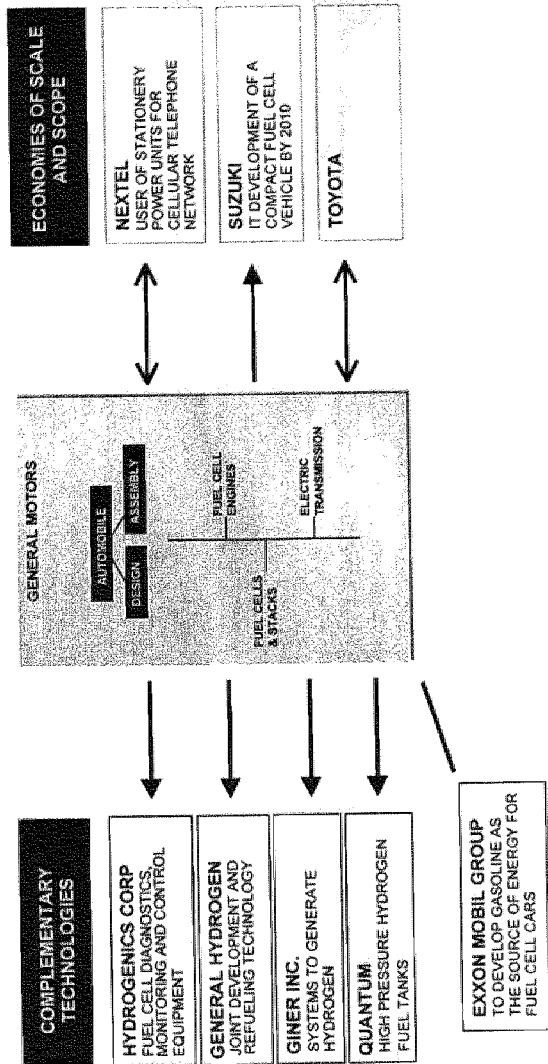


Figure 6

HYUNDAI: ALLIANCE STRUCTURE 2003

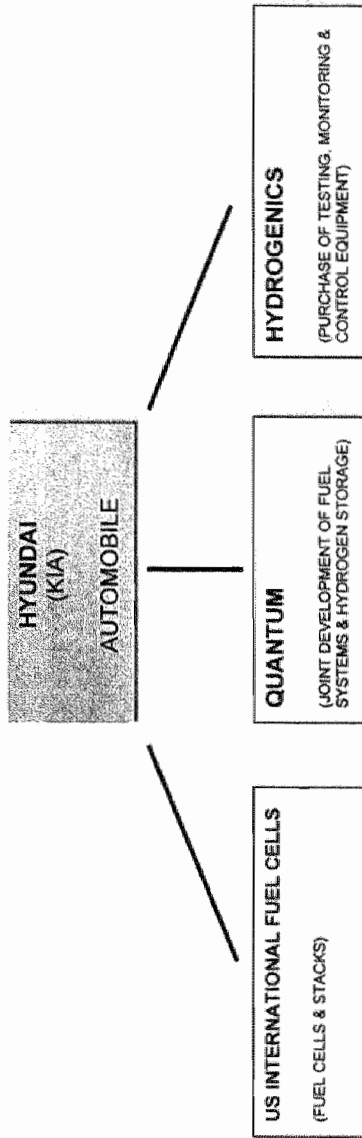
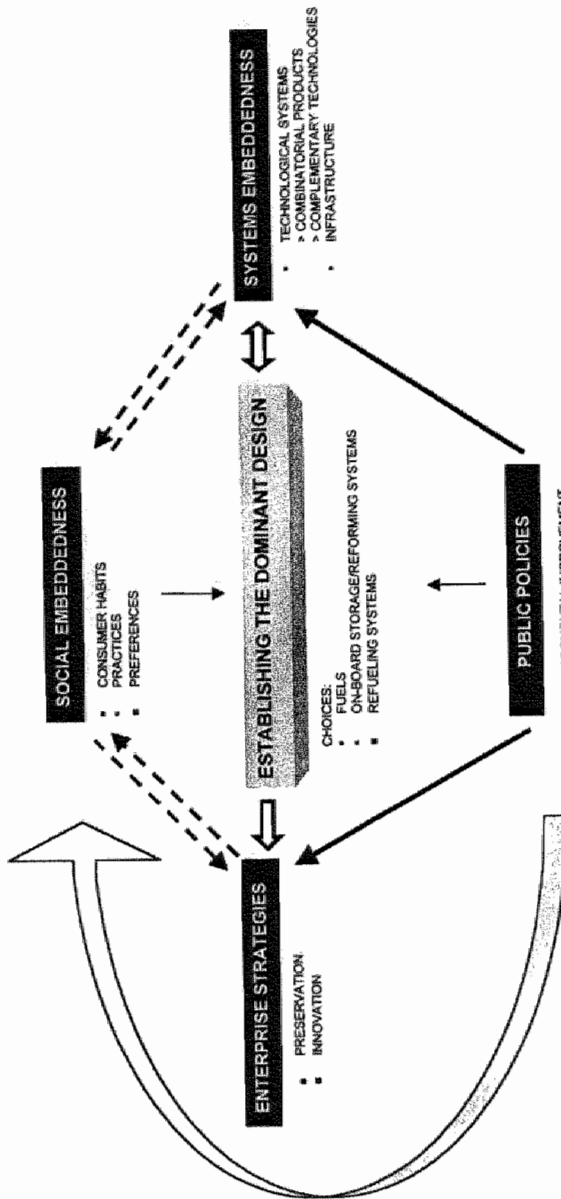


