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Fuel Cell Innovation:
A Developing UK Industry?

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Abstract

Considerable interest has been generated in alternative energy sources as a result of links between pollution, health and climate change. The opportunity exists, therefore, for radical innovation to address the societal and market problems that current technologies fail to address, and to develop sustainable technologies. Understanding the drivers, barriers and the interaction of company innovation processes and system drivers in different countries, is a necessary first step to address the key question: *How can the time-scales for development and diffusion of disruptive innovation be optimised?* This paper is a first report on research being funded by the Economic and Social Research Council under its Sustainable Technologies Programme.

The research findings provide insights into the barriers and drivers experienced by fuel cell developers in the UK, with initial results suggesting that fuel cell development and diffusion in the UK is not necessarily following the pattern suggested by the innovation literature. The role of Government is also highlighted, in terms of funding and regulation, where there is a perceived failure to support commercialisation of development and stimulate demand. Timescales for adoption in laptops – driven by market demand – are contrasted with timescales in automotive and power, shaped by emissions targets and controls.

Keywords

Fuel cells; hydrogen economy; sustainable technology; disruptive innovation.

1. Introduction

Considerable interest has been generated in the development of alternative energy sources as a result of links between pollution, health and climate change. International agreements such as Kyoto and those between EU, Japanese and Korean car manufacturers have been supplemented by legislation in both the US and Europe to control the use of power sources known to pollute the environment. There are also major concerns about (a) the long-term sustainability of fossil fuel energy sources, and (b) security of supply for fossil fuel energy in the current world political climate. The opportunity exists, therefore, for radical innovation to address these societal and market problems and to develop sustainable energy technologies. For example, fuel cells are an attractive, clean, quiet, reliable, and resource-efficient energy source, with a range of applications in the automotive, portable electronics, and power generation markets.

Fuel cell technology is based on science known in the 19th Century – combining hydrogen and oxygen in a catalytic chemical reaction to produce electricity and water – and has been used by NASA in the space programme since the 1960s. There are currently five types of fuel cell with different chemistries, operating temperatures, start up times and resilience to fuel impurities and movement which affect performance in certain environments (such as vehicles and electronics equipment). Technologies tend to be application specific and their present development status varies. However, development of commercially viable designs to suit a range of applications has only been actively pursued over the last decade, as environmental and security of power supply issues have grown stronger. California's 1990 'zero emission vehicle (ZEV) mandate' has notably driven automotive fuel cell development in Europe, N. America and the Far East. Nevertheless, Hall & Kerr (2003) highlight "expensive components, inadequate power densities and competing technologies, particularly the dominant internal combustion engine" as restricting fuel cell introduction.

The fuel cell innovations are potentially disruptive - fundamentally altering companies' capabilities, supply chains, product-markets, and people's behaviour. Replacing current power technologies such as the internal combustion engine which are well proven, with relatively low costs and an established infrastructure built on over 100 years of development and process innovation, poses significant barriers. The current system for electricity power supply met similar problems in the mid-late 19th Century, however, and overcame them.

This paper reports on the initial stages of a 3-year, ESRC-funded research study which uses the example of fuel cell technology to understand those inter and intra-company issues that impede the development and diffusion of disruptive innovation, and the practices that have successfully overcome these issues. A critical aspect of this is to understand the interaction of innovation and decision-making processes inside companies with the drivers and barriers in the environment outside. Companies do not directly control what goes on in this wider system, but such factors as regulation and governmental fiscal incentives can have a major impact on company behaviour and the pace of industry development. Hitherto, there has been little research attention to interaction between these two processes. Major theoretical statements about disruptive innovation, such as Christensen (1998) and Adner and Levinthal (2002), say almost nothing about the role of government yet public policy research on fuel cells in the UK (beyond the funding of basic research) has been framed almost entirely within a macro-economics perspective, concerned with market interventions through taxes, subsidies and regulation.

2. Research Objectives

The research has both specific and general aims, concerned with the adoption of sustainable technologies in general, the theory of disruptive innovation, and the fate of fuel cell development in the UK. It aims to:

1. Identify and describe the key factors and processes determining the development, adoption and use of fuel cell technology.
2. Identify the drivers and barriers to development, adoption and use.
3. Identify lessons for disruptive innovation involving sustainable technologies.
4. Contribute to the general theory of radical innovation and practice.

It will do this by examining fuel cell development in the UK, mainland Europe, North America and Japan, identifying innovation systems and best innovation practice.

3. Theoretical Background

Christensen (1998) highlighted the "innovators dilemma" - the problem from the incumbent company's viewpoint is that disruptive innovation involves uncertainty, and does not lend itself to a formal, structured process and conventional performance measures until the final phases of product development. Yet failure to innovate can make it uncompetitive. Although various tools have been suggested to improve product development outcomes, **disruptive innovation typically involves an exploration of various technologies** through early prototyping and testing that may take years and involve many false starts and dead ends. Utterback (1994) shows how technology development in most industries moves from a *fluid phase*, where typically there would be many new entrants to the industry all offering variants of the new technology, to a *transitional phase* with an emergent dominant design, and finally to a *specific phase* where cost efficiency and quality become essential to competition.

Adner and Levinthal (2002) suggest that the normal situation for radical innovation, is with progress being made in steps through marketing innovations to niches, and then broadening these niches until a mainstream market forms, a strategy also recommended by Moore (1999). Christensen, Raynor and Anthony (2003) **argue that disruptive innovation either creates a new market or takes the low end of an existing market** where customers are poorly served and incumbents are unwilling to defend to any degree.

The implication of a 'low end' niche strategy is that established large firm incumbents are less likely to be interested in radical innovation because it will destroy their existing investments and expertise. The question of whether **new or established firms** are the main source of radical and disruptive innovation has therefore been raised by a number of researchers. Schumpeter (1942**)** believed that innovation would typically come from smaller, new entrant firms, but that technological innovation often demanded a level of resources that could only be provided by larger companies. Others such as Kanter (1989**)** have remarked on the difficulty of effecting radical innovation within a large company, particularly if the innovation demands different capabilities and a different “mindset”. Winter (1984) attempted to reconcile this by proposing two kinds of ‘technological regime’, depending on the degree of discontinuity a new idea entailed – an ‘entrepreneurial regime’ involving a radically new idea attracting outsiders and new start-ups, and a ‘routinized regime’ where innovation is incremental and dominated by large firm incumbents. Clearly, though, if new entrants perceive an innovation to be radically different, while incumbents see it as evolutionary, they will co-exist. Much depends, therefore, on the strategic *perceptions* of firms.

