Strategic innovation in sustainable technology: the case of fuel cells for vehicles

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Abstract: This paper explores the gap between the implied theoretical 'assumption' that development of technologies for sustainable development should be a smooth evolutionary transition and the reality of such change. Here, we identify a split between macro, long-term models of transition to greater environmental sustainability through innovation, as found in theories of ecological modernisation, techno-economic paradigms and technology transitions and the firm level issues involved. Innovation theory, in contrast, has been concerned with contingent factors affecting the process of technology management and innovation strategy. While long-term models of change are predicated on the necessity of successful development and adoption of novel technologies, more specific, firm-based study of radical innovation demonstrates the complex and disruptive aspects of such change. In this paper, we investigate the interactions between these issues through a case study of fuel cell technology for vehicle propulsion.

Keywords: fuel cells; technology strategy; innovation; sustainability; commercialisation.

Reference to this paper should be made as follows: Peters, S.R. and Coles, A-M. (2006) 'Strategic innovation in sustainable technology: the case of fuel cells for vehicles', *Int. J. Environment and Sustainable Development*, Vol. 5, No. 4, pp.338–354.

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1 Introduction

This paper aims to investigate the role of firm-level innovation strategy in developing technologies for sustainable development. However, the concept of sustainable development has focused on change at the macrolevel, as it is incorporated as part of national policy goals, rather than at the microlevel of the firm. Even so, ideas on the success of sustainable development tend to rely on developments in discontinuous technologies (Jamison, 2001). Thus, it seems pertinent to investigate the nature of the relationship between wide scale sustainability goals and individual firm strategies. In this paper, we look at the development of fuel cell technology for vehicle propulsion, attempting to elucidate whether the sustainability agenda has been incorporated at the level of the firm.

Two macrolevel theories have made general observations about the route to sustainability through innovation in 'clean' technologies, Freeman's (1992) assertion relating to the advent of a green techno-economic paradigm and the theory of ecological modernisation developed primarily by Mol (1996). Both these approaches emphasise that innovation and institutional change are essential in moving towards environmental sustainability. It is axiomatic to the elaboration of these theories that individual firm technology strategies will be responsive to policy initiatives to encourage discontinuous innovation in untried (and risky) technologies (Green et al., 1999; Hall and Vredenburg, 2003). In addition, Geels' (2002) concept of long-term technological transitions, with the approach of strategic niche management suggests a means by which; strategic innovation can become 'purposive' transition to sustainability (see also Berkhout et al., 2004; Kemp et al., 1998).

Freeman and Soete (1997) regard a techno-economic paradigm as being composed of a series of interrelated technological systems, where a transition period is necessary for change, to enable build up of essential knowledge, skills and experience. In the case of ecological modernisation, business is encouraged to view environmental innovation as an opportunity rather than a cost and the theory predicts the greening of production process through market-based selection of environmentally benign technologies (see Mol and Sonnenfeld, 2000; Spaargaren and Mol, 1992). In fact, it is these contextual issues, which suggest current approaches from recent innovation theory could be constructively applied (Freeman, 1992).

Jamison (2001) for instance, has observed limitations in European policies to stimulate and promote the development of sustainable technologies, which tend to leave the impetus to market dynamics and business strategy. It is unclear, therefore, whether national policies or technological competition which will encourage firms to invest in sustainable innovation. In this paper, we consider the prospect for such a transition through the development of fuel cells for clean vehicle propulsion. Innovation research focuses at the organisational level and a major concern is related in maintaining a competitive advantage in global innovation process. In addition, study of emerging radical technologies has focused on a variety of interrelated factors affecting the early stage of development, such as the role of technological uncertainty and firm strategy. Recently, there has also been a focus on the dynamics of radical innovations in rigid and complex systems, which affects large-scale changes in systems and infrastructures (see Coutard, 1999; Rycroft and Kash, 2002). A major issue, therefore, is to identify the factors which encourage firms to invest in more sustainable technologies, such as the strategic issues which are at the core of the process whereby firms internally respond to external concerns about environmental sustainability.