Figure 7



References

Abernathy, W. (1978), *The productivity Dilemma: Road Block to Innovation in the Automobile Industry*, Baltimore: Johns Hopkins Press.

Amsden (1989) *Asia's Next Giant: South Korea and Late Industrialisation*, N.Y.: Oxford University Press.

Best, M.H. (2001) *The New Competitive Advantage The Renewal of American Industry*, Oxford: Oxford University Press, 2001.

_____ (1990) *The New Competition Institutions of Industrial Restructuring*, Cambridge, UK, Polity Press in association with Blackwell Publishers.

Chandler Jr., A.D. (1990) *Scale and Scope The dynamics of Industrial Capitalism*, Cambridge, Ma., The Belknap Press of Harvard University.

_____ (1964) *Giant Enterprise: Ford, General Motors, and the Automobile Industry*, New York

Department of Energy (2003) *Fuel Cell Report to Congress*, Washington D.C., February, Doc. No. ESECS EE-1973.

Delapierre, M. & L.K. Mytelka (2003) "Cascades d'innovations et nouvelles stratégies oligopolistiques" *Revue d'Economie Industrielle*, numéro spécial sur La morphogenèse des réseaux, éditeurs :P. Cohendet, A. Kirman, J-B. Zimmermann, forthcoming.

Desai, A.V., M.O. Lautier & H. Charya (1999), "Machine Tool Industries in India and Chinese Taipei : A Comparison" in Lynn K. Mytelka (ed.), *Competition, Innovation and Competitiveness in Developing Countries*, Paris: OECD Development Centre, pp. 33-76.

Eliasson, G. & A. Eliasson (1997), "The Pharmaceutical and Biotechnological Competence Bloc and the Development of Losec" B. Carlsson (ed.) *Technological Systems and Industrial Dynamics*, Dordrecht: Kluwer Academic Publishers, pp.139-168.

Ernst, D., T. Ganiatsos & L. Mytelka (eds.) (1998) *Technological Capabilities and Export Success in Asia*, U.K.: Routledge.

Fischetti, M. (2002) "Why Not a 40-MPG SUV" *Technology Review* (November), 41-46.

Freedman, D.H., "Fuel Cells vs The Grid: The Road to a True Hydrogen Economy is proving a long one" *Technology Review*, January/February, pp.40-47.

Freeman, C. (1982), *The Economics of Industrial Innovation*, London, Penguin.

Freeman, C. & C. Perez (1988) "Structural crises of adjustment, business cycles and investment behaviour" in G. Dosi, C. Freeman, R. Nelson, G. Silverberg and L. Soete, *Technical Change and Economic Theory*, London: Pinter Publishers, pp. 38-66

Gräedel, T.E. & B. Allenby (1998), *Industrial ecology and the automobile*, Upper Saddle River, NJ : Prentice Hall.

Geiger, S. (2003) "Automotive Hydrogen Infrastructure—On the way to a Hydrogen Economy" *Fuel Cell Today* (February), www.fuelcelltoday.com

Gereffi, G. & M. Korzeniewicz (eds.) (1994) *Commodity chains and Global Capitalism*, Westport CN: Praeger.

Henderson, R., L. Orsenigo & G. Pisano (1999), "The Pharmaceutical Industry and the Revolution in Molecular Biology: Interactions Among Scientific, Institutional and Organizational Change" in D. Mowery & R. Nelson (eds.) *The Sources of Industrial Leadership*, Cambridge: Cambridge University Press, pp. 267-311.

Hoffman, K. & R. Kaplinsky (1988) *Driving Force The Global Restructuring of Technology, Labour and Investment in the Automobile and Components Industries*, Boulder: Westview Press.

Hobday, M. (1995) *Innovation in East Asia: The Challenge to Japan*, London, Edward Elgar.

