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Technological change in niches: Auxiliary Power Units and the hydrogen economy

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Abstract

In studies of large scale systems innovations or technological transitions, niches have been given a prominent role as incubators for the seeds of future technological systems. It is often argued that immature technologies rely on niches for their development, before they are able to compete in mainstream markets. This paper combines insights from economic theory and from technology studies to formulate a framework for understanding the dynamics of technological change in niches, and applies this framework to the case of fuel cell Auxiliary Power Units (APUs). We conclude that the choice of technology for APUs will be of critical importance in determining the role this market could have in shaping future developments in hydrogen and fuel cells. However, a number of factors are not strictly dependent on the technology used in fuel cell APUs. These comprise factors influencing external economies of scale, network effects, the behaviour of users and expectations.

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1. Introduction

Any attempt to understand and plan for a future transition to a hydrogen energy system must rely on some understanding of the processes of technological change. Although our knowledge of such processes remains incomplete, the concept of 'niche' has provided a fertile area for discussion in studies of innovation in recent years. In studies of large scale 'systems innovations' or 'technological transitions', e.g. [1], niches have been given a prominent role as incubators for the seeds of future technological systems. In essence, it

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is argued that immature technologies rely on niches for their development before they are able to compete in mainstream markets. This is well reflected in discussions relating to hydrogen, with niche markets and products often seen as important in the development of a hydrogen energy system, e.g. [2,3].

The focus on niches in technology studies has given rise to both analytical recommendations (the call to characterise and understand 'promising niches' in scenario analyses [4]), and policy prescriptions (in the form of "strategic niche management" [5]). However, the technological change literature demonstrates a variety of understandings of what constitutes a niche, and there have been few attempts to characterise the processes likely to occur when technologies become established in niches. This paper combines insights from economics and from technology studies to formulate a framework for understanding the dynamics of technological change in niches. This framework is applied to the case of fuel cell Auxiliary Power Units (henceforth APU).

The paper is structured as follows. The next section describes and clarifies two concepts of the 'niche' in studies of technological change. In Section 3, a framework is presented for understanding the processes that occur in established niches. In the fourth section, this framework is applied to a niche market for auxiliary power aboard vehicles. Finally, in Section 5, we draw conclusions about the approach, and comment on the role of the fuel cell APU, and similar niches, for fostering developments towards a hydrogen energy system.

2. Conceptions of the 'niche' in studies of technological change

In the literature there are two dominant conceptions of niches: the 'market' niche and the 'technological' niche. By providing a brief description of the salient features of market and technological niches, this section seeks to bring some clarity to these different concepts of the niche. As we will see, the key distinction between market and technological niches is related to the time horizon on which the technologies are evaluated. In the technological niches, actors promote technologies thought to offer potential *future* benefits while in the niche markets consumers with particular and specialist needs value technologies for their *present* performance characteristics.

2.1. Technological niches

By the time a technology enters its first markets, it has already undergone a process of development involving networks of scientists, engineers, developers, entrepreneurs, financiers, and frequently activists. This pre-market stage is characterised by the development of the technology in 'protected spaces' [4] created by social networks in the belief that the technology may be important in achieving future goals, be they commercial, social, or military. Technologies at this stage need protection from the market as they are currently 'hopeful monstrosities' [6] whose performance is poor, but that show future promise. Schot and Geels [7] describe these protected spaces, or 'technological niches' as "*proto-markets created by actors to test and develop new technologies in order to develop larger market niches*".

Technological niches are frequently manifested through the formation of associations, partnerships and lobby groups (such as the London Hydrogen Partnership), which develop demonstration and deployment activities, seek resources for the technology, and build advocacy networks. In physical terms, technological niches exist through large demonstration projects (or "bounded socio-technical experiments", [8]) that focus on learning about the technology in its social and real-world context. Technological niches can also be thought of in terms of networks of actors embedded in particular local contexts, with regions and localities developing and deploying new technologies, in the expectation that they will 'roll-out' to broader areas [9].

While technological niches are frequently built around scientist–entrepreneurs and their inventions (of which Edison is the ultimate illustration), niches can also exist through entrenched and existing networks, such as:

1. *Technological activists*, who foster particular technologies in pursuit of social ideals, and are frequently both suppliers and users of the technology. Examples include early practitioners in the organic and green building movements [10].
2. *Governments and government agencies*, which establish large national technology projects, such as those to develop space exploration, nuclear weapons, and nuclear energy.
3. *Large companies*, which create spin-out groups or 'skunk works'[1] in a bid to avoid becoming wrong-footed by 'disruptive technologies' [11]. Lynn ([12] p15) described how companies "*developed their products by probing initial markets with early versions of the products, learning from the probes, and probing again. In effect, they ran a series of market experiments*".