2 Sustainable innovation

Identifying the factors that encourage firms to invest in the development of sustainable technologies helps to elucidate the relationship between issues such as innovation strategy, market development and environmental regulations. Dyerson and Pilkington (2000) suggest the main barriers are managers who resist radical change in mature technologies. Hinnells (1993) claims that environmental factors have a low priority in individual firm strategies unless there are competitive or legislative issues common to the sector and that firms are concerned that competitors should not develop a significant technical lead. He concludes that firms are concerned with reducing environmental impacts of their products if this objective overlaps with other business needs (see also Foster, 1986). However, there is a greater acceptance that environmental issues have become a driver for new innovation, as Mulder (2005) considers the innovation response to the ozone catastrophe as a case of 'forced' innovation. Trott (1998) describes how ICI also responded to concern about the environmental impact of cleaning products by both raiding its own knowledge archive and also acquiring the external competences of small firms to develop cleaner products. In addition, Huber (2003) supports the idea that process innovations are the major contribution to reducing environmental impact, while Senge and Carstadt (2001) as well as Freeman (1996) consider the firm as a critical source of cleaner technologies. Others, however, emphasise the systemic aspects to introducing clean technologies, involving the enrolment of a broader base of stakeholders in the development process (e.g. Connelly and Smith, 1999; Jacobsson et al., 2004; Porter and Van den Linde, 1995; Skea 1994; Theocharis et al., 2005; Wield and Braun 1994).

Rohracher (2001) discusses the challenges involved in developing a market for ecological products. He identifies an existing 'deadlock' of simultaneous lack of supply and demand, claiming that demonstration of new technologies can provide an opportunity for learning, far reaching change depends on creating the necessary infrastructures and institutions. Philmore (2001) considers the role of environmental regulations, which are often consider a 'cost' on innovation. He notes, however, a change in attitude in some quarters considering a more beneficial outcome of tough environmental regulations and related economic instruments, which promote innovation, growth and employment. While Philmore (2001) asserts that adopting high environmental standards, can help the creation and capture of emerging markets by accelerating technological development and new products may accrue 'first mover' advantage, in contrast Wallace (1995) found no evidence for such advantage arising from environmental regulations, which had varying impacts on innovation and competition.

Schot (1992) points out that legislation gives a role to national government in affecting the selection environment for sustainable technologies (see also Rothwell, 1993). It appears then, that firms develop sustainable technologies when these overlap with other business objectives, while legislation can help to shape the external pressures on the firm.

3 Discontinuous innovation

Transition to sustainability, therefore, centres on whether firms can be encouraged to develop a strategy for radical sustainable innovation. Radical innovation is, however, by its nature technologically difficult and financially risky (Rosenberg, 1996). Thus firms involved in such developments tend to deploy the risks by entering research collaborations or by adopting entrepreneurial strategies and investing in developments outside their core competencies (Christensen, 2001a; Howells, 1997, 2002). With more complex projects, it is not uncommon to find research networks emerging between large and small firms as well as research institutes in the public sector. Such development networks are now international in scope and this is evident in the case of fuel cells. This raises the question as to how national objectives for sustainable development might become incorporated into such development projects.

Investment in and development of radical technologies is notoriously uncertain, costly and unreliable (Genus and Coles, 2006; Peters, 2002). As Kemp et al. (1998) suggest they may appear first as niche developments in entirely disassociated sectors, although they may eventually have wide applications beyond their immediate function, with future impacts which are impossible to predict. In addition, the impact of globalisation has resulted in a more fluid position in terms of the locus of innovation, at least carried out by multinational firms, which has placed pressure on national innovation systems to defend established strengths as well as invest and encourage new technologies (Hislop et al., 1997; Mytelka, 2000; Tidd et al., 2001). The complex issues which face a firm innovating in discontinuous technologies raises issues about the dependence on radical leaps in development and diffusion of environmentally sustainable technologies. It also reveals limits to our understanding of how firms establish a strategy for such developments.

4 Technology strategy

When faced with the emergence of a radical technology, a firm needs to ensure it has an effective technology strategy. Freeman and Soete (1997) elucidate the problem faced by firms and the options open to them, in terms of actions circumscribed by its capacity to react to a changing environment. Arthur (1989, 1996) describes the extent of uncertainty facing the firms as the ‘technological fog’. The critical problem for firms is that they have little idea what direction the path of technological change will take in the future. Thus, it is often hard to pinpoint the type of strategy a firm is pursuing at this embryonic stage (Baba, 1989). This is made all the more important when firms have to develop new core competencies in a highly ‘disruptive’ technology (Christensen, 2001b). One way forward for a large firm is to embrace corporate venturing, when incorporated into an explicit strategic vision, designed to reinvigorate the competitive environment through radical innovation. The challenge then becomes one of reintroducing the 'entrepreneurial spirit' to these organisations through building competencies in a new technology (Utterback, 1994). Dess et al. (1997) suggests that firms may need to develop a more entrepreneurial approach in response to both uncertain environments and the need to manage discontinuous change.