The complexities and uncertainties of innovation, however, may make this not an either/or issue, but one best handled through collaboration. Thus, Afuah (1998) highlights the increasing use of **partnering and collaboration** in innovation, whilst Brandenburger & Nalebuff (1997) and Bentsson & Koch (2000) have described ‘co-opetition’ a blend of co-operating and competing with other firms at the same time. Practical and theoretical justifications for the decision to partner vary considerably, with commentators focusing on company capabilities, product characteristics, stage of development in the industry, or the nature of the technology.

Christensen, Raynor & Anthony (2003), believe that decisions on integration/partnering should be driven by understanding what drives the performance customers value. In the early days of a radical innovation, customers usually value factors that affect raw performance (e.g. design and assembly), but later, when competition moves to differentiation and customisation, companies may be better off specialising and retaining within the company only that which helps them specialise. Partnering is then a second stage development, when the emergence of a specialised supply chain allows outsourcing. However, it is unclear whether supply chain formation for a new technology must wait for this second stage. A supply chain is an interdependent network of firms extending from the end user to the basic materials used to create the product being offered (Forrester 1958). Christensen, Raynor & Anthony (2003) suggest that this occurs after the dominant design has been set, yet examples of high technology development such as the Personal Computer show that the supply chain can emerge during the technology development phase (Burton 1995). The extent to which the technology involves 'architectural' innovation (Henderson & Clark, 1990) - that is, requires direct collaboration to shape the innovation - may be a significant factor in when a **supply chain** emerges, the form it takes, **and** the build-up of an **industry capability**.

The key to success, however, remains the ability to develop an adequate market. Technologically sound innovations have a habit of failing when they do not develop sufficient demand and revenue quickly enough. The **need to build sufficient demand** to benefit from scale economies and ongoing process innovation is therefore critical (Moore, 1999; Christensen, 1997; Utterback, 1994). Companies need to learn about the technology, its applications and potential markets, and then communicate their knowledge to potential customers. Customers may not value claimed benefits, however, adding to the uncertainty that characterises disruptive innovation. Rogers (1995) thus referred to the need to build a "critical mass" of demand for innovation and how this can take time. The role of adopters at different stages – the innovator, early adopter, early majority, late majority, and laggard - is consequently important to the overall diffusion process (Rogers, 1995), with the gap from adoption by 'innovators' to adoption by the 'early majority' the key barrier – or 'chasm' (Moore, 1999) – to be overcome.

The fluidity that characterises the early stage of a radical new technology means the development path is vulnerable to the successful early marshalling of resources, especially **finance**. Afuah (1998) describes three roadblocks to funding disruptive innovation – (a) difficulty in describing the benefits, (b) financiers not being able to understand enough to fairly evaluate proposals, and (c) difficulty in controlling finance during the innovation process. Social and ideological interventions, whilst not necessarily decisive, can play a part in this (David, 1985; Lampel, 2001). But the way resources are captured for development can also lock development into paths that are sub-optimal and technologically inferior. The long time-scales currently anticipated for fuel cells increase the likelihood of 'hybrid' developments that end up blocking progress to more advanced versions (Adner & Levinthal, 2002). The scope for fuel cell applications to develop in conjunction with competing technologies – for instance, as an adjunct to the internal combustion engine in cars, and with gas turbines in large-scale power generation – makes this a real possibility. Hydrogen for use in fuel cells may also provide 'buffer' storage for wind and marine power generating systems where production is demand-independent.

Company innovation in potentially disruptive technologies operates within a wider context where progress in the basic science, the development of demand, and resource allocation depends on factors and institutions outside the company's control. In the case of fuel cells, **governments can play a powerful role** because of their necessary involvement in securing their country's energy supply and (if they choose to) in reducing carbon emissions from fossil fuels to stop global warming. To do this, they have a range of possible measures at their disposal – from grants and subsidies to develop the science, through to regulation and incentives to shift company and consumer behaviour. The precise impacts of these, however, remain uncertain, despite attempts to model their effects (ICEPPT, 2002; Hogg et al, 2003)

4. Research Model

The innovation literature has two broad foci – (i) the company and its processes, and (ii) the industry system and national context within which innovating companies operate. Both literatures are extensive, but largely disengaged from one another. In addition, far more attention is given routinely to the national systems context, and far less to how this impacts upon specific industries. We aim to consider these processes at all three levels - company, industry, and the national system - and to understand the interactions that form the drivers and barriers to radical innovation. Figure 1 reflects the various factors outlined in the foregoing review – the firm's innovation process engaging with a systems context of wider problems, opportunities and challenges that influence the firm's decisions to commit resources at the various stages of innovation. A key assumption, which the research aims to explicate and test, is that the progress of innovation depends on how firms 'read' these challenges, opportunities, and threats in their resource commitment process - i.e. the decision making process by which firms decide how best to allocate their resources to innovation opportunities.

The result is a complex intra- and inter-industry dynamic - made more complex, on the one hand, by the extent to which the industry comprises large and small new entrants and large established incumbents, all interacting; and, on the other, by the competition between alternative sources of sustainable energy. The progress of fuel cells as a disruptive innovation will be substantially affected by the latter, since alternative sources of sustainable energy (wind power, wave power, photo-voltaics, etc.) both compete with and complement fuel cells, within the external environment of government incentives, national priorities, physical resources, and finance. The model can be used to contrast these effects and the progress of alternative sustainable technologies, and to compare these in different countries and regions. This is part of our wider research agenda.