It is important to note that the survival of a technological niche depends on positive expectations about the future of the core technology[2]. Visions and expectations bring together the range of actors necessary to create the niche and to commit to its protection [13]. For example, in the case of grassroots 'green' niches "*both green builders and organic activists had quite a clear vision for the kind of housing and food systems to which they were contributing*" ([10] p2). At a larger scale, the national projects pursing the development of nuclear power in the second part of the last century were famously based on expectations of a world in which electricity was to become 'too cheap to meter' [14].

Clearly, activities within a technological niche do not always lead to successful market entry. Nonetheless, technologies developed within 'failed' niches can also move into mainstream markets in forms not originally envisaged by their champions. The failure of electric car commercialisation led GM, Ford, and Toyota to discontinue production. However, Toyota and GM both claim that this experience was useful, since the development work on electric drive trains and knowledge of market dynamics is now informing the development of hybrid and fuel cell vehicles [15,16].

Finally, we draw attention to the fact that when technologies do move from technological niches into competitive markets, the activities within the technological niche do not cease. The networks and actors promoting the technology remain active, grow and adapt, ultimately forming the basis for industry associations, lobby groups and the networks underlying a 'socio-technical system' [17].

2.2. Niche markets

In contrast to the technological niche, a niche market is defined not around a particular technology, but around a set of performance attributes — the functionality demanded by consumers and provided by technology (Table 1). Levinthal ([18] p220) characterises niches as "*populations of (potential) consumers*

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[1] 'Skunk Works' is the name of the experimental division of Lockheed–Martin, and has since become used as a generic term for a semi-independent research centre for the development of radical innovations [1].

[2] The core 'technology' is frequently defined broadly, e.g. 'fuel cells' rather than 'PEM fuel cell'. The result is that niches are not created for a single technological artefact, but for a technological family.

[that] are distinguished by the functionality they desire and their willingness to pay for these various attributes". A niche market is simply a small, specialist market where technology adoption decisions and market selection processes are no different from the mainstream market [19]. For example, users of small wind generators on pleasure boats and small yachts are not necessarily interested in fostering a wind-based energy system — they are simply purchasing the most convenient solution for their on-board power needs.

Niche markets may also be created by performance-related technology policies. Frequently, these *policy niches* represent attempts to internalise unaccounted social benefits of a technology. Since policy niches are defined by performance rather than technology, several technologies compete within such niches. For example, the UK Renewables Obligation, a policy introduced to stimulate the diffusion of renewable electricity, creates a viable market for a set of technologies such as wind, biomass combustion and biomass gasification. Through the obligation, 'renewable-ness' has become a performance criterion that is valued by the market.

Technologies move to the mainstream market from niche markets by three possible routes: market expansion, product development, and niche migration. Market expansion can be due to changing user preferences. For example, although ten years ago very few people felt that they 'needed' a mobile telephone, they are now considered indispensable. Secondly, product development taking place within an established niche (through processes outlined in Section 3) can allow the performance of a technology to improve so that it can compete directly with, and ultimately replace, the incumbent. Finally, the technology can develop by moving into new niches in new application domains [18], either directly or through hybridisation [1,20]. For example, the internal combustion engines used by the Wright brothers to

Table 1
Summary of niche processes, and how they relate to different types of niche

Niche processes	Niche markets	Technological niches
Internal economies of scale	Impact depends on size of the market and on organisation of the industry — can be substantial	Very limited, except with very large deployment or public procurement programmes
External economies of scale	Impact depends on size of the market and organisation of the industry.	The establishment of social networks are a key element of technological niches although their economic effects are limited because of small levels of production
Expectations	Success in a niche market may stimulate positive expectations about the future for a technology, which in turn may help mobilise investments	Continued positive expectations are important to the survival and expansion of technological niches. They are also a key source of motivation for actors involved
Articulation of user context	Likely to be very important — especially when the niche starts to include non-specialist users	It occurs in demonstration and deployment experiments through interaction with specialised users
Network effects, complementary technologies, infrastructure	Can be significant, dependent on the market	This is limited to learning about the infrastructure and complementary technology needs of the new technology, rather than their actual development, though large demonstration projects may create infrastructure nodes.
Revenue	Impact depends on the size of the niche market and on the organisation of the industry — can be significant	Very limited, occurring only in large scale demonstration and procurement programmes

power their first flight had been developed in what at the time was a niche market for motorcars. The technology moved from the motorcar niche into the new niche of powered flight. In an example of hybridisation, steam engines were first used aboard ships for auxiliary power, in combination with the sails that they ultimately supplanted [1].

