1. Introduction

The United Nations Conference on environment and Development held in Rio de Janeiro, Brazil in June of 1992 put ‘protection of the atmosphere’ on the global agenda¹. Since then two public debates have ensued with regard to ‘who is responsible for airborne pollutants’ and ‘who should pay the price of cutting back’. Both of these debates are seriously flawed: the first, because it creates a view of the problem as a hostile dichotomy between 'you or us'; the second, because it frames the debate in terms of exclusionary alternatives, such as the idea that cutting back on our consumption of hydrocarbons can only be accomplished at the expense of something else, growth, for example or equity. As this paper illustrates, there is always a range of choices. It is how we frame the problem that widens or narrows these.

Obviously there are some who think in more systemic terms and have done much to advance a richer debate. The Business Council for Sustainable Development, for example, sees environmental issues less in terms of end-of-the-pipe clean-up, than as part of a larger process in which investment in research and development is aimed at innovations that make production both cleaner and more competitive. Those who developed the notion of tradable permits viewed the world in holistic terms and looked for ways to reduce total global pollution even if it could not be reduced everywhere.

Such approaches are useful in avoiding unnecessary tradeoffs between objectives –the ‘either/or’ problem –but they remain partial. For example, they substitute trees planted elsewhere, for efforts at home or reduce the objectives to what is manageable within the existing paradigm of production and consumption, thus simply extending the life of older technologies. To exaggerate, but only a bit, it is as if at the end of the 19th century, we invested in breeding stronger and faster horses to compete with the emerging internal combustion engine. At the time, few would have predicted that the internal combustion engine would become the dominant propulsion technology in motor vehicles and indeed it had two

¹ The Rio Conference adopted, Agenda 21, an action plan for the 1990s and the 21st century aimed at realizing a transition to sustainable development within the context of a global partnership for environment and development (UNCTAD:1993,pp.139-142).
rivals: the steam engine, then downsizing into a small, efficient engine for public and private transport and the cheaper and less polluting electric cars and trucks.

How, then, might we better understand the process of change and plan for it? What factors shape the direction of change, establish a particular technological trajectory and affect the speed with which movement along this trajectory takes place. How are parameters set within which choices about change are made? What are the issues that this might raise for developing countries?

Section two develops an approach to analysing the emergence of hydrogen fuel cells, their application in the transport sector and the issues this raises for developing countries. It applies this approach comparative, in section three, to explore the development of the internal combustion engine (ICE) and the subsequent evolution of automobile technology based on this motive force. Going beyond technological constraints, this section pays particular attention to the institutional and economic considerations that led to the dominance of gasoline over electric powered vehicles. The co-evolution of technology in the oil industry is also brought out. Section four then applies the approach to analyze the emergence and development of PEM fuel cells across two periods –the ‘turning point’ years from 1994 to 2002 when a steep rise in interest and activity took place and the ‘hiatus’ year that began in 2002. It identifies a number of factors that affected the speed with which hydrogen fuel cell vehicles (HFCVs) were moving towards commercialization in each period. In this context, it includes a brief review of alternatives to hydrogen as a fuel in HFCVs and of alternatives to the fuel cell vehicles themselves. This provides a basis for discussing choice-sets in developing countries in section five. To better appreciate the dilemmas in which developing countries find themselves today, Section five begins by discussing the pressures to reduce pollution in the South and the persistence of north-south divides as new wave technologies emerge in rapid succession. It concludes by broadly sketching out some of the issues facing developing countries today in thinking about transitions to a hydrogen economy.

2. A framework for the analysis of Technological Change

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. The third phase is that of the mature technology. Innovation continues to take place but incrementally along the established technological trajectory.

With hindsight, the history of the internal combustion engine appears to have followed such a linear path, as did other mechanically based technologies of the past. But such an approach misses the many “inducement mechanisms and focusing devices” (Rosenberg:1976), that shaped the branching points in these technological trajectories.

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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.
overtime (Dosi:1988). Most of this earlier literature also failed to take into account the context within which these selection mechanisms operated and this has had particular ramifications for technological choice and the effectiveness of technology transfer to developing countries (Stewart:1977,22-29; Mytelka:1985, 2004).

New wave technologies such as information and communications technologies (ICTS), biotechnology, nanotechnology and hydrogen-based technologies, moreover, have three defining features that differentiate them from these earlier industrial technologies: their science-base, patent-intensity and systems embeddedness. These differences suggest that the forces and factors shaping the pattern of technological change are also likely to differ as will their impact on developing countries. In both deepening our understanding of innovation in earlier mechanical technology and in providing a predictive tool to analyze the process of technological change in new wave technologies, a more systems-oriented approach is thus needed.

This paper applies an innovation systems approach to analyse the establishment of the internal combustion engine in the automotive industry of the early 20th century and the emergence of hydrogen fuel cells as a possible successor as that century drew to a close. Its focus is on the firms and other organizations which, together with the institutions and policies that influence their innovative behaviour and performance, bring new products, new processes and new forms of organization into economic use. At the core of an innovation system are the flows of knowledge and information that link economic actors and provide both a stimulus to and the support for innovation. Underlying the ‘system of innovation’ approach is an understanding of innovation as an interactive process and a re-conceptualization of firms and other actors as learning organizations embedded within a broader institutional context (Nelson and Winter, 1982; Freeman: 1988; Lundvall, 1988). Institutions in this sense are not formal structures or organizations but “sets of common habits, routines, established practices, rules or laws that regulate the relations and interactions between individuals and groups” (Edquist 1997:7) and thus “…prescribe behavioural roles, constrain activity and shape expectations” (Storper 1998:24). Habits and practices such as these are learned behaviour patterns, marked by the historical specificities of a particular system and moment in time. Overtime their relevance may diminish as conditions change. Policies, whether tacit of explicit, can speed up or retard this process by setting the parameters within which actors in the system make decisions about innovation (Mytelka: 2000).

For developing countries, the characteristics of new wave technologies themselves will shape opportunities and constrain choices over the short and longer term. Anchored in the sciences, 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 divers roots, however, increasingly share a common platform – that of working at the nano-level of photons and genes\(^3\). As a result, the research laboratory has become central in the discovery and development of new products and processes based on new wave technologies.

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\(^{3}\) 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 photonics \(10^{12}\) bits/sec) (Best:2001,133).
Earlier models of technological change based on the experience with industrial technologies have traditionally distinguished between innovation in products and in production technologies and generally regarded these as sequential processes (Utterback & Abernathy:1975). This allowed for a more incremental process of catching up. New wave technologies, however, tend to fuse product and process innovation at the experimental stage, that is, in the laboratory. The importance of systematic research and the centrality of the research laboratory that this implies, puts developing countries at a disadvantage.

The products of new wave technologies are also 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.

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 integratedness 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. 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 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

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4 The remainder of this section draws upon Mytelka:2003.
5 Indeed,” …we routinely fly in airplanes the optimal designs of which are achieved by fairly ad hoc, trial-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).
technologies. In this, they resemble those few science-based industries of the past -- chemicals, petrochemicals and later pharmaceuticals\(^6\) -- 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\(^7\) has broadened the scope of 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 20\(^{th}\) 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

\(^6\) 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).

\(^7\) 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.
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.

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, require 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 the economic and social systems in which they are also embedded. Because of the uncertainties and systems-embeddedness in new wave technology, successful innovation processes are highly interactive. This opens channels for critical flows of knowledge and information and assists in coordinating the development of new infrastructure where it is needed. When such coordination involves changes in the habits and practices of consumers and producers, facilitating interaction may require the creation of systems-level intermediary organizations (van Lente et al: 2003). Traditionally, public policies have thus played a role in stimulating the emergence of such intermediaries in addition to shaping the parameters within which decisions about innovation are made by actors in the system8. This can be expected to significantly alter the pace of change, especially in new wave technologies where research and infrastructure costs are high and there is a need for extensive dialogue and coordination.