To summarise, there are macrolevel accounts of sustainable development through innovation, which take place over the longer term and involve the development and diffusion of radical technologies. However, we have little information yet as to how such goals will be enacted through incorporation into firm innovation strategies. Furthermore, it is clear that currently, firms invest in sustainable innovation when this coincides with more traditional concerns of competition and markets. In fact, firms may be reluctant to undertake radical innovation due to the technical risks and market uncertainties involved, while there is also resistance through continual incremental innovation in existing technologies. In addition, even for those firms which are interested in developing radical technologies, there are problems in developing an appropriate technology strategy to fulfil such a goal, while the role of environmental legislation on internal decision making is still uncertain. The development of fuel cells for vehicle propulsion is a suitable case, to investigate these issues, as considerable environmental benefits are expected through reduction of exhaust gases. The technology is currently undergoing rapid development in more than one company with interest in its commercial potential.

5 Fuel cell development for vehicle propulsion

Successful development of fuel cell technologies has been characterised by a long time lag between invention and commercialisation. In common with many radical technologies, initial prototype development was supported by public funds, in a number of countries, while the utilisation of fuel cells in the Apollo space programme, marked a success for NASA's own investment (Coles and Peters, 2003). Latterly, interest in fuel cell technology to power vehicles has developed into a global research and development effort and selection of a particular prototype technology has been aided by strategic support from the large automobile manufacturers. The impetus for fuel cell developments originates from a convergence of different pressures on the industry, which has given rise to investment in a radical technology.

Philmore (2001) also notes the role for technological 'fit' into existing technical and institutional systems of advanced industrial societies. The example of hydrogen-powered vehicles, as a direct substitute for the Internal Combustion Engine (ICE) gives it an advantage over other technical and institutional changes. Thus a hydrogen engine does not demand changing the style or use of the car and would exhibit a diffusion pattern in industrialised countries where regulative standards are increasing. The same pressures, however, do not apply in all countries where strict regulation is not in force, so faster diffusion of old technology could still outweigh the benefits to carbon reduction. In particular, three major factors interact to shape the eventual outcome, short-term business issues, legislation trends and existing technological capability.

6 Industry dynamics

Automobile manufacture is a significant global industry run by powerful transnational companies. In 1995 it contributed 9% of European GDP and is organised around complex supply chains consisting of Small- and Medium-sized firms (SMEs). It is linked into an existing infrastructure of fuel provision and maintenance that will be threatened by radical changes to engine technology (Talalay, 1997). There are various pressures to innovate, in terms of long-term business survival and expansion. In the mid-1990s, Wong et al. (1996) argued that from the manufacturers' perspective, there was a distinct lack of consumer interest in green vehicles. This lack of interest was dominated by concerns related to price, performance and convenience. However, this now appears to be in the process of changing as consumers have shown themselves to be price sensitive in the wake of surging oil prices and are alerted of the need to cut carbon emissions. In the study by Wong et al. (1996), manufacturers supported increased legislative standards as a fair way to place equal responsibility on all firms, to improve their environmental impact, rather than relying on an uncertain market demand.

According to Borroni-Bird et al. (2002), 12% of the global population currently own vehicles and in the past decade ownership levels have increased, particularly in Western Europe, the USA and Japan. In future, however, manufacturers expect levels of ownership to accelerate significantly in both the Newly Industrialising Countries (NICs) and Less Developed Countries (LDCs), while the major manufacturing areas will remain in Western Europe, North America Free Trade Area (NAFTA) and Japan. It is these areas where concern about the control of pollutants is paramount, yet vehicles account for a significant amount of carbon emissions. Leading manufacturers such as General Motors, Ford, DaimlerChrysler, Honda and Toyota have steadily developed a strong interest in methods to reduce carbon emissions, in response to both increasing demand for new vehicles and increasingly stringent environmental regulations in Western markets. In addition, a strategic move away from dependency on oil is seen as vital over the longer term due to the growing pressures on known reserves and wider climate change considerations (Johnston et al., 2004). To put this goal into operation requires an innovation strategy aimed at the development of technologies that offer a radical solution, even though developments to modify existing engine technologies via a number of 'hybrid' solutions is ongoing. Fuel cell technology, however, offers the potential for a 'sea change', moving away from conventional technology.