3. Processes occurring within established niches: a framework for analysis

This section considers the processes occurring once a technology starts to be produced and deployed within niche markets or through the demonstration and deployment activities of technological niches. This exercise, which draws on insights from sociology, history and economics, is needed to understand the likely direction and pace of the development in market and technological niches. The following processes will be considered:

1. internal economies of scale;
2. external economies of scale and industry development;
3. expectations;
4. learning around user and institutional context;
5. network effects and infrastructure;
6. revenue.

3.1. Internal economies of scale

Economies of scale, leading to reduced costs of the technology, is perhaps the most commonly cited mechanism assisting the diffusion of technologies beyond niche markets, although the concept is frequently used loosely. In economic terms, internal economies of scale occur at the level of a single firm, where cost per unit of output decreases as the output increases. Costs can be divided into fixed costs, i.e. not varying according to the output produced, and variable costs, i.e. influenced by the produced output. For a given output, total costs will be equal to the fixed cost plus the average variable cost multiplied by the level of production. If average variable costs per unit of product are constant, an increase in the output decreases the average product costs, as the firm's fixed costs are spread over a larger output. However, if economies of scale were due exclusively to fixed costs, they would be confined to the short run. In the long run, all production factors are variable, e.g. buildings can be sold, leases expire or employees can be made redundant. The importance of economies of scale based on fixed cost is clearly limited.

A second form of internal economies of scale occurs because the average variable cost is not fixed. Changes in average variable cost in relation to output are described by the concept of returns to scale. In the case of constant returns to scale, the average variable costs stay constant when the output varies, while in the case of increasing returns to scale, average variable costs decrease with the scale of the production. In standard theory it is assumed that firms have increasing returns to scale until a certain level of output and then decreasing returns to scale. Increasing returns to scale can be due to the effect of specialized inputs on manufacturing efficiency. As the scale of a firm increases, it can employ specialized labour and machineries likely to result in greater efficiency. The same applies in the case of R&D, managerial expertise and skilled labour. Increasing returns to scale can also be due to the existence of bargaining power or discounts offered to firms buying inputs in bulk and to the fact that big firms tend to raise or borrow capital at lower cost. On the other hand, decreasing returns to scale are due to the fact that beyond a certain level, inefficiency caused by difficult co-ordination inside the firm will become more and more important compared to the cost-decreasing factors mentioned above.

3.2. External economies of scale and industrial development

External economies of scale incorporate all factors leading to a reduction in the average production costs of a firm that do not immediately or directly depend on the actions taken by the firm itself. Here, it is the scale of the industry or local cluster, rather than individual firms, which is relevant. Geographical clusters, also called industrial districts, provide the most well known example of external economies of scale. As pointed out by Becattini [21] and Brusco [22], the effectiveness of the production of firms in an industrial district depends on the co-operation and the competition among the firms themselves. These two co-existing factors determine the extent of the stock of material and immaterial production factors which are shared by the firms belonging to the cluster. A firm in a cluster can benefit from:

1. rapid informal dissemination and absorption of innovations and new skills;
2. technology spillovers;
3. lower transportation costs;
4. business transactions occurring at lower costs;
5. the existence of qualified and easily accessible specialized labour;
6. the presence of local support industries;
7. the development of regionally based institutional or political strength, with local political leaders acting as champions for the industry.

Clusters also have a social dimension. In fact, the branch of the literature based on the notion of clusters as communities analyses the effect of common values, identity, institutions and rules on the competitive advantages of companies belonging to the clusters [23]. In many ways, the development of regionally or industry based clusters represents the development and growth of the networks that constitute a technological niche. The movement of the technology out of protected spaces and into markets strengthens the networks that support the technology. Cultural homogeneity, social values and sharing a common background makes transactions more fluid and provides an instrument to enforce the promises of business partners. However, this "social closeness" is not always a positive factor, as strong social ties may restrict economic exchanges [24].

The occurrence of external economies of scale also depends on the size of the industry, regardless of the location of the firms. These economies are related to the fact that as an industry matures and becomes more competitive, the industries providing inputs are also likely to become so. This may mean that:

1. Efficient machinery tailored to the needs of the industry are introduced.
2. Inputs to the industry can be bought at a lower price.
3. Supplier networks develop and become established so that transaction costs decrease.
4. Standards and product codes develop so that co-ordination among firms is easier and more effective.
5. The national or local government takes an interest in the industry as a source of employment and tax revenues and introduces measures to foster the well-being of the industry. As industries grow, they gain political power and develop an interest in lobbying.

In competitive industries all these cost-saving measures will be passed through the whole supply chain to the final consumers who will then increase demand because of the lower price offered by firms. In non-competitive industries firms having a higher degree of market power will enjoy higher rents. However, in developing industries rents can be reused so as to achieve the internal economies of scale mentioned above.