In the genesis and emergence of radical technological changes, moreover, 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. 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 parametric 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

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8 See, for example, the large number of such intermediaries created by the European Commission to stimulate research, innovation and competitiveness of European industries growing out of new wave technologies (Mytelka:2001).
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. 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.

Figure One Here

3. Shaping Technological Change: The Internal Combustion Engine

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). 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, the gasoline fueled internal combustion engine had emerged as the dominant design in motor cars.

There was nothing inexorable about the internal combustion engine’s victory over steam power and electricity in the motor vehicles of the 20th century. Why it triumphed was certainly not due initially to its superior technology, if superiority is measured by power, efficiency or reliability. Nor was the infrastructure in place to smooth the introduction of faster moving vehicles or long distance driving. When compared with electric vehicles there were many tradeoffs to consider. For example, although the range of electric vehicles before batteries needed recharging was far lower than the range between refueling stops, the fuel in internal combustion engines was itself a problem and led to frequent stalling. Compared to electric trucks, ICE powered vehicles were also more expensive and their use required more extensive organizational changes as well as significant modifications to existing habits and practices, notably, in the delivery service sector. Normally this would have implied a considerable resistance to change. How then do we explain the speed with which the gasoline powered ICE became the dominant design in motor vehicles. Why did a decades-long difference emerge in its establishment as the leading technology in the passenger car market and in the market for commercial vehicles?

A chronology of key technological changes that gradually increased the flexibility, power and dependability of the ICE is only a starting point, since "[t]echnical superiority resided not simply in the physical properties of the individual technologies but in the contexts and systems in which motor vehicles were embedded.” (Mom & Kirsch:2001,491). How that environment is perceived and defined, how the range of choices is delimited and how parameters are set within which these choices are made, are critical factors in pushing and pulling new technologies along or applying the brakes.

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9 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.
The transitional period, for example, was marked more by changes in production processes and organizational structures than by substantive technical changes in the internal combustion engine, though a number of innovations were introduced to increase engine power and make driving a motor vehicle easier. The major production innovation, for which the era is better known, 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. The transition period drew to a close when the Model A was introduced in 1928, followed shortly by the V.8 engine series. 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. Other companies soon followed suit.

Despite their many technological shortcomings, between 1908 and 1927 some 15 million Model T Fords were sold. Yet this was also the period in which gasoline powered commercial vehicles were vigorously challenged by electric trucks (Mom & Kirsch:2001). The latter had displaced horse drawn wagons for short haul transport from railheads. Like the horse drawn wagon, the electric delivery van was inserted into a broader context, that of the ‘service economy’ in which local department stores, breweries and other manufacturers participated as a means to win customer loyalty in urban areas. In this market, internal combustion engines were too costly to operate, since the principal advantage of such vehicals, was their greater range between refueling stops. Operating over a larger range and with less down-time while customers opened packages, inspected goods, tried on merchandise or tapped kegs were critical in amortizing the higher initial price of the gasoline fueled internal combustion engines which powered these vehicles. At the time, moreover, neither the power nor the reliability of these trucks were sufficient to challenge trains that dominated the long-haul market. It was not until these trucks could provide universal service across both markets that they posed a real challenge to the electric vehicle. Even then the choice was not based solely on technological strengths or even the habits and practices of the service economy which would later be forced to change, but on errors in competitive strategy that weakened the electric vehicle (EV) as a vehicle of choice. The ability of electric vehicles to compete in medium-haul markets, for example, was seriously weakened by the strategy of electric generating stations, notably in the United States, to monopolize the supply of electricity by integrating downstream to garages where electric cars and trucks could recharge their batteries. The alternative was to change batteries, a practice adopted at various times in Europe but one that never took hold in North America. Many of these factors reappear in the context of challenges to and pressures for the use of hydrogen fuel cells in the transport sector as we shall see in the next section.

The continued development and widespread use of the automobile powered by an internal combustion engine in the post-transition period, was for many years constrained by a number of other systems within which it was embedded. One of these was the system of

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10 These included synchronized transmission for easier gear shifting, air-collected engines, the Ricardo cylinder head, the mechanical fuel pump and the automatic choke.
11 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.
refining fuels, 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.

Mechanical innovations designed to solve the problems of carburation, valving and ignition could only go so far in making engines more efficient. This was because further improvements in engine design could not succeed in generating power and reliability in the absence of better quality fuels. Why did the oil industry not move more quickly to improve fuel quality? Here again, one of the critical issues was how they perceived their role and framed the problem. Petroleum refining technology was an adaptation of earlier coal oil processes and as such was based on thermal cracking. As the car market developed, the oil industry framed the problem as one of a potential fuel shortage. Their objective thus became the extraction of more gasoline from existing refineries. This was done by developing a continuous process of thermal cracking. The anti-knocking properties of tetraethyl lead were known\(^{12}\) and it was being added to gasoline in the 1920s. But this did little to raise the compression ratio of automobile engines or increasing their efficiency. It was not until demand for higher quality fuels from the emerging aviation industry rose, that research began in earnest to build the chemical knowledge needed to develop a continuous process of catalytic cracking and raise the octane levels of refined oil. The research was undertaken in the mid-1930s by a consortium put together by Standard Oil of New Jersey. The consortium spent $15 million US over three years to produce a more refined oil which made possible higher compression ratios that increased engine power and eliminated stalling.

The second constraint on the continued growth of automobile industry was the infrastructure upon which it 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.\(^{13}\)

In its ‘mature’ phase, technological 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

\(^{12}\) In the early 1920s, Harry Ricardo had led a study that identified tetraethyl lead as a suppressant of knocking. His engineering consultancy firm also noted, as early as 1923, that Ethyl Alcohol was in some respects a better fuel and could be produced using renewable resources thus solving the problem of future gasoline shortages as well as reducing pollution. See Compton:199.

\(^{13}\) 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.
significantly reduced. 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 carburator 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. 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 vibration (Fischetti: 2002,46). Gasoline direct injection and digital microprocessors 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. As in other cases, habits and practices of the actors and they way they framed the solution has meant a lengthy race to the bottom, as automobile manufacturers adopted the catalytic converter rather than undertaking more thorough going change. 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 undertaken 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

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14 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).

15 Most of these systems were first innovated in the late 1920s in mechanical form and later updated electronically.
incremental development path of the internal combustion engine since its application to transportation.

**Figure 2**

**Development of the Internal Combustion Engine**

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**

<table>
<thead>
<tr>
<th></th>
<th>Fuel Economy</th>
<th>Dependability</th>
<th>Price</th>
<th>Quality</th>
<th>Safety</th>
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<tr>
<td>1981</td>
<td>43</td>
<td>32</td>
<td>14</td>
<td>4</td>
<td>9</td>
</tr>
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<td>1987</td>
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</tr>
</tbody>
</table>


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 point in the evolution of technological trajectories -- the exhaustion of the current technological paradigm. Is the next wave of technological change upon us?


In the mid-1990s, fuel cells were regarded as a promising technology in the transport sector. Barely ten years earlier, this had not been the case and few were even thinking along these lines. By the end of that decade, they were being touted as the wave of the near-future. Today that horizon appears to have receded. As we saw in the previous section, the establishment of a technological trajectory is not the result of technology alone, nor is its evolution a linear process. How then might we explain these changes and what are their implications for the pace of change over the next decade.