In terms of maximising a reduction in carbon emissions fuel cell technology is the most radical solution enabling zero emissions to be obtained. Talalay (1997, p.271) recognised this potential stating that fuel cell technology "has the power to revolutionise the automobile industry, to fundamentally change the politics and economics of energy, to restructure the environment agenda...". The global nature of the business and potential for continual market expansion brings the question of environmental sustainability to the fore and particularly the role of legislation in continually raising environmental standards.

7 Fuel cell developments

Fuel cells produce electricity through an electrochemical reaction between hydrogen and oxygen to produce electricity, with water as the main by-product. The fuel cell has some major technical advantages over the ICE which include; a much lower rate of harmful emissions, the absence of any moving parts and operationally it is completely silent. Hoffman (2001) pinpoints the idea of using hydrogen as a fuel for vehicles back to the 1930s when a German engineer, Rudolf Erren, developed a hydrogen engine. More general interest in the application of hydrogen technology, however, waned until the 1970s. The event which dramatically reawakened interest in the potential of hydrogen technology was the oil crisis that struck in 1973. Concerns over the lack of alternative sources of energy to fossil fuels, especially oil, mounted steadily under the (then) difficult economic conditions.

One particular individual who was more aware of the problem than most and was of the strong belief the problem could only worsen in the coming decades was a Canadian engineer, Geoffrey Ballard. At the time of the crisis, Ballard worked for the US Department of Energy. One of the responses of the US government to the oil crisis was the establishment of a new office of energy conservation of which Ballard was made director of research. He was charged with the development of a research programme with the long-term objective of enabling the USA to become self-sufficient in energy (Koppel, 1999). From his vantage point, Ballard was only too well aware of the scale of the future energy problems. In 1974, the US transportation sector accounted for 53% of US petroleum consumption. By 1987, this figure had increased to 64% which was more than the *entire* US production of petroleum (Koppel, 1999). Without action, the country's dependence and consumption could only increase, which is indeed what has happened. The USA was a big enough problem and remains one in itself. In 2004, the US consumed 20.5 million barrels of oil a day, of which 58% was imported, up from 34% in 1973. According to the Energy Information Administration, a US government agency, this import dependence will rise to 68% by 2025 (Financial Times, 2005).

The real issue here for Ballard was the development of alternative sources of energy to fossil fuels. The focus on energy conservation per se was 'misdirected' as it did not address the fundamental question of how to meet the exponential growth in global demand for energy. This was where the real challenge lay. In 1974 Ballard set up a firm, which later 'evolved' into Ballard Research (and latterly into Ballard Power Systems), to exploit the opportunities opening up in this emerging field. The most immediate opportunity Ballard saw was a market for portable power devices, so he focused his firm's research on the chemistry of batteries to improve their power to weight ratio. For the rest of the decade until the beginning of the 1980s, this was the area where Ballard Research concentrated its efforts.

In 1983 with the Cold War still in full flow, Ballard Research came across an opportunity which would change the direction of the firm. The opportunity was a Request for Proposals (RFP) from the Department of National Defense (DND), in conjunction with the National Research Council, to develop a low cost solid polymer fuel cell (Koppel, 1999). This was the same type of fuel cell that had first been developed by General Electric (GE) for use in the Gemini space programme. The solid polymer fuel cell is known today as the Proton Exchange Membrane (PEM) fuel cell. Ballard recognised the significance of the RFP. The fuel cell was an alternative technology and its long-term potential for transportation was enormous. Furthermore, the only firms which could take advantage of this opportunity, were those with expertise in electrochemistry. This was the very area where Ballard Research had developed significant strengths through a contract it had once had with Amoco to develop a rechargeable lithium battery. Out of the six submissions the DND eventually received from firms, only two came anywhere near to satisfying the necessary criteria. Ballard Research was one of those firms and emerged as the winner of the contract (Koppel, 1999).

The first major technical challenge for Ballard Research was to learn about the technology, that is, to understand what GE had done and build upon it. Its initial step was to dismantle and analyse the old GE fuel cell (supplied by the DND) and purchased a cheap Sammer PEM fuel cell being sold off for lecture and demonstration use. The next hurdle was to learn how to build its own fuel cell and analyse ways to improve its performance and reduce costs. The first fuel cell built was known as Mark I. Some of the components were obtained from the old GE fuel cell, whilst others were made by Ballard Research, for example, the fuel cell plates (Koppel, 1999, p.77). In the early GE fuel cell these were made of nobium, which was a very expensive material, but Ballard Research substituted this with sheets of graphite (solid carbon) a much cheaper material in Mark I. This first fuel cell could ultimately be considered to have been successful. It was easy to assemble and worked despite its small size (seven and a half centimetres in height). To function it was given extremely pure oxygen and hydrogen and ran at a temperature of 55°C. Ballard Research knew the only way forward was extensive experimentation using different configurations of gases to fulfil the DND's objective of a fuel cell that worked on liquid fuels (Koppel, 1999).