3.3. Expectations

As mentioned above, the very existence of technological niches is premised on expectations about the future performance of particular technologies. Investors, policy partnerships, and associations all support technologies that they believe will be successful in the future, and thus create protected 'technological niches' in which such technologies are fostered. When a technology becomes successfully established in a niche market, expectations about its future performance are enhanced, and the protection granted to related technologies is increased. Expectations and normative 'visions' of what the future should be are not only thought to play an important role in directing change, but are also thought to be important in bringing about transitions towards more sustainable technologies and systems [25,26].

Van Lente [13] explored the role of expectations in the dynamics of technological change, and highlighted the way in which expectations direct search heuristics — i.e. expectations about future performance drive choices of technology developers to pursue particular solutions and are a resource used to mobilise support. When a technology succeeds in one area, investors gain confidence in the possibilities of the technology in other applications [27]. In an extreme case, these processes mean that expectations can become self-fulfilling prophecies, a phenomenon exemplified by 'Moore's Law' in the semi-conductor industry [13]. It is, however, important not to overstate the case: we are all aware of hype around technologies that fell short of their promises. Nevertheless, when technologies become successfully established in a niche, we may expect, at least in the short term, an increase in support, funding, and investment into that technology; and the increased interest of other industries and institutions in the new technology.

3.4. Learning around user and institutional context

Users' needs and demands are not always known in advance. When a technology leaves the laboratory and enters the market, firms learn about user requirements, and also about the socio-cultural meaning that develops around the technology. This learning goes on to inform marketing strategies and production decisions. In their analysis of the learning that takes place during 'strategic niche management', Hoogma et al. [28] identify learning around user needs as an important mechanism for shaping the direction of technological change. Other authors have argued that real-world and large scale demonstration and deployment projects ("bounded socio-technical experiments") can foster social learning leading to the development of more socially beneficial technological systems [8].

Learning around user needs is important, because these are often mistakenly thought to be known in advance despite the many historical lessons to the contrary. An interesting example is that of the telephone — the first telephone network providers were appalled that users wanted to employ the device for such frivolous activities as social chit-chat. They had envisaged the telephone as a business and government tool, and spent some time actively discouraging the social use of telephony before the market potential was realised [29]. Until technologies are experienced by day-to-day users, their design is likely to remain inappropriate for their best use. The feedback to manufacturers from this kind of learning is essential to the innovation process.

3.5. Network effects and infrastructure

In standard consumer theory the benefits of a product to a consumer (or more precisely the ’consumers’ surplus’, i.e. his utility from the good minus the price paid) depends on his preferences and on the market price. Where network effects exist, however, the consumer’s surplus is “affected by the number of agents taking equivalent actions” [30]. This implies that the consumer’s surplus is influenced by the preferences of other customers. One can distinguish between direct and indirect network effects. In the former, the consumer’s surplus depends on the number of customers owning that good or using that service. A classical example of a good with a positive network effect is the telephone: a higher number of subscribers make one’s telephone more useful. In the case of an indirect network effect, the consequences of the increased adoption of a good or service are mediated through the market. As the number of customers of a certain product increases complementary products can be developed, which can increase the incentives for customers to buy that product in the first place. For example the development of user-friendly software for personal computers has increased the utility of a PC. In addition, as the number of buyers of a product increases, service and maintenance networks targeted at that product are likely to develop. An example is the diffusion of shops where mobile phones can be taken for repair. The existence of this maintenance network will benefit consumers as it decreases the operation and maintenance costs needed over the whole life of the product.

3.6. Revenue for technology development firms

It is easy to forget that for many of the companies developing new products, little or no revenue is generated through sales — the technology as yet has no market. The beginning of sales into a market or into demonstration projects provides a source of revenue for technology development firms.

4. Hydrogen niches: the fuel cell Auxiliary Power Unit as a case study

There are already a range of studies exploring aspects of the wider fuel cell technological niche (i.e. the actors, networks and initiatives protecting and promoting the development of fuel cells) [31–33]. This section outlines the prospects for the technologies developed in the fuel cell technological niche to gain a foothold within the niche market for auxiliary power on board vehicles. Auxiliary Power Units (APUs) are often hailed as one of the more promising early applications of fuel cells (FC) [2,34]. In this market fuel cells do not replace the main internal combustion engine (ICE) as a source of propulsion. Instead, they provide power and heat for onboard services, such as entertainment, heating, air conditioning, and so on, for which ICEs are not particularly efficient. APUs can improve generation efficiency, reduce emissions, extend the engine life and eliminate noise. Two of the competing fuel cell technologies for APU applications are Proton Exchange Membrane Fuel Cells (PEMFCs) and Solid Oxide Fuel Cells (SOFCs). A number of publications discuss the advantages and disadvantages of PEMFCs and SOFCs [34–38]. Some authors consider SOFCs as the clear winner [35,36,38], others consider PEMFCs as the most competitive alternative [34] while some others conclude that the two technologies will be used in different applications. Another fuel cell technology, Direct Methanol Fuel Cell (DMFC) has been already introduced in the market on board recreational vehicles.