Although a first working fuel cell, was demonstrated by Welsh Scientist, Sir William Grove in 1899, it was 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.

Fuel cells reverse the long known process of electrolysis, which uses energy to split water into its components. Instead they use a fuel supply to combine hydrogen and oxygen thus generating an electric current. The first proton exchange membrane (PEM) fuel cell was developed in the 1950s by General Electric (GE) 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.
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, Ballard, a new, Vancouver-based startup then working on lithium batteries, won a Canadian Department of National Defense 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 replaced its polystyrene resin membrain with a Nafion® membrane and the GE flow field plates made of niobium by sheets of graphite with carefully machined fine groves on the electrode side of each plate (Koppel:1999,77). Both of these innovations 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\textsuperscript{17} would result in yet another steep jump. Some at Ballard believed that ‘these power densities and overload capabilities could make the electric automobile happen’ (Savage:1987,16). Over the next five years Ballard built ever more powerful and smaller PEM fuel cell stacks.

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 produced no exhaust emissions.

\textit{The Turning Point: 1994-2002}

The year 1994 was a major turning point in the emergence of the PEM fuel cell as the prime contender to replace the Internal Combustion Engine. The dramatic rise in patenting is one indicator. 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 show a sharp rise in patenting activity in the ‘automotive fuel cell patent family’ from some twenty per year in

\textsuperscript{16} 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).

\textsuperscript{17} 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.
1994 to 60 in 1998 and 180 in 2001 (USOTP:2003,3) and strong patenting activity in the ‘hydrogen storage patent family activity’ from 1996 onward (OTP: 2003,3 & 23). The investments in research that led to this patenting activity accelerated the speed with which new technologies moved from the drawing boards to prototypes and augured well for the pace at which technological solutions might be found for existing problems.

Over these years every major automobile company announced programmes to develop fuel cell vehicles and built alliances and/or created the in-house capability to do so. 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 car in 1999 and General Motors later also developed a partnership with Millennium Cell as to Peugeot-Citroen (PSA). Honda and Nissan, working initially with Ballard Fuel Cell Stacks, Hyundai and BMW using stacks produced by International Fuel Cells and Renault and Fiat working closely with Nuvera Fuel Cells also joined the race.

A proven concept, performance capabilities, the accelerating pace of technological change, competition amongs rivals and a shortening time horizon all played a role in the rapid turn around from skepticism to action on the part of automobile manufacturers. 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. In addition to DaimlerChrysler other automakers were also 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 earlier, limited road testing of this new generation of FCVs, an important step towards commercial production, was envisaged within a few years.

Little doubt remained 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 be able to 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 advantages 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\(^\text{18}\) (Williams:1994; Swoboda:2002,10).

By the late 1990s, the main question was no longer whether Fuel Cells could supplant the internal combustion engine as the dominant design in the automobile industry but rather when this would likely occur. Although some articles continued to place the time horizon for

\(^{18}\) ‘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.
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.

Was this hype or reality? Like other research-intensive industries of the 1960s and 70s, as the pace of technological change accelerated, so, too, did the pressure to form alliances through which consensus on a dominant design and common standards could be forged and systems integration could be rapidly pursued. Two broad alliances emerged in this period\(^\text{19}\). Fundamentally different in construction, the first was centered on Ballard and modeled itself on a structure existing in the information and technology sector where networks formed around rival component solutions and their producers, such as INTEL in microprocessors or Microsoft in software. The second, centered on General Motors (Truett: 2001) and 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. Rival networks such as these characterized the emergence of a dominant design in the development of the VCR, of computer disks and a variety of telecommunications equipment, but the time frame, infrastructure investments and costs to the consumer and society were far lower than they are likely to be in the development of a fuel cell vehicle.

Within these alliances, all producers thus remained flexible in the types of fuel cells they produced, tailoring these to their customers. Ballard Power Systems, for example, initially focused on direct methanol PEM fuel cell technology that would not require an on-board reformer, but also supplied hydrogen fuel cells to their clients on demand\(^\text{20}\). Nuvera Fuel Cells, which estimated that it would still take some 20 years before a hydrogen society came into existence stressed that “[u]ntil 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”.\(^\text{21}\) Nonetheless, although specialized in gasoline fueled FCs with a metallic stack architecture, Nuvera worked with its partners and customers to produce other types of fuel cells as well. The absence of a dominant design as fuel cell technologies began to emerge, did not then seem to be a serious impediment to realizing a commercializable FCV.

Each of these alliances pushed forward its own agenda with regard to several critical choices. Paramount among these was the choice of fuel, as it is linked to the choice of engines, fuel cell design and the need for either an on-board reformer or an on-board fuel storage system. Costs, technological complexity, regulatory pressures and time to market are major factors affecting tradeoffs here. But the choice of fuel is also systems embedded and the availability of infrastructure and social acceptance as well as the habits and practices of auto manufacturers and oil producers and refiners 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).

\(^{19}\) Other alliances such as that between Hyundai 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.

\(^{20}\) See the Ballard Power Systems website at www.ballard.com

\(^{21}\) Statement by Roberto Cordara, President & CEO on the Nuvera website: www.nuvera.com
The choice of fuel for fuel cells, in this period, was mainly focused on three alternatives, hydrogen, methanol and gasoline. Curiously the initial choice of fuel by core members of the two broad alliances whose influence was paramount in shaping competitive pressures had 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. General Motors, which began with hydrogen and a radically new car concept, became the major proponent of gasoline fuel cells and characterized its 1999 partnership with Toyota and ExxonMobile as a means “...to speed the development of a clean hydrocarbon fuel for FCVs ...[and] an important bridge to a pure hydrogen infrastructure.” Some might question, however, whether continued use of hydrocarbon based fuels is a bridge or a barrier to a radically new technology.

Hydrogen, faced the greatest hurdles in establishing itself at the outset as the preferred fuel for FCVs. Hydrogen, for example, had an image problem to overcome as some still emphasize its explosive potential if stored as a gas. But a number of solutions to the distribution and on-board storage problems were already commercially available. These derived from earlier experiences with the liquefaction and compression of natural gas (LNG & CNG) and demonstrated the safety of hydrogen in these two forms. Some hydrogen powered fuel cell vehicle prototypes used. They stored hydrogen on-board under high pressure in canisters made of lightweight, high strength material such as aluminium wrapped with carbon fiber. Hydrogen powered FCVs are environmentally friendly but the complementary technologies needed to ensure well-to-wheel environmental sustainability, cost efficient hydrogen production and the infrastructure for delivering hydrogen at the pump or to the home were in their infancy. The infrastructure costs of building a distribution network from scratch, moreover, were very high.

Towards the end of the 1990s, public-private sector alliances emerged as the basis for concerted efforts to develop the necessary fueling infrastructure. One of these was the California Fuel Cell Partnership (CFCP) in the United States. DaimlerChrysler and its partners were among the founding members of the California Fuel Cell Partnership (CFCP) in April 1999. A year and a half later, General Motors and Toyota joined the CFCP. Another was the European Union’s 5th Framework programme. The Ecological City Transport System project, ECTOS, began in March 2001 and ran until February 2005. It involved “…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). Given the need for more research and testing, while most acknowledged that hydrogen fuel cell vehicles were the wave of the future, many turned to intermediate solutions to deal with the fuel and fueling problem.