Apart from experimenting with the configuration of gases, another area of focus that had a dramatic effect on performance of the fuel cell was the amount of platinum used on the electrodes. It was found that the fuel cells which used lots of platinum, similar to those originally produced by GE worked well. The fuel cells which used less platinum the performance declined significantly after the first 100 hr. Continuous experimentation proved absolutely crucial as small changes made to the amounts of platinum used could have a dramatic affect on the level of a fuel cell's overall performance. Building prototypes and running them for extensive periods of time permitted Ballard Research to learn fast about the technology. After the Mark I fuel cell, Ballard Research spent only a short time on Mark II. This was little more than a larger version of Mark I. Where the firm started to get into serious development work and showed its prowess with the technology was with the Mark III. This particular model was especially important as it was a 'replica' of the fuel cell built by GE for use in the Gemini project. Ballard Research achieved an important milestone with this model. With access to the original design from an internal GE and Los Alamos report the firm made a good replica of the original and also matched the same performance as GE at a fraction of the cost compared to GE's investment, which had run into several million dollars (Koppel, 1999).

In mid-1986 the DND contract expired. Unlike many defence-related contracts, where firms 'struggle' to meet their contractual obligations either through serious cost over-runs and technical problems, Ballard Research greatly *exceeded* them. Back in 1983, the DND had envisaged a fuel cell with a power output between 50 and 100 watts. Little more than two years later, Ballard Research had developed a 12-cell stack with a power output of 280 watts, more than double the specified requirement. Ballard Research had shown it had mastered the technology. When the first contract expired the DND wanted to extend it for a further year. This was easy for the DND to justify as it only had to point to the stunning progress Ballard Research had made with the original contract. Ballard Research received a further $248,000 to ensure work on the fuel cell went uninterrupted. The DND's objective remained the same of lowering costs through the use of new materials. Ballard Research had already been very successful in this area by reducing the levels of platinum used. There were other areas that provided additional scope for further improvements, one of those prime areas was the fuel cell's membrane (Koppel, 1999).

The membrane Ballard Research had been 'dependent' upon was DuPont's Nafion®. The membrane was produced in relatively small quantities mainly for use in industrial-scale electrolysis of sodium chloride gas and later used by the US Navy to generate oxygen through the electrolysis of seawater on board submarines (with the oxygen being inhaled by the crew and hydrogen vented). Under these conditions, Du Pont had little commercial incentive to lower costs (Koppel, 1999, p.90). Ballard Research was obligated to find an alternative. The best membrane the firm came across was one produced by Dow Chemical. The need to find an alternative to DuPont's Nafion® was a godsend, in retrospect. When Ballard Research started testing its new membrane in the mid-1980s in 6- and 12-stack fuel cells, the performance of the fuel cell was dramatic. The essential feature of the new membrane was it boosted the power output of the fuel cell by a factor of four. This massive boost in power output turned the fuel cell into a very serious commercial proposition. For the first time, the output of the Ballard PEM fuel cell was sufficient to now power a vehicle. From this moment on, Ballard Research went from strength to strength (Koppel, 1999).

So Ballard Research could maintain its rapid progress on the fuel cell, the DND awarded the firm one final contract to complete its original project and at the same time the firm started to attract venture capital. The importance of venture capital for the firm was that it signalled a growing 'recognition' by the financial community of the fuel cell's huge potential in transportation. The fuel cell's commercial prospects were given another major boost in 1993, when the firm gave a public demonstration in Vancouver of its fuel cell bus (Koppel, 1999, p.151). This was the product of an opportunity Ballard had himself spotted emerging in California in the late 1980s as the state sought to control vehicle emissions through the passage of stringent environmental legislation and the promotion of clean technologies. The Ballard fuel cell was of great interest to the California Air Quality District, which Ballard developed a long-standing and close relationship with. The technological competencies of Ballard Research in the PEM fuel cell, which had been growing since the early 1980s, attracted the attention of the automobile manufacturers DaimlerChrysler and Ford. Recognising the commercial potential of the fuel cell, DaimlerChrysler and Ford formed a strategic alliance with Ballard Research in 1997 to develop the technology commercially (Griffiths, 1998). More significantly, it marked the concern of leading manufacturers' to secure an interest in leading fuel cell developments for use in vehicles.