The interest in the development of FC APUs is a result of the considerable rise in electric power demands onboard civilian vehicles [37], as air conditioning, heated rear windows, catalytic converters, active suspension and other functions become standard, and as more and more consumers choose to install extra information and entertainment devices, such as GPS systems, passenger seat TVs, and so on. Kurani et al. [39] highlight the increasing numbers of 12 V electric outlets offered in many midsize SUVs, and link the spread of mobile communications and electronics with a potential opportunity for fuel cells in vehicles. Nonetheless, there are good reasons to be sceptical about some of the expectations and market projections for fuel cell auxiliary power [40].

Following Lutsey et al. [41], seven different markets for FC APUs on board civilian vehicles can be identified: public transit vehicles; contractor truck/pick-ups; recreational vehicles; specialised utility vehicles; refrigeration unit vehicles; luxury passenger vehicles; law enforcement vehicles; and line-haul heavy-duty trucks. In a survey of these markets, Agnolucci [42] identifies luxury passenger vehicles, law enforcement vehicles, recreational vehicles and line-haul heavy-duty trucks as the most promising markets for early adoption, and these markets are consequently the focus of this article. For the other markets, user requirements for efficient auxiliary power or silent operation appear too low to overcome the cost barriers, at least in the near future [42].

Recreational vehicles (motorised caravans) offer a promising market for FC APUs. In fact, the noise from their operation prevents the use of diesel generators in most recreational vehicle parks, where electricity is normally provided by electricity plugs. While the availability of electricity decreases the attractiveness of FC APUs, these devices would allow users to experience in the wilderness the same comfort that is currently enjoyed only in recreational vehicle parks. Adamson [43] reports that an APU from Smart Fuel Cell has been integrated as standard equipment in the S-class, i.e. the premium line of Hymer vehicles (http://www.hymer.com/eu), although it is only an option in all other classes. The adoption rate of the FC APUs in these other classes will be indicative of the future trends of FC APUs in recreational vehicles.

In the luxury passenger vehicle market, the trend for increasing power demands is as strong as in other markets, but the luxury vehicle sector is less sensitive to cost, and is thus more likely to adopt FC APUs. However, APUs are a competitive alternative to ICEs only for those devices requiring more or less constant power when the ICE is off [41]. Meissner and Richter [40] are sceptical about the need for new power sources as several of the new functions, especially those aiming at improved reliability and comfort, can be satisfied by existing 14 V electrical systems. Although higher electrical loads are being supplied when the engine is off or on idle, energy management systems can keep the batteries in their best operational window so as to ensure that critical components are supplied with power. FC APUs would be weakened by the diffusion of diesel or gasoline hybrids, as these vehicles will have large batteries. On the other hand, specialised vehicles such as limousine will very likely adopt FC APUs due to their driving pattern, i.e. stop-and-go in city traffic, and the presence of electricity-thirsty gadgets.

Law enforcement vehicles seem another attractive market for FC APUs as policemen are likely to idle their cars longer and might not be very concerned about the loss of trunk space to accommodate FC APUs. However, the use of APUs will be accepted only if the cars' performance, in particular speed and acceleration, is not impaired. Even in this case, FC APUs will still face competition from high-performance alternators which are already optionally fitted on police cars [41]. Although law enforcement agencies, being public sector bodies, could be particularly sensitive to energy savings, emission reductions and improved air quality delivered by FC APUs, they are also likely to be responsive to the cost of these devices. Although law enforcement vehicles are unlikely to be a major market for FC APUs, they might be an important niche enabling further diffusion.