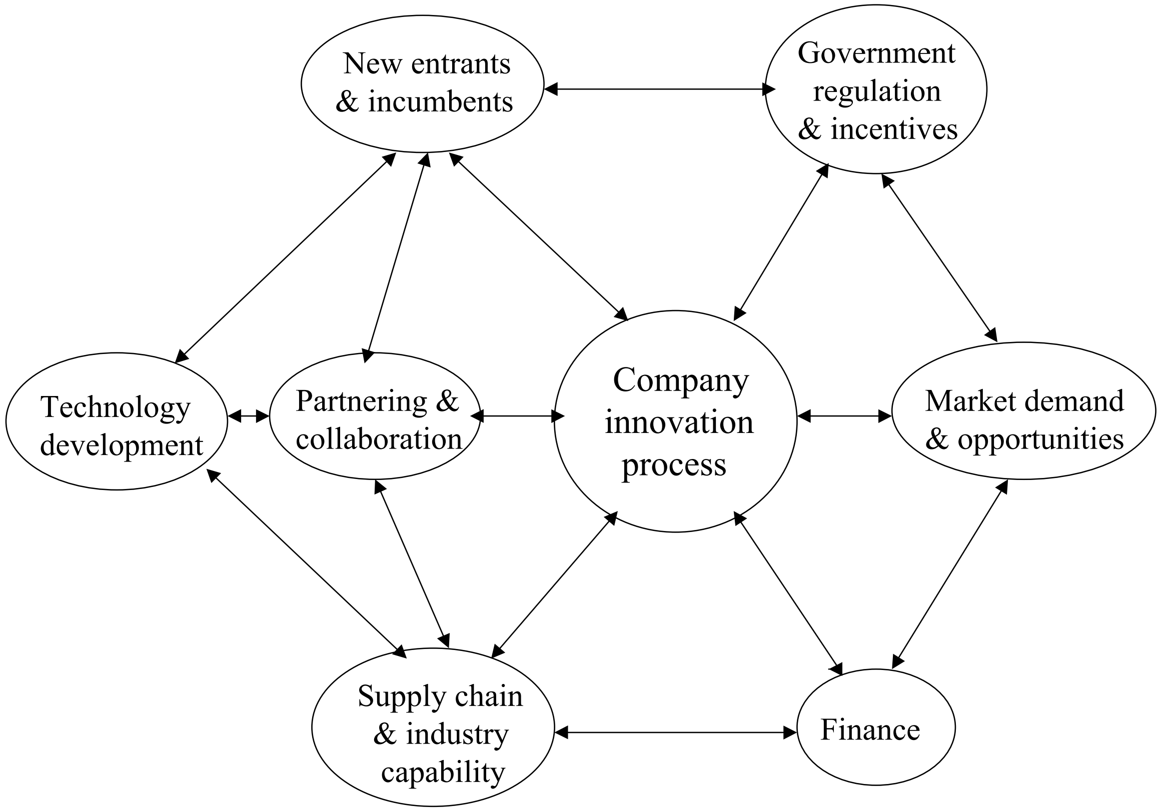

Figure 1: Research Model

5. Research Design and Methodology

The research is being conducted in four stages, studying three industries across three continents. This paper is concerned with initial research in the UK involving:

1. Interviews, conferences and reports involving a broad spectrum of stakeholders in the UK, including government departments, academic researchers, consumer groups, and industry associations, to understand the general context for fuel cell development in the UK and worldwide.

2. Interviews with companies in the UK active in the development of fuel cells, fuel cell components and infrastructure, to establish an initial picture of the issues and drivers affecting their development and commercialisation, and to develop hypotheses and potential access for longitudinal cases later.

Twenty UK-based companies, active in fuel cell (and related) technologies, were selected from the E4Tech (2003) report, UK fuel cell networks, and fuel cell newsletters. This was a purposive sample to include many of the most prominent companies involved in different types of fuel cell and in different parts of the supply chain, including the fuel infrastructure. The resulting sample comprised ten new small firms (having fewer than 100 employees) and ten larger incumbents representing divisions of national and multinational companies. Many of the latter, however, still have relatively few employees dedicated to fuel cell development.

Method

Single interviews were conducted in each company, using an unseen semi-structured questionnaire, derived from the research model, and covering company processes and perceptions of the wider industry context.

Eighteen interviews were conducted face-to-face, with two respondents requesting a telephone interview. Interviewees were encouraged to talk freely about their experiences and perceptions of fuel cell development, with the schedule as a prompt. Where permitted (< 50%), interviews were recorded for transcription, but in all cases handwritten notes were taken . Two interviewers each took half the sample, and wrote up the interviews as case studies according to the following themes identified in the literature:

- Origins and history of fuel cell development in the company
- Position in supply chain, any partnering agreements, and markets addressing
- Company innovation process and its application to fuel cell development
- Critical customer/market issues
- Key drivers (internal and external) for continued company involvement in
- Barriers (internal and external) to be overcome
- Development and commercialisation strategy, with future plans and timescales
- General incentives and disincentives driving the industry (including the role of government)

The twenty cases were then independently and jointly analysed in a series of iterations by the team of three researchers, to develop common agreed themes and interpretations of the data.

6. Overview of the Sample

Table 1 provides an overview of the companies interviewed.

Company	Size	Technology	Supply chain	Markets	Notes on Origin
A (2001)	80	Hydrogen production & storage	Technology Research and product development	PEM and stationary power applications	Intellectual property business of former government technology agency
B (1996)	6	SOFC	Technology Research and licensing	Stationary, portable 100W-15KW	Spin out company from university research
C (1950)	(4,000)	Industrial gas production and supply	Hydrogen supply	Industrial markets now but commercial in future	US parent was original supplier to NASA
D (1998)	7	AFC	System integrator	Stationary, remote power applications 2-10KW	Background in LPG cars and involvement in ZETEK case
E (1980)	(99,000)	PEM	System integrator	Transport	Parent is major automobile manufacturer
F (1990)	5 (90,000)	Hydrogen production, storage and supply	Hydrogen supply	Transport	Part of major UK fuel group with extensive activity world-wide in fuel cell demonstrator projects
G (2001)	17	SOFC	Technology Research & product development	Stationary applications 1-25KW	Intermediate temperature SOFC, operating at around 550°C. Spin out from university.
H (1999)	10	Control systems for AFC	Component Control systems	Stationary, remote power applications up to 20KW,	Produced control equipment for ZETEK fuel cells.
I (2000)	40	PEM	Fuel cell stack	Stationary distributed power up to 25KW. Portables up to 100W	Spin out from university
J (2000)	15	Specialised polymers for PEM & Alkaline MEAs	Materials/Components Research and prototype validation	PEM applications generally	Spin out from university research
K (1980)	(6,500)	PEM	Components MEAs	Transport and stationary up to 75KW	Part of major UK group with extensive experience in MEAs. Major supplier to Ballard
L (1985)	(15,000)	PEM, SOFC, MCFC, and Direct Methanol	Materials/Components. Carbon bipolar plates and ceramics	Stationary, transport, portable	Part of major UK group. Early supplier to Ballard
M (1995)		PEM	Materials. Bipolar plates (in USA)	Stationary and transport	Division of established UK group with expertise in specialist ceramic materials
N (1988)	230	Modelling and evaluating new forms of energy	Technology Research & consultancy	Stationary	Consultancy division of UK power supplier
O (2001)		PEM	Technology Research &licensing	Portable, initially for military applications up to 5KW	Former government technology agency
P (1988)	34 ( )	SOFC	Fuel Cell / System integrator	Stationary distributed power 50KW-1MW by 2007, and up to 10MW	Division of major UK engineering group
Q (1999)	3 ( )	Direct Methanol Fuel Cells	Technology Research & consultancy. Eventually stack manufacture	Portable electronic devices (above 20W)	Invented, patented and demonstrated a new platform technology relevant to all fuel cell types.
R (2001)	6	PEM, + Alkaline	System integrator	Stationary (UPS) and transport. 500W-5KW	Founder was part of ZETEK. Company buys stacks, and designs/ builds customised systems.
S (2002)	4	PEM	System integrator	Portable electronic devices 100W-1KW	Extensive network of suppliers and collaborators
T (2001)	2 (500)	Hydrogen production	Technology Research & product development	Defence (naval) applications	Defence division of UK engineering group. Fuel cell related activity goes back 30 years, but now very small