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22 Others such as the Hydrogen-on-Demand Natrium® Fuel Cell Vehicle developed by DaimlerChrysler using Borax were also in the pipeline.
23 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.
24 See, for example, WWW.gm.com/company/gmability/adv_tech/700-partners/index.html.
Methanol, derived from natural gas, represented 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 automotive markets have significant natural-gas vehicle fleets. 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. 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. The methanol option also continues the pattern of dependence on hydrocarbons and fails to achieve the zero emission promise of hydrogen fuel cell vehicles from well to wheel.

From the environmental perspective, the life cycle of gasoline is even less optimal. Nor does the choice of gasoline improve fuel security in the short to medium-term, unless it is accompanied by expanded exploration and development. 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 older products, existing infrastructure and traditional habits and practices with respect to rapid refueling at a multitude of existing fueling stations, gasoline, was the least disruptive of the choices. If speed to market is the goal, then a gasoline powered fuel cell car might also give the appearance of being a rational choice, at least, in the short term. But appearances, in the GM case were deceiving and after years of trying to development a small on-board gasoline reformer, General Motors seems to have abandoned this option, but not before Nissan and Renault followed suite, fearing that a gasoline powered fuel cell car could become the American standard, at least in the medium term.

While gasoline is no longer high up on the list of fueling choices for fuel cell engines, this was not because a consensus had emerged on the dominant design for a Hydrogen Fuel 25 26 27 28 29 30

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25 Italy, Argentina, New Zealand, the Russian Federation and the United States. (IEA:1999)
26 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)
27 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.
28 This is a particularly important consideration in a post-9/11 world or where the stabilization of oil prices depends on Saudi Arabia’s ability to increase oil output, something that is now being put into question
29 Suggestions that this be carried out along the California coast or in the Arctic, have been under fire until recently.
Cell Vehicle. To the contrary, by the turn of the century, HFCVs were being pushed off centre stage and gasoline was showing signs of a comeback.

From the mid-1980s to the mid-1990s, Toyota had slowly expanded its research on electric batteries and motors. This is reflected in rising patenting levels in this family of activity which rose from under 25 in the pre-1994 period to 50 in the year 2000 (Kuroki & Masaru: 2003). Triggered by California’s\textsuperscript{31} effort to reduce pollution levels quickly through the adoption of stringent emissions rules that no existing internal combustion engine could meet, Toyota’s research on hybrid vehicles moved into high gear. From under 30 patents in 1994, the number of Toyota hybrid patents jumped to nearly 200 in 2000 (Kuroki & Masaru: 2003). In 1997, Toyota introduced the first gasoline-electric hybrid vehicle. Its performance characteristics would not have tempted an American buyer any more than earlier electric motors had done. This early version of the Prius was sold only in Japan. Four years later, Toyota was ready with a car that matched the preferences of its American clientel.

Once introduced into the American market in 2001, the hybrid vehicle changed the rules of the game. Able to meet emissions standards of the future, with the performance characteristics of pure gasoline engines and the advantage of substantial fuel economy, the Prius became the car to beat. Within a year, Honda’s version of a hybrid went on sale in the United States and was followed by Ford and others\textsuperscript{32}. Wedded to heavy, gas-guzzling, Sport Utility Vehicles (SUVs), the emergence of hybrids seemed like a godsend in a period of rising oil prices.

This is the context within which increasing R&D investment by American and Japanese auto companies in the period from 1996 to 2001 must be interpreted. In the US, investment by the formerly sluggish automobile industry amounted to some $18.4 billion in R&D in 1997, higher than any other manufacturing sector in the that country (OTP: 2003,3) and R&D investments by 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). Government also announced programmes of R&D funding for the development of FCVs and supported consortia to work on complementary technological systems. The US government, for example, 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. Although its stated primary objective was to promote the development of hydrogen as a fuel for cars and trucks much of the research undertaken through this program addressed improvements in existing ICE –based technologies that would increase fuel economy and engine performance and the new ICE engine programmes put in place during this period will not end until 2012/2013 (Truett: 2001, 39). In Japan, research, as we saw above, was heavily focused on the development of a strong electric motor capability that

\textsuperscript{31} Toyota was already a major player in the California auto market when the California Air Resources Board approved new emission standards requiring that 2% of the vehicles offered for sale in the state by 1998 would have to be zero emission vehicles with this rising to 10% by 2003.

\textsuperscript{32} In December 24, 2002 the Wall St. Jouranl reported that GM and Toyota had decided to “gear 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 vehiclea. 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.
became the basis for the lead taken by Toyota in the commercialization of hybrid cars later in the decade.

**Figure 3**
Development of the fuel cell engine

![Graph showing the development of the fuel cell engine with timeline from 1800 to 2100.]

**The Hiatus**

At issue in determining the pace with which a dominant design emerges in an entirely new technology, 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. The interplay between government and business has been particularly important in shaping the process of arbitrage between innovation and the preservation of established ways of doing things, that has been taking place with regard to HFCVs in this first decade of the twenty-first century. As Carlotta Perez pointed out,

> 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 inertia stemming from routine, ideology and vested interests. (Perez: 2002,26).

Under these circumstances it would be highly unusual if technological trajectories were strictly linear. The current period is no exception. By 2002 both government and business had became increasingly outspoken in dampening down the expectation of a rapid move to HCFVs. GM’s top management pushed openly for incremental innovation along established trajectories and Elizabeth Lowery, Vice President for Environment and Energy at Geneval Motors, told The Globe 2002 Conference on Business and Environment that ‘gas and diesel powered cars would not disappaeer for another 50 years’. Her explanation for this far
distant frontier was a lack of current consumer demand for alternatives to fossil fuel powered vehicles, "...customers don’t want to make trade offs," (Financial Post:2002,7). As innovation-based competition across a wide range of consumption goods illustrates, consumer tastes are not immutable.

In the same year, the European Union’s High Level Group, created with a view to formulating “a collective vision on the contribution that hydrogen and fuel cells could make to the realisation of sustainable energy systems in the future “ (EU:2003,5) reported out in favour of short and medium term efforts to “improve the efficiency of fossil based technologies and the quality of fossil-based liquid fuels” (EU:2003, 21-22). In June 2003, at the EU conference on “The Hydrogen Economy. A Bridge to Sustainable Energy” at which this report was launched, the US and EU agreed to collaborate for the purpose of accelerating the development of hydrogen as an energy source. At the same time, however, conference documents reflected a subtle shift in the time frame within which it was expected that commercialisation of hydrogen fuel cells would take place. Moreover, though President Bush had announced an increase in funding for the hydrogen economy in his State of the Union message in January 2003, of the $1.7 billion in funding over the next fives, only $720 million, would involve new funding (EU:2003, 5)33. The US inspired International partnership for the Hydrogen Economy (IPHE) which held its first Ministerial meeting in November 2003 was similarly off to a slow start in tackling the key issues that appeared to be holding back the emergence of hydrogen as the new energy source and the application of HFCs in the transport sector. Over the following 18 months its focus has been on the development on common codes and standards to facilitate a transition and the preparation of an IPHE Roadmap to shape that process in a coordinated manner. But if the problems were more fundamental and required major investments in frontier research, the IPFE partnership did not appear to be the vehicle through which this would be done.