In line-haul trucks APUs could substitute discretionary idling, i.e. all occasions in which idling is aimed at increasing the drivers' comfort, especially when drivers sleep overnight in the truck [34,35,44]. On board line-haul heavy-duty trucks, FC APUs will have to compete with a number of other alternatives, namely direct-fired heaters (for heating only), thermal storage systems, ICE APUs and electrification of truck stops[3]. The potential market for FC APUs and of these technologies can be assessed with reference to their payback period, i.e. the amount of time needed to recover their cost when compared to the costs of idling a truck engine. Brodrick et al. [34] found that the average payback for an FC APU is 3.2 years, although the range of values caused by the uncertainty on the parameters goes from 6.5 years to as low as 1.3 years. Considering that the American Trucking Association desires a 2-year payback on equipment purchases, the results from Brodrick et al. [34] are encouraging. On the other hand the payback of direct-fired heaters, thermal storage, direct heat with storage cooling, ICE APUs and electrification of truck stops are much shorter [44] although only the last two options provide a range of services comparable to those from FC APUs. Truck stops electrification seems to be the most serious competitor as it not only matches the services offered by FC APUs, silent mode included, but also offers additional services such as telephone connection, wireless internet, movies on demand and interactive driver training programs [45]. The fact that electrified trucks force drivers to stop at determined locations does not seem to be a big drawback as drivers are likely to stop at truck stops anyway to use showers, laundry and restaurants [46,47] and because of concerns about the safety of the carried goods. In summary, if electrification of truck stops proceeds at a high pace or if the price of FC APUs stays high, the potential market for FC APUs on board line-haul trucks could be quite limited. However, the intense activities of FC APUs manufacturers, see [43] for a review, testifies to a confidence either on achieving significant cost reductions or on the willingness of consumers to pay an increased price for improved services.

The most promising near term market for FC APUs seems to be military applications. The United States Army in conjunction with government, academia, the national laboratories and industry is actively pursuing fuel cell technology. The use of FC APUs is particularly appealing to the army in 'Silent Watch' settings, i.e. a tactical mode of operation demanding full electrical power for all mission activities except mobility, without the acoustic and infrared signature of an internal combustion engine. One of the advantages of the R&D carried out in the army is that the demands on the level of reliability of FC APUs are higher than those in the civilian market. On the other hand, civilian consumers are likely to be more price sensitive than military consumers. Of course, civilian product specifications will differ from those of the military, and it is unlikely that military-grade fuel cell devices will find their way into civilian markets. However, the military could represent a significant niche, providing a space for fuel cell APU development from which civilian products may emerge in time, as occurred for many other technologies in the past.

From the analysis presented above, it is clear that many of the more optimistic projections for fuel cell success in APU markets require some qualification: significant cost barriers remain before markets will take off. However, considering the substantial activity within the sector, it is clear that technological

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[3] Direct-fired heaters which can be used to heat the cab and the engine are lightweight and widely commercialized, but their market share is low, reportedly because of retrofitting costs and unknown reliability. Diesel APUs are small diesel ICEs equipped with heat recovery normally mounted externally on the truck cab. Thermal storage systems (TESs) are devices able to store heating or cooling energy from vehicles' engines or air-conditioning systems while vehicles operate. They can provide heating and cooling but not electrical power. In the case of electrified truck stops, the trucker would simply "plug in" electrical devices into electric hook-ups.

developments will, and are, taking place, therefore improving performance and reducing cost. Current activities include initiatives by BMW, and through the US National Energy Technology Laboratory's SECA programme. With both public and private R&D, and the market moving in this direction, it is possible that fuel cells will be providing auxiliary power on board civilian vehicles within a decade. In particular, it is likely that military applications will be the first market to take off, followed by line-haul trucks, recreational vehicles and luxury cars. In the case of civil markets, policy incentives could be particularly important to facilitate the diffusion of FC APUs.

5. APUs and the hydrogen economy: applying the niche analysis framework

This section uses the framework outlined in Section 3 to analyse likely developments within the fuel cell sector should fuel cell APUs become established in one or more of the niche markets explored above. By examining each of the development processes that would be likely to occur in established niches, the potential role of APU niches in a transition towards a hydrogen economy is assessed.

5.1. Internal economies of scale

In the case of economies of scale, the impact of FC APUs on the other fuel cell markets, i.e. stationary power and vehicles, will crucially depend on the size of the market for APUs and on the technology adopted. In terms of the size of the market, as discussed above, there are some reasons to be hopeful on the diffusion of APUs, especially on board line-haul trucks and recreational vehicles. Unfortunately for hydrogen enthusiasts, PEM FCs seem to have a secondary role in these niche markets where SOFCs and DMFCs are the more interesting technologies. This implies that the improvements in machineries, technological learning and the skills acquired by the specialised workforce in the firms producing FC APUs might only have a limited role in the diffusion of the hydrogen economy. On the other hand, most actors working in the FC APUs industry are small scale firms which are likely to experience a reduction in average unit costs as FC APUs diffuse. It seems likely that for a very long time, the increasing scale of the firms producing FC APUs will not have any negative effect on the co-ordination inside the firms. Although maybe of limited importance to the coming of the hydrogen economy, economies of scale are likely to be an important force driving down the cost of FC APUs.