Table 1: Overview of Sample Companies

(1) Company - with date when fuel cell activity started, or company formed

(2) Size - number of employees in UK
(3) Technology - main fuel cell technology the company is working on
(4) Supply Chain – approximate position in chain as defined in Figure 2
(5) Markets - principal markets directly or indirectly addressed

The UK fuel cell industry focusing on PEMFC and SOFC technologies, neatly illustrates how two different ‘technological regimes’ (Nelson & Winter, 1977; Winter, 1984)) can co-exist within the same industry. On the one hand, there are companies (like C, E, F, K, L, M, N, P, T) that have an established presence in the ‘energy’, ‘industrial materials’, and ‘transport’ fields. They have discovered their competencies are relevant to the emerging field of fuel cell technology and are adopting an incremental (or 'routinized') approach that builds on these strengths, making use also of their connections with leading global players in the industry. On the other hand, there are companies (like B, G, I, J, Q, R and S) that fit into the ‘entrepreneurial’ type of technological regime. Five of these seven companies have come directly out of the university (or consultancy) research environment (an impressive percentage of the whole sample), and are developing products that take advantage of this academic research. In the main, these companies are working with PEM technology, but two (B and G) are into SOFC, albeit with products delivering much lower levels of power output than large company P, which is also in SOFC. The presence of smaller start-ups in PEM-related technology probably reflects the relatively lower ‘entry barriers’ in PEM technology. These companies are somewhat unsure about precise market opportunities and could well look to licensing for their revenue. Additionally there are the two former government technology agencies (A and O), which seek to commercialise their experience in fuel cell technology by licensing it to others.

Finally, there is the interesting case of companies D and H. These are the only UK firms currently working in the superseded alkaline technology and are now partners in an international consortium that aims to supply alkaline fuel cells for remote power application in Africa. This could test the Hart and Christensen (2002) recommended strategy for a company with a 'new' technology - namely, to introduce it into an under-developed country with an emerging market need and to market low-cost, reduced-specification products, which it can later transfer as disruptive innovations to developed countries.

7. Findings

Technology Development

Fuel cell development currently faces a range of technical problems still to be solved among competing forms of fuel cell, the achievement of competitive costs, and the building of a support infrastructure, including suitable, effective sources of hydrogen (Hall & Kerr 2003). The use of hydrogen raises safety issues, as well as more basic technical problems such as re-fuelling and storage. Given the drive towards fuel cells that are emission-free, the production and distribution of hydrogen must also be environmentally friendly. It is apparent that fuel cell development is in a 'fluid phase' (Utterback, 1994), and that multiple new entrants, and solutions should be expected.

The UK development activity is polarised around only two fuel cell technologies – the Proton Exchange Membrane (PEM) and Solid Oxide fuel cells (SOFC). Whilst PEM design is broadly established, it is by no means a dominant design (Utterback 1994), with ongoing development activity to alter materials, size, performance and resistance to factors such as contamination and localised hot spots. SOFC is undergoing even more active development - even the basic physical design is fluid with ongoing debates on the relative merits of planar, cylindrical and elliptical structures.

In each case, the achievement of costs that are competitive with existing technologies will determine eventual success. Whether costs are bearable, however, depends on the markets in which fuel cells are used. In automotive, for example, cost breakthrough (for PEMs) is envisaged in the range $50-90/kW (compared with present costs of around $3,000/kW); $500-800/kW for stationary power (compared with $4,500/kW SOFC systems now). Scale economies will reduce costs dramatically but material and assembly costs, for what is a complex product, are presently such that many believe only fundamental level improvements in materials and simplification of system infrastructure will reduce costs to competitive levels. UK companies are focusing on such innovations.

Hydrogen as a fuel stock itself poses problems, technical and social. A new fuel infrastructure needs to be established, including production, distribution and storage, taking into account emissions from the whole production/distribution cycle. Various production methods are possible but have specific issues. Electrolysis of water to split off hydrogen requires capital expenditure on new plants (which raises the overall cost) and consideration of the pollution impacts of the electrolysis residues. Biomass generation of hydrogen is a possible alternative, but requires sufficient biomass. An interim solution, breaking down coal or oil (‘reforming’) means additional work, adds cost, and reduces the emission saving through the carbon dioxide released, but has been argued as a way to accelerate the adoption of fuel cells in advance of a hydrogen fuel infrastructure. Early fuel cells for portable electronic products will use methanol as a fuel and a special type of PEM fuel cell called a Direct Methanol Fuel Cell. Methanol has been discounted for other fuel cell applications such as automotive power owing to environmental and health issues, but has been judged an acceptable interim fuel stock in the small quantities required for portable electronic applications.

Market Creation and Building Demand

The timeline for commercialisation of fuel cells proposed in the DTI report (E4Tech, 2003) has general support. Hitherto, the military (more especially the US military) have been early adopters. These niches have supported premium prices in return for improved performance over existing products. These applications also overcome the absence of an extensive hydrogen infrastructure. For the future, portable electronic equipment is predicted to be the first to offer fuel cells to mass markets, followed by niche business applications for stationary power (standby generators, Uninterruptible Power Supply (UPS), and remote site applications such as telecommunication masts and temporary traffic lights). NEC is reported to be offering a fuel cell powered laptop computer for sale in 2004 (FuelCellToday, July 2003), as they seek a more effective power source than the re-chargeable battery, and a number of other manufacturers have declared their intention to launch similar prototypes over the next 12 months. Car manufacturers, meanwhile, are using demonstrators and hybrid cars to learn prior to mass marketing the commercial fuel cell car, probably around 2015. Ford's vision is 25% of new cars running on fuel cells by 2025. Fuel cells are expected to emerge first in larger commercial vehicles such as buses.