By 1999, most automobile manufacturers were looking at fuel cells as a radical alternative to existing technology. Furthermore, DaimlerChrysler had imposed a time limit for the commercial launch of its fuel cell powered car in 2004, using methanol as the hydrogen fuel source, even though this detracted from the zero emissions objective (Burt, 1999a). Demonstrations of a commercially viable car powered by the fuel cell in 1999 showed the speed of development. The Chairman of DaimlerChrysler predicted that the firm's New Electric Car (NECAR) would be the first fuel cell car available on the market as a genuine competitive product needing no financial subsidy to encourage the consumer. He wanted to see a supporting fuel distribution infrastructure developed to encourage the diffusion of the technology and favoured the use of methanol, as a hydrogen source. In addition, DaimlerChrysler reported an intended investment of $1.4 billion to turn NECAR into a commercial reality (Brooke, 1999).

Others noted a development race emerging between two powerful alliances, as General Motors and Toyota signed a five-year partnership in April 1999 to develop fuel cell technology. Meanwhile DaimlerChrysler-Ballard-Ford, attempted to gain a significant advantage in cost reduction, resources and materials and to boost the automobile manufacturers' environmental credibility (Brooke, 1999). The objective was to save on the massive development costs and to speed up development, a risk sharing strategy. Jason Mark, a technology analyst with the Union of Concerned Scientists commentated 'both new pacts are seem as a serious step towards commercialising fuel cells' (Brooke, 1999). Also, the companies were participating in the Californian Fuel Cell Partnership, a collaborative regional project to test feasibility, market demand, cost and fuelling infrastructural needs for fuel cell vehicles.

DaimlerChrysler can claim to be the leading global company, spearheading the commercialisation of fuel cell vehicles, in collaboration with other vehicle manufacturers, oil companies, energy suppliers and political institutions. The company states its belief that fuel cells stand the best chance of becoming adopted as clean vehicle technology of the future, as "they combine the reaches of conventional combustion engines with high efficiency, low fuel consumption, and minimum or no pollutant emissions at all, at the same time they are extremely quite and comfortable" (DaimlerChrysler, 2004). The company has already achieved a global lead with demonstrations of fuel cell powered public transport, particularly buses with hydrogen drive. Since their launch in 1997, fuel cell powered buses have become established in Vancouver, Canada, while in 2001 Amsterdam adopted the first fuel cell urban buses used by a European transport operator. A major European fuel cell bus demonstration in ten major cities started in 2004 using DaimlerChrysler technology. In November 2005, three buses powered by fuel cells, were adopted by Beijing as part of a two-year demonstration project led by the Chinese Ministry of Science and Technology and supported both by the Global Environment Facility and United Nations Development Programme (Ballard Power Systems, 2005).

Other manufacturers are also actively involved in projects to demonstrate the feasibility of hydrogen-powered vehicles to facilitate adoption and diffusion for example the collaboration between General Motors and Shell Hydrogen in Washington, DC where a hydrogen pump is installed in a Shell retail petrol station to support a fleet of hydrogen-powered vehicles (see Benjamin et al., 2005; Tyrrell, 2003). In London, in 2002, a hydrogen partnership was announced, with the intention of participation in the European demonstration project (Genus and Coles, 2003; Jollie, 2002). In July 2002, the Honda FCX, became the first and only hydrogen-powered fuel cell automobile in history to be certified by the US Environment Protection Agency (EPA) and the California Air Resources Board (CARB) to be approved for commercial use. In December 2002, Los Angeles leashed the first of five Honda FCXs, which are now in daily use. In 2005, Honda launched its second-generation hydrogen-powered FCX automobile (Honda, 2005). DaimlerChrysler and Honda are at the forefront of the promotion and development of fuel cells on different fronts as they regard it as the 'ultimate solution' to the sustainability problem. Some of their competitors, for example, BMW and Volkswagen (VW), have chosen different strategies which focus on the development of alternative technologies. BMW is developing a hydrogen driven ICE and VW is developing low emission fuels. These alternative technologies, however, are at best 'bridging technologies' as they in themselves do not offer a long-term solution to the sustainability problem. As the likes of DaimlerChrysler, Ford and Honda amongst others, have turned their attention to the fuel cell, a technological bandwagon has steadily developed as it is the optimum technology. Until now the momentum of this bandwagon has been relatively slow. Should the technology be shown to work commercially, however, the speed of the bandwagon can be expected to increase at a very rapid rate.