5.2. External economies of scale

Success in APU markets would allow the fuel cell industry to grow. As with the internal economies of scale, the impacts of this will be highly dependent on the size of the market and the choice of technology (PEM FC vs. SOFC). Although the development of tailored machineries, and input suppliers for SOFC or DMFC APUs is likely to be of limited importance for PEM FC used in the vehicle or stationary power markets, a number of other factors likely to produce external economies of scale are much less likely to be technology-specific and can be more easily shared across the whole fuel cell industry. This is likely to occur because of the development of a service sector able to cater to the needs of the FC industry as a whole. Some of these needs are unlikely to be specialised on a technology basis, for example legal, marketing and external affairs. Although the impact of these professional skills with established markets may be limited, they might be extremely influential in the case of emerging technologies whose competitive terms with incumbents are much more fluid. Growth of APU markets would mean greater influence for the fuel cell industry as a whole through strengthened lobby groups and industry associations, and greater cohesion, purpose and drive within the fuel cell industry. It would enable the development of a larger pool of skilled fuel cell engineers and manufacturers (and lack of skills are currently seen as an important barrier to the industry [48]). Finally, it would enable the industry to address potential regulatory barriers that become obvious once fuel cells are deployed in real-world situations. This could include regulations around hydrogen and methanol storage, waste and decommissioning, and health and safety. Learning about these issues, and removal of potential regulatory barriers, could facilitate the development of fuel cells in other markets. For example, developments in DMFC for portable fuel cells have lead to a reappraisal of airline prohibitions on the carrying of methanol on aircraft — a barrier to methanol fuel cell development. On the other hand, while these developments might be beneficial for the fuel cell industry, their implications for the establishment of a 'hydrogen economy' are less clear. If the dominant technology in FC APUs does not involve the use of pure hydrogen, the development of the APU market could conceivably shift attention in the industry away from hydrogen as a fuel.

5.3. Expectations

The successful entry of fuel cells into one of the APU markets outlined in Section 4 would be likely to have an important impact on expectations around fuel cell technologies in general, providing confidence in the sector, and confirming the positive expectations that already drive developments. The fact that APUs would see the introduction of fuel cells on board vehicles in particular could have an important psychological dimension, strengthening confidence in the future role of fuel cells in the automotive sector. This general effect would be to enhance investment and activity within the fuel cell sector as a whole. This is particularly likely to happen because a key driver behind government support for fuel cells in many countries, including the UK, is the desire to create and foster competitive industries [49]. Governments have an expectation that fuel cells will become an important technology, and it is to the national advantage to develop a world leading position in the field. The success of early fuel cell applications will help to strengthen this expectation, and may lead to further concerns from national governments that a failure to support the industry may result in the country 'falling behind'.

Further effects would depend on which technology (PEM, SOFC, or both) comes to dominate the APU market. In particular, the use of PEM fuel cells, with a direct hydrogen supply, would provide the first market for hydrogen to be commercialised as a fuel. In contrast, a unit that works through fuel reformation could re-invigorate perceptions of the viability of fuel reformers. In the public eye, it could also break the perceived overlap between fuel cells and hydrogen energy. It is also possible that the use of fossil fuels to power APUs may lead to a backlash, with fuel cells no longer seen as the clean technology of the future.

5.4. User and social context

The deployment of APUs on vehicles would present users with new functionalities, and with opportunities to change the way that they use their vehicles. Some authors have suggested that the increasing demand for on-board electricity is a function of the trend towards the increasing integration of transport, communications and power infrastructures [39]. If this is the case, we can expect motorists to start to use ever more electricity onboard, and to start to use vehicles differently, with cars increasingly seen as mobile offices or entertainment and recreation facilities. Kurani et al. [39] link this putative change in user behaviour with the fuel cell vehicle, arguing that because FCVs can provide both propulsion and stationary power at high efficiency, users will be prepared to accept losses in other performance attributes, such as range. The deployment of APUs will allow for learning about users' responses to greater on-board power, and whether changes in vehicle use will make fuel cell vehicles a more attractive proposition. It should be noted, however, that such a change could lead to increased energy demand, which could make a transition to a low carbon hydrogen energy system even more challenging.

The deployment of APUs also allows learning about the barriers to fuel cell uptake — are consumers concerned about unproven technology, or about their ability to get the thing serviced? Several studies have suggested that the establishment of fuel cells in a niche such as that for APUs will make consumers more familiar with fuel cells, and hence more likely to accept them in other applications [50,51], as have participants in a stakeholder workshop exploring possible transitions to a hydrogen economy [48]. As FC APUs will be adopted because of private benefits related to the increased supply of on-board power, potential users will have an incentive to learn how to operate these devices because of the benefits directly accruing to them[4]. Finally, the deployment of APUs will contribute to the articulation of a socio-cultural meaning around fuel cells. Will fuel cells be seen as a green choice, or the latest in a series of wasteful on-board luxuries? This ties directly into how best fuel cell products should be marketed, since this will involve identifying the attributes and meanings that people will positively associate with fuel cell products.