However, it is in electricity generating that fuel cell use in the UK is most uncertain. Given the reach of the UK's electricity grid, the current focus of fuel cell use has been on how to utilise it within the national grid. Government rules on electricity generation and connection to the grid have discouraged smaller generators in the past. The incumbent generating equipment suppliers are therefore focused on ways of incorporating fuel cells into central power generation, focused on the medium-to-long term (i.e. at least 10 years). US development, by comparison, is more wide-ranging, given the absence of a national grid, a large geographical area, and a poorly co-ordinated (and ageing) system. The concept of using fuel cells in distributed generation (i.e. reduced centralised power generation) is being actively pursued even to the extent of local generation schemes encompassing a building or a geographic area. In the UK, local generation is confined to a few schemes sponsored by local government. Woking Borough Council has established a generating facility based on PAFC (with funding from the US Department of Defence), but there is little further development or piloting elsewhere. Yet UK generating equipment suppliers have the knowledge and competence to supply generating equipment world-wide, using fuel cell technology - unlike automotive and portable electronic applications, where the knowledge, competencies and key resources are largely found in North America and the Far East. Central government intervention may be necessary to encourage adoption and exploit the most promising opportunity for a UK fuel cell industry.

Typically, innovation timelines are driven by market need, unless there is Government intervention, when factors such as legislation and regulation become more important. Thus, the drive for fuel cells in cars is being driven by regulation, stemming from the ZEV mandate in California and anticipation of further restrictions. In portable electronics, by contrast, fuel cell development is driven by market need, with fuel cells providing instantly recognisable user benefits. Hence adoption can be expected to be faster. Power generation falls between the two, with remote applications responding to a market need and central generation depending on the regulatory and licensing regime.

Rogers (1995), however, has stressed how difficult stimulating demand for socially desirable ‘preventive innovation’ can be – as in the case of health-related innovations. The relevant benefits tend to be longer term and hence ‘invisible’ to the majority of adopters. Arguing that lowering carbon emissions will prevent future climate change is unlikely to persuade many people to act now, particularly when action may reduce benefits currently being enjoyed (e.g. in car performance). A niche market approach for stationary and automotive fuel cell use may therefore allow relevant benefits to be more instantly recognisable – for example, using fuel cells to allow car heating to be left on overnight without the engine running.

Whether UK firms pursue any of these markets will depend, however, on their reading of the opportunity offered. This involves factors such as - competing innovations that could eliminate the theoretical advantage of fuel cells (for example, improved batteries for portable electronics); their estimation of their own relative capabilities; government support for the growth of a fuel cells industry; whether the UK offers the right environment in terms of world markets for customers and suppliers; and complementary UK technological strengths (given, for example, the virtual absence of an indigenous car, truck and bus industry).

Against this background, as noted, most UK companies take the view that early market opportunities will come from niche applications, particularly UPS, commercial standby power, and power in remote sites for telecommunications and rural homes. These markets are being actively targeted by companies C, D, H, I, R and S. They are unconvinced that the UK Government will provide any meaningful support to develop a new UK industry offering such products, and are therefore developing strategies to deal with resource constraints by either partnering or focusing their activity.

The distinction between a 'market incremental' and 'product incremental' strategy, in this connection, provides a starting point in characterising the behaviour of firms (Adner & Levinthal, 2002; Winter, 1984). Product incremental innovation works initially within a known domain, while market innovation takes an untried technology and seeks applications. The former is typical of large firm incumbents - the latter technology-driven approach is more typical of smaller firms yet to find a market. A number of small UK firms (B, G, J, Q) at the research end of the chain (see Figure 2) are thus developing technology with broad market application, and are willing to partner to address specific applications as they emerge. This provides opportunities for the technology to be applied eventually in a more radical, even disruptive way. Conversely, larger companies are focused on particular markets (E, P) and existing user-led applications (L, O). However, between small firms R and S - along with the stack company (I), which is also relatively close to customer markets - and the larger firms there is little basic difference in the perceived desirable markets and how to break into them. This involves creating partnerships with large firms that are already well placed in major markets. As Company I put it:

> *Our main focus is not on particular countries, but on companies that have substantial markets themselves, which could use fuel cell technology. There are some parts of the world that are going through a huge electrification process and this could be an opportunity area for us. But we would prefer to work through an established organisation that is in that business.* (I)

Whatever the eventual success attending this strategy, it casts doubt on Christensen, Raynor and Anthony's (2003) 'low end' prescription as a preferred route.

The system integrators (D, R, S, E, P) see themselves exploiting a gap in the supply chain, by developing applications that customers can use and exploiting existing opportunities. This generates market take-up, revenue and learning, but is dependent on the availability of materials and components. The larger 'applications' companies, meanwhile, start from established product needs in core markets, working from their core competencies. They are also driven by the opportunity to address emerging needs, and ways of delivering better efficiencies, which will allow them to migrate fuel cell technology to applications in new markets. Company P has a clear public strategy for this:

> *We like air, and we like it hot and under pressure. We understand materials in this environment, so when we looked at technologies, we eventually settled on solid oxide fuel cells as one where we felt we could win. We will start big by establishing working systems that operate with proven technology, and then over time improve the power/density ratio by incorporating newer technologies as they are discovered. Once we figure how to do it on a scale that makes it economic, we will then compress it.*
>
> *The size of organisation we aim at it is therefore one that has enough electricity usage to have a facilities manager on site with energy expertise. In this market, there is less resistance, as these people are experts in energy supply and do not have any of the hang-ups there may be in the domestic market. There is a market there already, and we are not dealing with issues about lack of market pull or finding markets. We have a viable business selling into the industrial generation market as an extension of what we already do. As the market develops this may change, and not require this level of expertise in the customer, and so the entry point may change.*
>
> *The first generation of product we go to market with will be cost-effective, equivalent to what is on the market already and not 'premium cost for added value'.*

> *We are starting at the large end and working downwards, whereas other companies are starting at the smaller end and working up. Our vision is that when the volume/power density improves, there is no reason why we should not put this into other applications - certainly marine propulsion systems, but possibly in the longer-term aircraft. Stationary power is our entry point, but with any technology you look to see how you can position it in alternative markets.* (P)

Christensen (1997) has argued that an incremental strategy of this kind exposes a firm to new entrants taking away markets before they can exploit the opportunity to expand. On the other hand, if the winning technology(ies) (PEMs or SOFCs, or even MCFCs and PAFCs) is not yet certain, an incremental niche strategy not only reduces risks, but positions a company like P to benefit as any switchover begins to happen.

Partnering, the Supply Chain, and IPR

While new firm formation is naturally regarded as important, the specific development of a supply chain capability to support product innovators is relatively neglected – certainly in UK government policy that seems to regard economic incentives as sufficient. We therefore include it for particular consideration. Recent consultancy studies of the UK fuel cell industry highlight issues of expensive components (Hall & Kerr, 2003) and a fragmented supply chain (E4Tech, 2003) as among the major problems in commercialising fuel cells in the UK.