Humphrey, J. (1998) "Globalisation and Supply chain Networks in the Auto Industry: Brazil and India" paper prepared for the International Workshop on Global Production and Local Jobs , Geneva: International Institute for Labour Studies (ILO), 9-10 March.

International Energy Agency (IEA) *Automotive Fuels for the Future The Search for Alternatives*, Paris: 1999.

Kim, L. (1997) *Imitation to Innovation: The Dynamics of Korea's Technological Learning*, Boston: Harvard Business School Press.

Kim, L. and G. Yi (1997) "The Dynamics of R&D in Industrial Development: Lessons from the Korean Experience" *Industry and Innovation*, Vol 4, No. 2 , December, pp. 167-182.

Kim , L and R. Nelson (2000) *Technology, Learning and Innovation, Experiences of Newly Industrializing Economies*, U.K.: Cambridge University Press.

Koppel, T. (1999) *Powering the Future: The Ballard Fuel Cell and the Race to Change the World*, Toronto: John Wiley.

Lall, S. (1990) *Building Industrial Competitiveness in Developing Countries*, Paris: OECD Development Centre.

Landes, D. (1970) *The Unbound Prometheus, Technological change and industrial development in Western Europe from 1750 to the present*, Cambridge, U.K.: Cambridge University Press.

Masao, O. (2001) "Driven to a Global Economy" *Look Japan*, September, pp. 14-16.

Mytelka, L. K. (2003), "Clustering, Long Distance Partnerships and the SME: A Study of the French Biotechnology Sector" *Journal of International Technology Management*, (forthcoming).

_____ (2001) "Mergers, Acquisitions and Inter-firm Technology Agreements in the Global Learning Economy" in D. Archibugi & B.-A. Lundvall (eds.) *The Globalizing Learning Economy*, U.K.: Oxford University Press, pp.127-144.

_____ (1999) "The Telecommunications Equipment Industry in Brazil and Korea" in Lynn K. Mytelka (ed.), *Competition, Innovation and Competitiveness in Developing Countries*, Paris: OECD Development Centre, pp. 115-162.

Neufville, R., S. Connors, F. Field III, D. Marks, D. Sadoway & R. Tabors, (1996) "The Electric Car Unplugged" *Technology Review*, January, pp. 30-36.

Newcomb T.P. and R.T. Spurr (1989), *A technical history of the motor car*, N.Y. & Bristol, England, A. Hilger.

Office of Technology Policy (2003), *Fuel Cell Vehicles: Race to a New Automotive Future*, Washington, D.C.: US Department of Commerce, January.

Ogden, J., R. Williams, E. Larson (2002) "Societal life cycle costs of cars with alternative fuels/engines" *Energy Policy* (in Press), pp. 1-21.

Pack, (2000) " " in L.Kim and R. Nelson (eds.) *Technology, Learning and Innovation, Experiences of Newly Industrializing Economies*, U.K.: Cambridge University Press.

Perez, C. (2002) *Technological Revolutions and Financial Capital The Dynamics of Bubbles and Golden Ages*, Cheltenham, UK, Edward Elgar.

Rosenberg, N. (1982) *Inside The Black Box: Technology and Economics*, Cambridge, UK., Cambridge University Press.

Schumpeter (1939) *Business Cycles: A Theoretical, Historical and Statistical Analysis of the Capitalist Process*, N.Y.: McGraw-Hill.

Somerscales, E.F.C. & A.A. Zagotta (eds.) (1989) *History of the internal Combustion Engine*, Dearborn, Michigan: American Society of Mechanical Engineers. Chapter by Amann.

Swoboda, F. (2002) "GM's Creation Rewrites Rules of Auto Design" *International Herald Tribune*, 9 January, p.10.

Truett, R. (2001) "Why GM bets on gasoline fuel cells" *Automotive News*, 21 May, pp.9,12.

Utterback, J.M. (1994) *Mastering the Dynamics of Innovation*, Boston, MA., Harvard Business School Press.

Utterback, J.M. and W. J. Abernathy (1975) "A Dynamic Model of Product and Process Innovation" *Omega*, Vol. 3, No. 6, pp. 639-656.

Williams, R.H. (1994) "The Clean Machine", *Technology Review*, April, pp. 21-30.

Womack, J., D. Jones & D. Roos (1990) *The Machine That Changed the World: The Story of Lean Production*, N.Y.: Rawson Associates a division of Macmillan Publishing Company.

Wong, Poh-Kam and Chee-Yuen Ng (eds.) (2001) *Industrial Policy, Innovation and Economic Growth*, Singapore: University of Singapore Press.

Yarime, Masaru (2003) *From End-of-Pipe Technology to Clean Technology, Effects of Environmental Regulation on Technological Change in the Chlor-Alkali Industry in Japan and Western Europe*, Thesis presented to the Universiteit Maastricht, 8 May 2003.