The European Union’s 6th Framework Programme, now underway, reflects a similar view of the time frame and activities needed to reach the hydrogen economy. Within the 6th Framework Programme’s Its focus is on the production of cleaner fuels, though not necessarily hydrogen and on early preparatory work in the organization of fueling distribution systems. Most of the funds, therefore, will be spent on producing clean hydrogen rich synthesis gas from methanol and preparing for the hydrogen economy by using the existing natural gas distribution system, studying supply options across Europe’s regions, setting standards, engaging in major fleet demonstration projects and supporting the Hydrogen Technology Platform Secretariat. Of the sub-programmes relevant to the hydrogen economy, only ‘hydrogen end use’ involves new research: 5 million euro for work on a direct hydrogen internal combustion engine, 12.6 million in research funding for Solid Oxide Fuel Cells used in stationery power plants and 8.8 million euro for powertrain development for direct HFCs in cars and auxilliary power units for trucks and 5 million to study stack designs and high temperature polymer electrolyte membrane fuel cells.

In 1994, an article in MIT’s Technology Review noted that “Serious pursuit of the fuel-car option will require a major redirection of U.S. automotive R&D” (Williams: 1994,28).

33 As of May 2005 the bill which would have authorized these funds had still not left the senate for a Conference between Senate and House of Representatives to harmonize the two versions of this bill.Present Tours Hydrogen Fueling Station in Washington” Press Release, Office of the Press Secretary, May 25, 2005. WWW.Whitehouse.gov/news/releases/2005/05/20050525-1html
Since then, the data show that governments continue to underfund research on hydrogen fuels and fuel cells and have done remarkably little to change incentive structures for producers or consumers. This has sent very strong signals to the automobile companies that real competition, for the foreseeable future, will be in established markets. Auto companies, such as Ford, thus emphasize that they are “...actively engaged in the development of four promising future alternatives to today’s gasoline engines including clean diesels, gasoline-electric hybrids, hydrogen internal combustion...” and hydrogen fuel cell vehicles (Ford:2005). Three of the four alternatives preserve the internal combustion engine as the core technology and two support continued movement down a hydrocarbon-based fuel trajectory. Similarly, in April 2004, GM and Ford announced a $720 million investment to design and build an all-new, fuel-saving, 6 speed front-wheel-drive automatic transmission which “is expected to offer up to four percent improvement in fuel economy over traditional 4-speed automatic transmissions available in today’s front-wheel-drive cars” (General Motors:2004). If recently released figures by the US Environmental Protection Agency (EPA) on fuel economy trends in the United States are to be believed, model year 2005 vehicles were estimated to average 21.0 miles per gallon (mpg), which is five percent below the fleet average fuel economy peak value of 22.1 mpg reached in 1987 (EPA:2005). The new GM-Ford transmission, even if it does function as expected, will not even return average fuel economy figures to that of nearly 20 years ago.

With attention directed elsewhere, the pace at which a dominant design is emerging in the development of hydrogen fuel cell vehicles appears to have slowed down; but for how long? Many of today’s debates are reminiscent of those that took place in the early decades of the gasoline powered ICE (see section 3). The quality and ability to deliver the hydrogen that would be needed if HFCVs were to take off, is one such example. Hydrogen proponents, however, see arguments over infrastructure as red herrings. “U.S. industry currently produces 50 million to 60 million tons of hydrogen per year, so it’s not like there’s no expertise in handling hydrogen out there” Ballard’s former CEO Denis Campbell noted (Ashley:2005,57). Herbert Kohler, vice president of body and power-train research at DaimlerChrysler, however, argues that “[t]ifty to 60 percent of the problems we have with our fuel cells arise from impurities in the hydrogen we buy from industry” (Ashley:2005,57). Looking back to the early days of the ICE powered automobile, however, the developed world seems particularly well endowed with hydrogen refueling stations, some 60 to 70 of which are operating in Japan, the EU and the US at a point in time when there are no commercial vehicles yet on the road. Is the cost of new fueling infrastructure way beyond our means or is it as Ballard’s CEO pointed out, considerably less than what is being spent on infrastructure by ICT firms around the world?

Business scepticism about the speed with which some of the remaining technical problems will be resolved, such as reducing the costs of hydrogen storage, curiously echoes the situation facing automakers in the 1920s who found themselves up against the traditional research habits and practices of the oil companies who continued to focus on increasing the quantity of gasoline being produced rather than improving its quality. With regard to the high costs of hydrogen on-board storage, Bill Reinert, National Manager for Toyota’s advanced technology group was quoted as saying “I’m less than hopeful about reducing costs sufficiently and I’m quite pessimistic about solving hydrogen storage issues...high volume production could be 25 years off” (Ashley: 2005, 52). Yet, both government and business are investing far less than is needed to deal with this problem. In January 2005, for example, General Motors and the US government’s Sandia National Laboratories launched a
programme to develop metal hydride storage systems based on Sodium Aluminium Hydride. Only US$10 million is to be invested in this research over a four year period. This is too little and perhaps even too late. Delft University and the Colorado School of Mines have already developed a lab version of a hydrogen hydrate storage system in which hydrogen is trapped in molecular-size cavities in ice and a “promoter” chemical, tetrahydrofuran stabilizes the gas hydrate under far less extreme pressure than is currently the case: 1,450 vs. 36,000 psi. Theoretically this should make possible the storage of 6kg of hydrogen in about 120 kg (120 litres) of water, increasing the range of fuel cell vehicles to that of gasoline powered internal combustion engines and substantially reducing costs (Ashley: 2005, 55).

There are also a number of new technologies under development that appear to have the potential to dramatically cut costs. Hitachi Maxwell, for example, “used technology for synthesizing ultra-small particulate magnets –technology created during the company’s development of magnetic tape--to uniformly deposit oxide particles a mere one nanometer in diameter on a substrate...when the deposited particles reach one nanometer in size, their reactivity increases dramatically. Consequently, if this new catalytic material is used in combination with platinum as the catalyst in a fuel cell, for example, the catalyst performs just as well as a pure platinum catalyst even though the amount of rare metal used has been decreased.”

Poly Fuel, a small company in Mountain View, California announced the creation of a hydrocarbon polymer membrane that reportedly cut in half the price of DuPont’s Nafion material, while 3M has boosted catalytic activity by creating nanotextured membrane surfaces covered with tiny columns” (Ashley:2005, 53-54).

While, clearly there remain many problems to be solved in producing, distributing and storing hydrogen, it is unclear whether any of these problems require a major scientific breakthrough. If they are more like the ‘knocking problem’ that reduced the power and reliability of the international combustion engine early in its history, then it should be possible to refocus research efforts on the issue of consistancy in the production of high grade hydrogen. As pure hydrogen was not required for earlier industrial uses, a change in the habits and practices of hydrogen producers will be needed.

What we find, however, is that, although research on hydrogen fuel and fueling problems is still continuing, the fuel issue itself is being redefined away from critical hydrogen issues and towards short and medium term considerations by both business and government. Research funding for ‘cleaner’ hydrocarbon-based fuels has thus increased. To compensate for their relatively limited contribution to overall pollution, the range of acceptable fuels has thus been widened to include alternatives, such as Ethanol and bio-diesel for use in modified internal combustion engines making the latter less environmentally damaging and the former more of a contributor to sustainable development and greater efforts at using natural gas and expanding both natural gas production and infrastructure. The need to further reduce pollutants in the environment also led to the introduction of government funded incentives to stimulate the purchase of hybrid vehicles. Neither higher taxes on gasoline nor higher insurance premiums on SUVs were introduced as part of a coherent package of incentives that might change existing consumption patterns. Instead, competitive pressures are reenforcing efforts to extend traditional technologies by stimulating the rapid entry of newcomers into the market for hybrid cars and focusing attention on the need to bring out

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34 This was reported in a short article “Highly Reactive Carbon Black Catalyst Unveiled” in the Jpan Journal of March 2005, p.23.
hybrid SUVs with the performance characteristics of the original. As auto companies move
down this alternative trajectory, they make it easier for consumers to hold onto old habits and
practices and salve their conscience by buying green.