Figure 2 shows the basic value chain in the development of commercial fuel cell applications. There is collaboration at both ends of this chain, but the UK supply chain remains fragmented and incomplete, with the role of fuel stack builders/suppliers in particular as yet ill-defined and specialised roles and domains of activity in general not clearly established.

Although firm strategies are quite varied and the resulting industry structure fluid as yet, PEM development is characterised by a willingness to operate within alliances to build the supply chain, while large-scale SOFC development and manufacture appears to be more vertically integrated in large companies. This may have something to do with the importance of meeting high operating performance standards (Christensen, Raynor & Anthony, 2003) – Company P, for example, arguing that, in “incubating its own supply chain”, it retains all aspects of development in-house to guarantee quality standards. This tendency may also reflect the high development costs and hence costs of entry for suppliers in SOFC.

A key problem for the supply chain relates to the complex of sub-assemblies and control electronics to enable fuel cell stacks to operate efficiently and deliver electricity. This is the 'balance of plant' and its supply in the UK is perceived to have significant gaps (E4Tech, 2003), with problems ranging from over-engineered components at non-commercial prices, supplier failure, and unwillingness of suppliers even to contract. In an emergent industry, these problems are common. Company D, however, with skills originating in automotive engineering, has been able to utilise its network of previous suppliers to source commercial grade components at acceptable prices.

The supply chain problem seems in part therefore a reflection of prior industry knowledge, with academic and research-based institutions disadvantaged against existing engineering companies.

It is evident also that firms do not have a very clear idea of the added value (and profit) to be achieved at each stage in the chain, other than (in one instance) a broad perception that the mark-up will be two to three times at each stage. Some analysis of this kind has been done (Arthur D. Little, 2000), but it is a mark of an immature supply chain that the build-up of costs for fuel cells remains distinctly hazy.

The major influences on active partnering in fuel cell development, upstream and downstream, are twofold. Firstly, the availability and cost of capital is a major driver to technology development, and can produce sudden shifts in sourcing and partnering strategy. For example, in the US SECA programme for stationary power, government funding is often conditional on companies collaborating. The other major factor is the area of application. The major applications for PEM technology are in automotive, in small-scale distributed and remote uses, and in portable devices (including electronics). In automotive and portable, this involves redesign and rethinking of the overall product to accommodate the new energy source – that is, the PEM fuel cell acts as an ‘architectural innovation’.

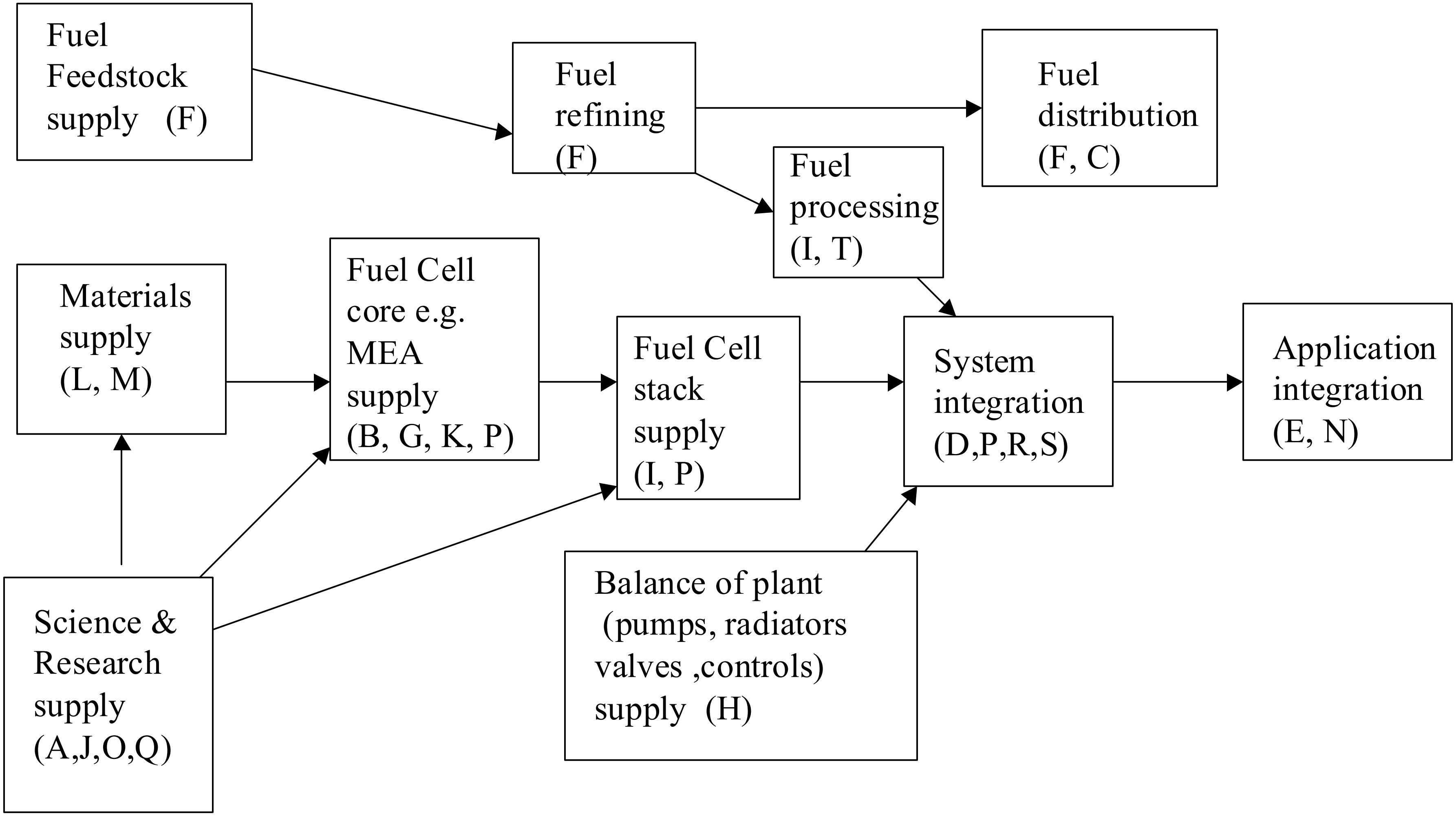

Figure 2: The Fuel Cell Industry Value Chain

The fuel cell stack manufacturer has, therefore, to work closely with the end-use manufacturer. SOFC applications, in contrast, are in larger scale, power generation where a few big suppliers serve the market and are integrating fuel cells into proprietary solutions (i.e. without the benefit of partners). The fuel cell R&D of these big suppliers is mostly internally funded, but takes advantage of government money where possible. Their R&D encompasses both basic technology research as well as being application-based, delivering patents and tacit knowledge for exploitation in future production. The focus is on how fuel cells can improve efficiency for their existing major customers.