Development of fuel cells appears to be explained by firm-level decision making and innovation processes. Innovation strategies, however, should take into account trends and changes in the business environment. Automobile manufacturers must include consideration of legislative trends and the likelihood of more stringent emission standards in the major markets of the developed world. The impact of legislation on innovation in the automobile industry is an area of considerable dispute (Neale, 1999). Dyerson and Pilkington (2000) claim that development of new forms of fuel technology has been a response to increasing legislation aimed at reducing vehicle emissions. Wong et al. (1996) also contends that automobile manufacturers view stringent legislation as a spur to innovation when it comes to reducing emissions.

Burt (1999b) made similar claims, arguing that the pace of innovation is driven by new environmental legislation rather than internal research strategies. Thus, he claims that it is the threat of new environmental legislation in important markets which is a pressure for the development of more sustainable technologies. He quotes the President of the Toyota Motor Corporation, Fujio Cho, asserting that an alternative to petrol is necessary, as "we must move forward in advancing environmentally friendly vehicles" (Burt, 1999a). This sentiment was also echoed by an industry spokesman as early as 1997, Director of the Board of General Motors, John Smith Jnr said that, "environmental pressure will force changes in the automobile industry…no car company will be able to thrive in the future with 100 per cent dependency on internal combustion engines" (Hoffman, 2001, p.102). Hoffman (2001) claims that this quote demonstrates that, environmental concerns are now on the agenda for long-term business survival. So, it is argued, it will not be consumer demand which will be the key driver of innovation in the future, but legislation (Griffiths, 1999).

The largest example of international cooperation has been the California Fuel Cell Partnership (CFCP). This started in January 1999, when two state government agencies joined with six private sector firms to form the CFCP, which had the aim of demonstrating and promoting the potential for commercial fuel cell powered vehicles as clean, safe and practical. There were originally eight founding partners; fuel cell manufacturers, Ballard Power Systems, UTC Fuel Cells; automotive manufacturers, Daimler-Benz and Ford; energy providers, BP, Shell Hydrogen and Chevron Texaco; as well as government agencies, the CARB and the California Energy Commission. Over the time the project ran, new partners were added (California Fuel Cell Partnership, 2000). Activity in this radical development by significant automobile manufacturers is encouraging in the sense that this appears to be a strategic investment in technology with environmental goals, although the disruptive effects would be felt mainly by firms involved in the ICE technology rather than the automobile manufacturers themselves.

The question is whether a significant change has taken place and manufacturers now see it in their interest to cooperate with the most stringent legislation for sound business reasons, particularly due to the desire to enter rapidly developing markets, increasing the total number of vehicles and the potential to implement a radical technology that presents a possibility for 'creative destruction' of the ICE, as well as offering superior technological performance. In this case, stringent regulations will not only provide a spur to innovation, but also a competitive advantage to the companies that lead in innovation.

8 Discussion

Fuel cell technology is clearly a radical innovation which has some claim to contribute to sustainable development through its potential to considerably reduce vehicle emissions. It is therefore a good case through which to investigate the process of business led sustainable innovation, particularly the relative role of micro- and macrocontributions to establishing firm strategy. Here, it seems that such innovative strategies are influenced by a range of organisational and technological pressures as well as both sector and regulative environments, which implies that factors influencing sustainable innovation in one sector may not easily be made more general. Automobile manufacture is a mature sector, established companies are involved primarily with incremental innovation of an embedded technological system (Hughes, 1983). It appears to offer little prospect of radical technological change, as it fits the profile of mature organisational and product development (Jamison, 2001). More specifically, there is 'lock-in' to the ICE, both technologically and organisationally through complex supply chains.

The proactive investment, its size and scope, by the leading manufacturers in fuel cell technology for over a decade, therefore requires explanation, as there is a conjunction of factors which make this a desirable innovation. The successful demonstration of the Ballard fuel cell development, a small, entrepreneurial outfit making technological strides with an untried, risky technology, was the key to attracting the attention of the global industry. The character of Ballard himself could almost fit the classical Schumpeterian notion of the inventor/entrepreneur, combining moral vision, with technical and organisational talent, making huge strides in a technological niche with huge disruptive potential. The speed with which two leading companies, DaimlerChrysler and Ford moved to secure access to the Ballard fuel cell, however, indicates a proactive strategy towards the innovation, where traditional pressures coincide with the need to respond to present and interact with future environmental legislation. This is supported by the rapid emergence of a more traditional 'development race' with General Motors and Toyota. A successful fuel cell technology will simultaneously allow manufacturers to 'leapfrog' ahead with regard to clean emissions, adopt a technology that they regard as superior in terms of providing an enhanced product to the market and forestall voracious criticism as they attempt to hugely expand global markets. It is the coincidence of these factors that help to explain the rapid technology development race that has developed in the sector, no major firm wants to concede 'first mover advantage' in an innovation which they clearly see as strategic.