In terms of priority setting the above review of options raises a number of critical
questions. 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. 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?

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? There are some indications that it will differ. For
fuel cell manufacturers, for example, dual use –transport and stationery energy- technology
has been essential. Will it be easier to set standards and develop a dominant design for
stationery power based on hydrogen fuel cells and should this be pursued more vigorously
than the application of hydrogen fuel cells in the transport sector? With respect to fuel cells
and the transport sector, however, we have far too little information on costs to evaluate this
process. This gives rise to still other questions.

If the future is still ‘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 multiple solutions, gasoline, methanol and hydrogen, for example,
coexist and be developed 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, energy 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. A dialogue of sorts has developed within the European Union as it builds its hydrogen platform but the dominant voices in the dialogue are reluctant to champion radical change. For this to take place, governments in the North will thus have to take a more pro-active stance in ‘promoting the new’ and 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.

5. Issues for Developing Countries

Given the pressures upon governments, both North and South, to deal with environmental pollution, can developing countries wait until a consensus process plays itself out in the North before taking their own decisions? Even more fundamentally, 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?

Dealing with Pollution

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 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). Initially envisaged as a programme in five mega cities with serious pollution problems and with a strong scientific and engineering base - Shanghai, New Delhi, Sao Paulo, Mexico City and Cairo – only two of these are fully operational today. The high cost of the programme and the possibility of implementing alternative strategies such as the conversion of buses to CNG, the construction of new forms of public transportation in urban areas and the development of sustainable fuels such as ethanol and biodiesel have been a disincentive to participation in this programme. Even then, however, most developing countries are neither learning through such testing programmes nor are they aware of or able to implement the alternatives, a point to which we will return below.

Diversity of Needs
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 consumption and revenues, potentially within 20 years. While this allows for a 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 the transition these painful.

More broadly still, many 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 consumption 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. 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 world-wide. 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 new wave technologies such as these, 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. In the early phase of a catch up process there was thus little need for domestic R&D. 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 function 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

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36 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.
a process is even necessary. In the absence of attention to capacity building processes now, developing countries run the risk of further exclusion.

**The Problem of Exclusion**

Although most people date the emergence of new wave technologies to the advent of the semi-conductor, in many respects, new information and communications technologies (ICTs) were initially a transitional technology, emerging within the paradigm of earlier mechanically based industrial revolutions and only later incorporating the genes, proteins and particles at the nano-level that are central to new wave technologies. Their introduction into products and processes was gradual, modular and additive as components of existing products were progressively transformed from mechanical to digital and new products were created by combining upgraded versions of existing components in novel ways\(^{37}\). They were only a foretaste of what might be in store.

Like mechanically-based industries of the past, entry into the electronics industry was still possible at low skill levels and most manufacturing activities that located in the developing world required only semi-skilled labor. “Although this required a conscious effort to learn, opportunities for catching up were present where industries matured slowly, product life cycles were longer and competition from lower wage entrants was not yet intense. The need for domestic R&D in the early phase of the catch up process in ICTs was also limited and patent protection was not very important. This encouraged reverse engineering within the firm and the adaptation and modification of imported technologies that made further learning and innovation possible\(^{38}\).

Even then and despite the many benefits that this new generic technology brought as it transformed traditional information and telecommunications process, led to the creation of knowledge-based products in a wide variety of different industries and stimulated the development of the Internet, there emerged what has become known as the ‘digital divide’. From the outset the digital divide was defined mainly in infrastructure terms, as access to telecommunications and computers. This, it was assumed, could be remedied by higher doses of technology transfer from North to South, notably through the extension of electric generation and telecommunications switching and transmission equipment. The knowledge dimension and the way in which scarce knowledge resources affect the use and diffusion of new technologies, was largely ignored. Since developing countries were widely regarded as users and not producers of the new information and communications technologies, state-initiated efforts to master these technologies were criticized as inefficient and market distorting\(^{39}\). The ‘learning to learn’ and the extensive knowledge accumulation and innovative capacities that such efforts could create were simply dismissed and little attention was paid to the emergence of a “domestic digital divide” (Hibert & Katz:2003,63) that progressively excluded large numbers of potential users in education, research and business where reliance on computers and the internet was increasing (Oyelaran-Oyeyinka & Adeya:2004; Oyelaran-Oyeyinka and Lal:2005 and Rasiah & Oyelaran-Oyeyinka: 2004) . Had developing countries

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\(^{37}\) In this, the early ICT industry paralleled the technological trajectory that characterized the internal combustion engine and its application in the auto industry.


\(^{39}\) These criticisms were particularly directed at efforts to develop computers in Brazil and digital switches in Brazil and India. For a discussion of some of these debates see Tigre:1983, Gorensson:1993 and Mytelka:1999).
been regarded not merely as passive technology users but as potential knowledge creators and innovators and had a systems-oriented approach been taken from the outset, the problems of domestic content, costs and the development of the ancillary educational, research manufacturing and service activities needed to indigenize a learning and innovation processes would likely have been resolved sooner and access widened more quickly. But this was not the case and the digital divide is still very much with us.

Since the 1990s, a second wave of technological change has transformed the development of new products and processes in ICTs and brought about the application of biotechnology to pharmaceuticals and agriculture. In these new wave technologies, the knowledge dimension, is now much more evident in the strong role that the science base plays and the intensity of patenting activity. 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. It is in this context that the role of the South as a ‘technology user’ is becoming even more problematic and raises the specter of a cumulative and path dependent growth in inequalities between and North and South in the future. Catching up in these science-based, patent intensive technologies, whether as users or producers, will require more attention to the development of tertiary education and public sector research capabilities, not only to widen the range of choice, reduce costs of final products and adapt these new technologies to local needs but also to provide the basis for more informed policy-making processes.

**Strengthening tertiary education and public sector research**

The 1980s and 1990s were years in which the contribution of public sector research institutes and universities to innovation, especially in the United States and a number of European countries, came under strong criticism and support for these knowledge-based organizations began to erode. It was no surprise, therefore, that faced with the austerity measures imposed as part of World Bank/IMF structural adjustment programmes in many developing countries, the budgets of these organizations were sharply cut.

In the current context, such strategies need to be rethought. 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. While, universities and research organizations are once again regarded as potential contributors in dealing with the challenges of growth and development, simply returning to past practices in which reform of the science and technology sector focuses mainly on the supply of researchers and research outputs, however, is not likely to solve the ‘innovation’ problem, where innovation is understood as the application of new knowledge in production.
As research on new wave technologies in developing countries has shown, pumping up the supply of science and technology outputs alone will not be enough. The ability to use these new technologies and to adapt and apply them across all productive and service sectors will require not only more attention to the development of tertiary education and public sector research capabilities, but also new stimuli for both producers and users of knowledge, whether private sector firms, government ministries, innovation intermediaries, environmental services organizations, NGOs, regional and local organization to work more closely together.

To conceptualize the set of policies and programmes, the channels for knowledge and information flows and the financing mechanisms that sustain an innovation process, a more systems-oriented approach will be needed from the outset. Only in this way will technological change open opportunities for the development of a robust and competitive SME sector alongside the science and engineering based capabilities needed to adapt ‘new wave technologies’ to local needs. Thinking about transitions early in the process of a technological revolution thus has the potential to narrow gaps rather than widen them.