Arguably, then, PEM is more liable to promote technical collaborations, with system integrators geared to a market bringing together components and expertise to bear upon complex problems. This role is becoming well established in the USA among the PEM majors (DTI & Synnogy, 2003), and we see a number of UK firms (E, R, S) aspiring to this, even though the UK supply base remains fragmented and incomplete. The two firms involved in AFC for remote applications are driven by similar requirements to partner, including the need to provide hydrogen on site to 'power' the fuel cells.

The long-established UK materials companies (K, L and M) have all been drawn into fuel cell development through some basic material produced (carbon, platinum, ceramics), and work with leading companies downstream. Thus, Company K has "collaborated on a range of products worldwide to kick start fuel cell activity", while Company M's approach is to "focus on generic technologies and work closely with leading companies to provide specific products for specific solutions", an approach which has gradually increased its exposure in fuel cells. The smaller companies fall into two groups. B, G, J, and Q are working on variations in the basic technology with a view to establishing themselves with partners further down the supply chain when the technology is proven; while the three system integrators (D, R and S) seek components on a global scale to incorporate into products with immediate market appeal:

> *We believe the technology is there today to build a profitable business. We seek 'best of breed' components in the UK, Germany, and Canada for PEM stacks, and then design and make the control equipment to go round it to make it a product proposition.* (S)

The larger companies thus tend to occupy the materials and fuel cell stack end, and theirs is the most clearly defined role, with the smaller companies either developing basic technology or attempting to act as systems integrators in bringing fuel cell based products to market. Both are viable strategies, given the UK's strengths in materials and membrane electrode assembly (MEA), and the present opportunities for system integrators worldwide to bring products to market (DTI & Synnogy, 2003). The major UK weakness is the absence, compared with the USA, Germany and Japan, of large firms at the applications end of the chain in key markets – what N calls "intelligent buyers". When multinationals that could use fuel cells (E, N) do their R&D outside the UK, product sourcing tends to follow, and they also keep their research from their UK subsidiaries. All of this emphasises the need for UK firms to engage with and supply the fuel cell industry globally, especially in the USA (DTI & Synnogy, 2003), as the major suppliers are seeking to do:

> *We see ourselves more of an American company in this respect - much of our future research and development funding will come from American sources rather than European ones. America is bigger, there are more companies, it is easier to make partnerships, easier to recruit people with knowledge of fuel cells. If you put down all the factors needed for a good research and development environment then America (and Canada) has got them all.* (L)

However, in the background to all collaboration is IPR. Firms are keenly aware of the need to guard their IPR, but also of the need to work with collaborators to realize a commercial return on their investment. There is a growing awareness in a number of firms that they are at something of a cross-roads - that collaboration can reduce the cost of technology development, and that, while patents are important to exploit commercial success, equally important is incumbents' market knowledge and networks, without which they have no market entry.

The immediate value of patents is that they "are crucial to raising capital", especially for university spin outs; they "give credibility with clients (Q); and are "the only thing we have to negotiate with when we do deals" (L).

> *Everybody has evaluated fuel cell companies on the value of their intellectual*

> *property, so everybody was very protective and not prepared to open up to share this knowledge. But a patent has only got value if it translates into money in the market, and at the moment no company is making money. The more enlightened companies are beginning to realise they do not have to own and do everything themselves. Financial constraints are pushing us more towards collaboration.* (L)

But, as two other companies commented:

> *We cannot afford to wait until 2005 for the patents to be awarded before we talk to anybody.* (J) … *We can't afford* <u>*not*</u> *to talk to other organisations. (K)*

Even so, a number are wary of collaborating, particularly with universities because of "battles over intellectual property" (R, S), and those that do are careful to write agreements that avoid giving anything away (Q).

Funding and the Role of Government

The funding issue has to be seen in the context of the current stage of development and the financial precariousness of the fuel cell industry as an emergent sector. Government is faced with fuel cell constituencies with different goals and different capabilities to influence the direction of fuel cell development. There are few final products on the market; no company's fuel cell activity is thought to be profitable; major manufacturing investments are rare (only G and K); and there has been no VC funding or IPOs, although one VC deal is pending. Most companies therefore face funding difficulties.

Funding in our sample derived from four sources:

(a) internal corporate funding (10 large firms)

(b) DTI/EPSRC/regional grants (9 small, 1 large firm)

(c) MoD, EU and US research projects and contracts (12)

(d) investment funding from private placements (6)

Taking (b) and (c) together, 80% of firms have received some kind of grant. Although many are ready to criticise Government for insufficient development funding, DTI SMART grants have been widely used, and some companies are highly appreciative of this: “We have lived on DTI grants - the DTI have been fantastic as far as we are concerned” (J). Most small firms feel they can only make progress with development grants (G), while large corporations (K, L, M, P) benefit disproportionately from MoD, EU and US projects. Perhaps the most surprising figure in the present climate is the large sums raised through private placements by small companies such as G (£4m), I (£11m), J and R. Fund-raising and grant-getting for these firms is a key marketing activity:

> *Our main marketing is fund-raising. We have 45 shareholders each contributing £5,000-75,000. This creates a network of sophisticated investors, each with their own networks, so the second time around we will have more opportunities to raise funds. It will take a lot more money to get to the point where efficiency and durability can be demonstrated. It is not going to happen out of a $2-3 million grant - it is going to take maybe $20 million. We need to develop enough technology and links with other companies, so we have built a picture of achievement for the next round of financing. We are selling ‘futures’, and money for demonstration projects is part of the communications issue.* (J)

The greatest perceived need is for government-funded projects to support the development and building of a supply chain, and initiate a market in fuel cell-based products, “to get the industry over the hump” (P). MoD, EU and US projects have contributed, but the UK and EU commitment falls far below the substantial funding needed.

> *The UK is the worst place in Europe in which to operate right now. Funding and general industrial support is missing, and government support has been appalling.* (R)

Kemp & Schot (1998) suggest that national and local governments can provide “temporary protected spaces” to help the development and use of promising new technologies. This supports experimentation to aid learning, development and the application of the new technology. Government is therefore central to the innovation system, and needs to consider all aspects of the system when establishing its strategy and actions. Incentives and subsidies therefore need to be specifically targeted if they are to benefit fuel cells and these are currently not available in the UK. Government action to regulate and influence the timescale of adoption in the power generation and automotive sectors is critical. Of the means to hand, demonstrator projects of a sufficient size and scale are favoured by many. The impending CUTE bus project in London, and fuel cell initiatives in Teeside, are miniscule in comparison with US national and state government initiatives.