This case indicates the relationship between radical innovation, competitive pressures and high-technical standards set by the most stringent regulation. It remains to be seen, however, whether the high cost of development of fuel cell vehicles means that there is a rapid pattern of diffusion such that fuel cells become the 'standard model' for vehicles available to all markets. It is this latter scenario, itself driven more by business dynamics than environmental concerns, which would make innovation in fuel cells the radical solution to the problem of vehicle emissions. Thus, it is clear that a reliance on 'the market' on its own in this sector is unlikely to bring forth the type of radical developments in clean technologies that are necessary for sustainable development. However, it must be acknowledged that more traditionally understood competitive pressures arising from the introduction of radical technologies, are still in evidence.

What is marked in this case is the rapidity of entry and size of investment by major automobile manufacturers into the technology. However, it again appears that this behaviour is not entirely driven by environmental concerns but also involves some assessment of improved technical characteristics resulting in improved product development.

This case also illustrates some issues about the influence of macrolevel concerns on firm-level technology development strategies. In this sector, wider environmental concerns have historically been channelled through legislative pressures in developed markets. A significant factor is the debate surrounding its acceptance or resistance by the major companies, as adoption of fuel cell technology would exceed emission standards in most countries. This case, then, does indicate support for the idea that the most stringent environmental regulations (as adopted in California) are a stimulus to the emergence of radical solutions, as a heterogeneous alliance emerged between international organisations interested in promoting fuel cell development. In other ways, this case confirms the innovation literature on sustainable developments, as firms have reacted to try and prevent the DaimlerChrysler-Ford-Ballard alliance from developing a significant technological lead. In addition, these international alliances have emerged to reduce the risks and uncertainties investing in the early stage of radical innovation.

It is apparent that DaimlerChrysler in particular has been the company to adopt an offensive technology strategy towards fuel cell development. Not only was it the first company to monitor and evaluate Ballard's success in demonstrating the technology, it provides the vehicles for the European public transport project. Together with the level of planned financial investment and deadline for launch of the private car, these activities indicate a commitment to the fuel call as the preferred technological trajectory for vehicle propulsion. This case demonstrates previous analysis of sustainable innovation and the role of firm strategies in balancing technical and commercial aspects, while wider pressures for environmental sustainability are taken up at the level of the firm.

9 Conclusion

This discussion of the factors influencing fuel cell development for vehicle propulsion demonstrates an alliance between environmental imperatives and commercial objectives in the development of radical, sustainable technologies. The evidence presented here relating to companies' activities in fuel cell development have shown that they are making a serious investment, if not, yet a total commitment to commercialising the innovation or at least adopting a hedging strategy to prevent any one firm emerging as dominant in a potentially important future technology.

In conclusion, it is possible to identify in this case, several factors which have been highlighted more generally as factors affecting the process of sustainable innovation:

1. the fuel cell fits into industry concerns with commercial competitive pressure, by offering not only improved environmental impact but also better technological performance
2. large manufacturers have taken steps to minimise the chances of any one firm taking a lead and having an emerging development gap
3. fuel cell technology is a radical development in terms of engineering principles, but it has a 'fit' with the existing technological system

4 development has been undertaken in international networks, with firms strategically acquiring access to emerging competencies

5 developing a potential zero emission vehicle puts manufacturers in a good position with legislators, both to advise on best practice and to demonstrate how infrastructural elements need to change.

This case demonstrates how large, multinational firms can incorporate sustainability objectives as part of their overall innovation strategy where these do not conflict with corporate objectives for competitive advantage. Fuel cell development, therefore, appears to exemplify the approach to European sustainable development that Jamison (2001) identifies in terms of the coincidence of public and private factors that will stimulate sustainable innovation. It gives some support, however, to the idea that increasingly stringent environmental regulations can be a spur to the development of radical technologies with improved environmental performance. The case demonstrates how the process of ecological modernisation and the emergence of a sustainable techno-economic paradigm through technological transitions are dependent on episodic and contingent factors at the microlevel of firm behaviour, rather than results of a smooth, evolutionary transition as the theories tend to imply.

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