**Building capacity in Hydrogen, Fuel cells and HFCVS**

A small number of developing countries with strong science and engineering capabilities have created teaching and research programmes in the chemical and electrochemical engineering and natural science bases that underlie the emerging hydrogen economy. These countries are also participating in a variety of networks through which they are able to learn about hydrogen, fuel cells and their applications in both the transport and stationary power sectors and monitor the frontiers of change in these fields. But this is not the case for the majority of developing countries.

What to learn, how to advance the learning process at home and diffuse such knowledge more widely requires further reflection. Study tours by science, technology, energy and education ministries from interested developing countries should be organized to leading developed and developing country teaching and research institutes with a view to building the knowledge about critical science and engineering inputs needed to design programmes at home.

In a few of these developing countries, research programmes are already underway on hydrogen fuel cells for both stationery energy and transport and alternatives such as electric vehicles. Brazil, China and India are in the forefront of these activities. All three are members of the International Partnership for the Hydrogen Economy (IPHE).

China’s 863 programme, which began in March 1986, is focused on new wave technologies, notably on the development of information, biological agricultural, material and environment and energy technologies. During the $10^\text{th}$ five year plan period (2001-2005), The Ministry of Science and Technology (MOST) approved an 880 million Yuan (US$106

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40 Brain drain is a classic instance of the effect of a mono-focus on the supply side as opposed to a dual focus on strengthening both supply capacity and domestic demand for new technologies building the linkages between users and producers that stimulate an innovation process.
In contrast to previous programmes, the current focus is on the commercialisation of fuel cells in the auto industry, particularly through the development of two large 150kW fuel cell buses by 2005 and the work will be done by a number of local institutes and companies including Shanghai Shen-Li High Tech Co. Ltd, Beijing LN Green Power Company, Dalian Sunrise Power, Beijing Fuyuan Fuel Cell Group, Beijing Jinfend Aerospace S&T Developments Company, Dalian Institute of Chemical Physics, Tongji University, Changchun Institute of Applied Chemistry, Beijing Institute of Technology and Tsinghua University.

A large number of universities, research institutes and private firms in India are also involved in research and development on fuel cells for use in the transport sector, notably in buses and two wheeled vehicles and for power generating devices. In addition India is active in carrying out research on a range of alternative technologies such as natural gas and biodiesel extracted from local non-edible oilseeds. Bharat Heavy Electrical Ltd. (BHEL), for example, has developed and tested a prototype 50 KW Phosphoric Acid Fuel Cell (PAFC) system operated with by-product hydrogen from a chlor-Alkali plant. In 2002 BHEL acquired PEM fuel cell technology from the Indian Institute of Science in Bangalore and has refocused its work on PEMFCs. Tata Energy Institute is testing Ballard fuel cell driven bus and the SPIC Science Foundation is working on PEMFC. Among others involved in hydrogen fuel cell-related research are the Central Glass and Ceramic Research Institute, Central Electro Chemical Research Institute, Scooters India Limited, Banaras Hindu University, Birla Hightec, Gas Authority of India Limited and the National Chemical Laboratories. A Hydrogen Energy Development Board, under the Ministry of Non-Conventional Energy Sources (MNES) was formed to co-ordinate and implement fuel cell development in India.

Much of the research and development related to electric vehicles and hydrogen fuel cell technology in Brazil is carried out with the support of Petrobras, the national oil company and its affiliate, CENPES (Rio de Janeiro) and The Instituto de Tecnologia para o Desenvolvimento (LACTEC) (Curitiba). A first international workshop on fuel cells was held in Campinas in October 2002 and a paper on the development and construction of three PAFC based Plants was presented. (Cantao: 2002). The objectives of this project, which brought together the Brazilian natural gas network, Ethanol producers and research institutes, include: to demonstrate the viability of fuel cells for stationery power, analyze differences in energy efficiency, costs and emissions when using different fuels and provide sites for further research and training. Research on PEMFCs is also underway and prototype 5KW PEMFCs have been developed by Unitech and Electrocel, Brazil’s domestic fuel cell manufacturing company. Brazil is also developing bio-diesel fuel to reduce pollution and meet its commitments under the Kyoto protocol (Motta & Calmon: 2005).

While the creation of full-scale training programmes in the developing world will take considerable time, it would be possible now to establish networks of centres of excellence involving universities and research institutes in Africa, Asia and Latin America. These would be anchored by established research and training programmes in countries such as India, China and Brazil as well as partner institutes in the North. Exchange of post-graduate students and confirmed research would in only a few years supply core staff for local research and training.

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41 There is no is Only a small amount of the total budget will be alloated to establish two power generation plants, a 50kW MCFC and a 5kW SOFC also by 2005. [http://www.most.gov.cn](http://www.most.gov.cn). See also, [http://chemport.ipe.ac.cn/cgi](http://chemport.ipe.ac.cn/cgi), [http://www.fuelcell.ac.cn](http://www.fuelcell.ac.cn) and [http://chinafcb.org/index-english.html](http://chinafcb.org/index-english.html)
training capabilities and provide support to government monitoring and policy-making activities. They would provide the basis, moreover, for an expansion of the country’s absorptive capacity and thus enable local research and production to emerge more quickly.

Leapfrogging in the development and use of Fuel Cells for Stationery Power

Hydrogen fuel cells are a dual use technology and can be developed for both the transportation and the stationery power sectors. For fuel cell manufacturers, such as Ballard Power Systems, for example, maintaining a foot in both camps has been essential in growing the company. Ebara Ballard, was thus there when Japan decided to move towards the development of co-generation plants in Tokyo.

Even though full-scale production of FCVs for most companies will not take place much before 2010-2020, dual-purpose usage in stationary power systems and in FCVs is creating economies that 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.

Both PACFs and PEMFCs have been installed widely in the US, Japan and Europe since the mid-1990s, and more recently in Canada, Korea, India, Brazil and China. This would be an opportune moment for other developing countries to study these technologies and build up a capacity to evaluate the conditions under which these cells operate well and the costs involved. This may be an opportunity to avoid environmentally damaging construction of hydroelectric dams and the costs construction of a power grid that transmits energy with decreasing efficiency over long distances by building a more distributed form of energy generation and one that might operate by using bio-based fuels and solar cells.

Learning Through HFCV Testing Programmes

Over the past five years, testing of newer types of fuel cells and stacks, as well as a variety of fuel production, distribution and on-board storage systems has progressed considerably in Europe, North America and Japan. Much of this was supported through public funds or involved public private sector collaborations such as the California Fuel Cell Partnership, the Japan Hydrogen and Fuel Cell Park or the EU’s CUTE project. Experimental hydrogen fueling stations have been set up in Japan, Iceland, the European Union and California as part of programmes to road test hydrogen powered FCVs. By 2005, fuel cell bus testing, underway for several years in Canada, Europe and the United States, had been extended to a small number of developing countries.

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43 The Energy Information Administration’s Natural Gas Monthly of May 1994 listed the companies that were already operating fuel cell stationery power systems using PAFCs. There were some 30 power companies in the USA, 7 in Europe and a several others which now would have had 10 years of experience in operating these plants.

44 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.

45 These are being carried out by the California Fuel Cell Partnership.
Under the Global Environment Facility (GEF) of The United Nations Development Fund (UNDP) a programme to deploy and test fuel cell buses in five developing countries was adopted. The programme, which would test up to 40-50 buses, was anticipated to cost approximately $130 million USD. The choice of countries and within them of specific cities for testing these vehicles reflects a dual consideration: the large, urban, highly polluting transport systems in cities such as Beijing, Shanghai, New Delhi, Sao Paulo, Mexico City and Cairo, on the one hand and the strong engineering base needed to undertake these testing programmes and learn from them.