Where the UK government has been active, and is increasingly so, is in disseminating knowledge and attention to fuel cells, through funded research, study groups, seminars, overseas missions and FC networks, and the recent 2003 Energy White Paper. Although this has mobilised the fuel cell community, one aspect of special interest to the theory of disruptive innovation is the role of a small number of industry and academic experts that have been typically involved in these activities. Whilst Rogers (1995) has suggested that adoption of innovation is helped by active opinion leadership, diversity is also necessary to stimulate creativity (Leonard-Barton, 1992). The ascendancy of a group of 'industry experts' could therefore be counter-productive if it guides Government strategy and funding policy on a path that favours, for example, incremental innovation strategies. Policy is vulnerable in this respect because of the Company L perceived lack of technical knowledge within UK government on fuel cells compared with the USA's Department of Energy. Most of the large firms are active in national and international bodies setting standards and timescales for fuel cells and regulatory change.

Conclusion

Our findings at this stage should only be regarded as indicative, being based on only 20 companies across the fuel cell chain in the UK. Our purpose is not to provide a definitive account of the industry, but to highlight theoretical issues for further testing with a larger international sample and subsequent longitudinal cases, while identifying areas for action.

Clearly, development remains in a fluid stage (Utterback, 1994). The competition between different types of fuel cell as to which (if any) will be commercially successful will remain unresolved for some time, with production only in the prototyping and demonstrator stage as yet and much development work still going on in research laboratories.

In this phase, many companies, large and small, are involved, including an unusually large number of spin-outs from UK universities and research laboratories compared with the experience in other newly emerging high technology sectors. Government grants have been a conspicuous source of early-stage funding, but the presence of as many small companies among these as there are large ones does suggest more active support through into the commercial stage for small firms would pay particular dividends in fuel cell development.

A feature of the small firm/large firm dichotomy is that the two different theorised styles of innovation – ‘entrepreneurial’ and ‘routinized’ (Winter, 1984) - are both very much in evidence, and both are very clearly articulated by companies. However, they are happening at the same time, rather than in a sequential fashion, when the expectation might have been for large firm incumbents to enter only at the later stage in life-cycle development (as in biotechnology). This confounds expectations for disruptive innovation.

A second departure is that partnering between companies is occurring very early on in development. Fuel cells are a complex product, currently going through a very volatile phase. Yet we see extensive partnering taking place and being sought, contrary to Utterback's (1994) expectation that this will only tend to happen in the more stable 'specific' phase of technology development, when cost efficiency and quality considerations become important differentiators. As with the personal computer, this may have to do with the complex assembly of parts and sub-systems that have to be integrated and therefore co-designed (the technologically determined, 'architectural innovation' view of collaboration (Henderson & Clark, 1990)).

Fuel cells address three broad markets, each with different drivers for innovation. In the absence of an immediate strong market need, particularly when the major benefit being sought is reducing emissions and slowing future climate change, government action, even legislation, is critical to diffusion. It also leads to very different behaviours by those seeking to compete in these markets. Lobbying and being on bodies that can influence acceptance and development of the industry become key to commercial strategy, and is something at which large firms are particularly adept. We therefore see partnering taking place to influence government action and opinion. This gives rise to two observations. First, it shows firms themselves employing institutional levers for change, alongside as well as to combat those with a radical agenda to advance sustainable energy sources **(**Berkhout, Smith & Stirling, 2003**)**. Second, it shows how under-theorised is collaboration by firms in the academic literature. Innovation generally, and disruptive innovation in particular, would benefit from closer analysis along these lines.

The involvement of large firms in fuel cell development, and the means they are using to facilitate it, eventually, however, must raise the question, ‘what makes fuel cells a disruptive innovation?’ Disruptive innovation is usually defined through examples of disruptive technology, such as the internet (Christensen, 1997), but disruptiveness is clearly application-specific. Large companies developing SOFC technology reduce uncertainty by targeting known markets and improving operating efficiency in electricity generation before tackling more disruptive applications. Even car companies are managing the introduction of fuel cells in a measured way, intended to be non-disruptive to their existing investments and capabilities. This of course extends the timescale to 10-15 years, whereas laptop manufacturers are showing that fuel cell technology can be introduced far more quickly.

In truth, it is too early to say whether fuel cells will be genuinely disruptive, and to whom or what. It appears that disruptive innovation may only be identifiable in retrospect much as Utterback(1994) stated about dominant design. The problem is that the disruptiveness of a new technology lies in the ‘technological discontinuity’ that offers marked benefits in cost, quality or other benefits over existing offerings (Foster, 1986).

The uncertainty surrounding the adoption of fuel cells also raises a question that the ‘disruptive innovation’ literature has so far not adequately addressed – ‘whether, and how far, resources applied to what turns out to be a transitional or even ‘dead-end’ technology damages the ultimate success of others, or whether the attention and resources generated overall have an enhancing effect?’ This has particular salience in the development of sustainable energy, since fuel cells compete for development funds not just with one another, but with alternative sources, such as wind and wave power (as well as with established sources that continue to improve their operating performance).

Finally, major technological change in sectors such as power and transport that are now heavily regulated and deeply embedded economically and socially suggests a need for much closer government/industry cooperation to minimise the transition problems (Kemp, 1998). The question is, whether UK government has an appropriate and valid model for this development in mind. The Energy White Paper (DTI, 2003) was a start, in attempting a comprehensive review of energy use, but the proposals for fuel cells hardly match the professed ambition for the UK to be "at the cutting-edge of fuel cells technology" Firms are keen to see the creation of an 'expert facility' of some kind. Only the proposal for a new EPSRC/DTI/Carbon Trust research programme dedicated to fuel cells, and helping UK firms to identify partners to participate in European (6th Framework) R&D projects do much to match the ambition. However, the UK approach to fuel cells remains "uncoordinated", and "a UK fuel cells network more of a sideshow than anything else" (Q). Projects such as CUTE, Woking and Teeside are undeniably of value in providing covert subsidies and grants for testing and improving designs, helping firms to begin manufacturing, giving credibility in the eyes of investors and suppliers, and raising public awareness. But they need to be targeted in technology/manufacturing areas where UK firms can benefit, with installations that have significant UK product content. DTI LINK-type projects are an appropriate device and would generate partnering that helps build the supply chain, including partnerships involving smaller firms. Given the relative success so far in transferring fuel cell technology from the universities, LINK projects might also stimulate further research that leads to the infusion of new firms. The scale of the UK fuel cell industry urgently needs an increase in critical mass.

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