At present, the programme in China is furthest along and China hopes to complete this first phase in time for the Beijing Olympics in 2008. The Tata Energy Research Institute is currently testing a Ballard Fuel Cell Bus, but given the high cost of these buses, New Delhi, which only recently converted its bus system to CNG vehicles, has not begun a broader testing programme. The same is true in Cairo and Mexico City which have adopted alternative programmes for the reduction of urban transport pollution.

To diffuse knowledge across the developing world, countries in both North and South with on-going fuel cell bus and car testing facilities might consider the formation of a consortium for knowledge production and sharing on the lessons learned from testing programmes. This might take a number of forms. Systematic comparative analysis across testing programmes could form the basis for an understanding of the strengthens and weaknesses of various technologies and the social, economic and environmental conditions under which they work optimally. The lessons learned from testing can be incorporated into training manuals for researchers and policy-makers from other developing countries. Such manuals would include information on the operating parameters within which testing is taking place, performance criteria and evaluation, techniques for learning and analysis, adaptive choices and changes in the course of testing programmes and the impact of lessons learned on policies, programme and future technological trajectories in countries with testing programmes. The consortium could also plan a series of training programmes on a country or regional basis to diffuse this information more widely. Consortium members could also open their facilities and programmes to visiting scholars for internship, training and collaborative research programmes.

Evaluating alternatives and making informed choices

There is currently a wide range of alternatives for reducing pollution in the transport sector. Not all of these push the technological frontier forward or bring about more fundamental changes. Nor are there methodologies available which enable developing countries to evaluate these alternatives from a multi-goal, long term perspective. Most methodologies continue to take a narrow problem solving approach to the pollution problem, such as simply using end of the pipe solutions or transferring the center of the pollution problem from the final user to the source of energy. This may hide it briefly from public view but does little to change the overall environmental impact or the underlying consumption and production models that are generating it. It tends, moreover, to prolong the life cycle of earlier technologies when the moment to invest in newer, potentially more effective, efficient and sustainable technologies may have arrived.

46 See the paper by Dr. Gelil.
There is also a problem in choosing among alternatives. Which criteria are used can lead to the choice of technologies that bridge the move to a technological revolution or become barriers to it. Policies have a particularly important role to play in this respect as they shape the parameters within which choice-sets are established and criteria selected. Today, for example, policies and the competitive practices of critical actors that they help to shape have tilted interests towards the continued use of fossil fuels such as gasoline and natural gas, albeit with efforts to produce cleaner fuels and the development of hybrid vehicles that reduce overall pollution levels and creation greater fuel economies. This was the logic implicit in the approach to the choice of alternative fuels presented in a report prepared by Adnan Shihab-Eldin, Director of Research at OPEC and presented to the 8th International Energy Forum in Osaka, Japan on 21-23 September 2002. The argument begins with the affirmation that world energy demand will continue to grow through 2020, especially in the transport sector and inquires into the technologies that might be available to meet this demand. Oil and natural gas are finite but still very abundant and relatively low additional costs would be needed to expand production or infrastructure of these two fuels. These hydrocarbon based fuels, along with bio-ethanol, also have mature technologies, but increasing output of the latter and of bio-diesel, a newer technology available mainly for pilot projects and at high cost, are limited by land. Both, however, can use existing gas stations and conventional ICEs. Nature gas, on the other hand, competes with increasing demand for power plants. The sole problem with oil, when compared to the others, is its emissions problems. But cleaner fuels in the transport sector can deal with these problems. The report thus concludes that “...cleaner fossil fuels will continue to dominate the power sector, as well as most other sectors, for decades to come, if not throughout this century.” (Shihab-Eldin:2002,305).

Most efforts at evaluating alternatives take existing trends as given and inflate the costs or difficulties of reversing them. The preferences of consumers for SUVs is one example. Few efforts at evaluation, moreover, place dynamic longer-term goals, such as learning, high up in their list of priorities. Yet for countries in the South learning is the key to future growth and development. Developing countries will need to factor opportunities for learning and capacity building into the evaluation process so that they will be able to set off down a path that widens their choices for the future.

Evaluating alternatives also requires attention to the direction of change. Setting off down a path that diverges over time from what becomes the main technological trajectory of the future can be very costly. How to deal with this problem is of some concern to developing countries. What short term approach, for example, should be taken to ensure that natural gas infrastructure that might be built is compatible with hydrogen and what might be learned by using natural gas-hydrogen blends in the short term in CNG vehicles where access to natural gas is economic?

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47 The following comparison is drawn from Table 10 and the categories used their to compare these alternative fuels (Shihab-Eldin:2002, 294).

48 See, for example, the way in which pressures to reduce potentially toxic mercury effluent within a very short time-frame, led to the adoption of an intermediate technology by Japanese firms in the chlor-Alkali industry and the reconversion at high cost, to a more suitable technology when it appear on the market only a few years later (Yarime: 2001).

49 See for example the paper by Dr. Tapan Bose of the Universite de Quebe’s Hydrogen Research Institute, “Pathways for Transition to Hydrogen in Developing Countries “ presented at the 15th World Hydrogen Energy Conference, Yokohama, Japan, June 28-July 1, 2004.
A number of steps can be taken to facilitate the choice process. One of these is to put in place a system for monitoring the pace of change in fuel cell technologies and for analysing the factors affecting it. Most developing countries cannot afford to undertake such a continuous monitoring and evaluation system on their own. Fortunately a small secretariat and extensive networking through the internet can provide a solution to the problem of timely data collection. But the analytical problem remains. More work will need to be done to develop methodologies for evaluating change and deriving from them an appreciation of the range of alternatives, the conditions under which they can be effectively implemented and the speed with which new technological trajectories are emerging that might displace these alternatives.

Moving towards CNG vehicles as a way to reduce urban pollution in the medium-term is but one example. Are the conditions within which this choice can be effectively implemented already in place? CNG, for example, was available in New Delhi when the Supreme Court set the deadlines for conversion of the municipal bus fleet in that city but the infrastructure was not sufficient to meet demand once so many vehicles were converted at the same time (Sing, A. et al.:2001). From a learning and innovation perspective, the ability to replace imported conversion kits with locally developed and cheaper kits was a plus. In contrast the pace at which CNG vehicles are being in Tokyo where fueling stations were not readily available and CNG vehicles were more expensive than diesel vehicles is extraordinarily slow (Yarime:2002).

Going beyond a choice based on a single criteria, it would also be essential to take a number of other key factors into consideration in choosing among alternatives. Which way to move, how and when? How to make such choices and how to ensure that they are ‘evidence-based’? For example, what are the economic and social costs of conversion and who bears these costs? What kinds of capacities need to be built and what provisions need to be made to ensure that the capacity-building process does not exclude segments of the population?

Policies, whether tacit or explicit, shape the parameters within which decisions about investment and innovation are taken. They inevitably impact on the direction of technological change. Policy timing and sequencing as well as the need for complementary policies to offset inequalities in the ability of actors to respond to market signals are often needed. Building the channels for a continuous dialogue amongst domestic stakeholders thus plays a critical role in enhancing the benefits of science and technology for all people. It is though such dialogues that awareness of a wider range of choices with regard to domestic research and technology trajectories can emerge and research programs that include sustained innovation in the smallholder agricultural sector, as in the choice between ethanol produced from sugar grown on large scale plantations and bio-diesel produced on smallholder farms from non-edible oils and in small and medium-sized manufacturing and service sector firms can be developed. Research is also needed to analyse alternatives in situ and to identify possible collaborative partnerships and structure these to ensure that learning and capacity building takes place.
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