5.5. Network effects, complementary technologies, and infrastructure

The take-up of FC APUs seems unlikely to cause any direct network effects arising in the FC APU market and in the development of a hydrogen economy. Nonetheless, a number of indirect effects are likely to occur. In terms of the development of complementary products, it is worth recalling that when the lighting dynamo was introduced for cars about one hundred years ago, its primary task was to generate electric power for lights. Today, a multitude of applications have been added to increase the safety and comfort features of cars, e.g. heated rear windows, anti-lock braking systems (ABS), power locks, seat adjustment and heating, electronic motor and gear control, which have become standard equipment [37]. The availability of efficient, 'engine-off' power on board vehicles would be likely to create a market for an increasing range and variety of in-vehicle appliances, the diffusion of which would in turn make an APU more attractive. Another indirect network effect would be related to the development of service and maintenance facilities. As more customers adopt APUs, the number of garages offering servicing and maintenance of APUs will increase, making adoption more attractive to new consumers. The diffusion of FC APUs will also influence the attractiveness of competing technologies. For example, if FC APUs become popular on board line-haul trucks, alternatives such as truck stops electrification will lose appeal. Finally, the uptake of FC APUs will also facilitate the development of a fuel distribution infrastructure. In the case of APUs running on fuels other than petrol or diesel, a fuel distribution infrastructure (e.g. methanol or hydrogen cartridges sold in service stations, for example) would develop, as more customers purchase APUs. This could facilitate the development of a hydrogen economy by creating a distribution

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[4] This conclusion assumes that the incentives to learn how to operate a new technology are related to the benefits directly accruing to them, i.e. the private benefits.

infrastructure that enables other fuel cell products, such as portable fuel cells and fuel cell scooters, to expand into the market.

5.6. Revenue

The amount of revenue for the fuel cell industry that could be generated by APU sales is quite clearly dependent on the size of the market and on its composition (i.e. a competitive industry will imply a low margin for producers). Considering the presence of many start-ups in the FC APU industry, it is likely that these actors will need considerable margins to scale-up production and prosper. However, in the case of the hydrogen economy the revenues arising from the sales of FC APUs are unlikely to be extremely important as car manufacturers and maybe oil companies, i.e. the actors likely to be crucial in the diffusion of a new fuel, are deep-pocketed actors whose plans for development are not going to be influenced, at least from a financial perspective, by the diffusion of FC APUs.

6. Conclusions and policy implications

This paper has combined insights from economic theory and technology studies to formulate a framework helpful in understanding the dynamics of technological change in niches. The application of the framework to the niche of Fuel Cell (FC) Auxiliary Power Units (APUs) has provided insights into the importance of this market to the development of a hydrogen economy.

We conclude that the choice of technology for APUs will be of critical importance in determining the role this market could have in shaping future developments in hydrogen and fuel cells. PEM FC APUs running directly on hydrogen would provide most impetus to a hydrogen economy. However, if, as seems likely, Direct Methanol Fuel Cells and Solid Oxide Fuel Cells dominate APU markets, the impacts for the hydrogen economy would be limited but not negligible. A number of factors are not strictly dependent on the technology used in FC APUs. In particular, factors leading to external economies of scale, such as those related to the regulatory setting, legal framework, marketing and external affairs, apply across fuel cells as a whole. Second, the diffusion of FC APUs would also alert consumers to the possibilities offered by FC technology and would facilitate the emergence of a servicing and possibly a refuelling infrastructure. Third, users may change behaviour and demand increased availability of power on board their vehicles, a factor ultimately giving a competitive advantage to FC vehicles. Finally, successful diffusion of FC APUs would advance a hydrogen economy and the development of the FC industry through increased expectations and confidence in fuel cells as a generic technology. On the other hand, a failure in the development of FC APUs, for example due to the diffusion of truck stop electrification, could cause a potential expectations backlash for the hydrogen economy and the FC industry as a whole.

Governments wishing to support moves towards a hydrogen fuelled transport system can therefore justify limited and targeted support for fuel cell APUs as part of a wider hydrogen strategy, as well as on the basis of the direct environmental benefits provided by APUs in some circumstances (such as reducing truck idling). Because of their proximity to markets and the existence of private benefits, the government support does not need to be large. In the case of the average technical and cost specifications in Brodrick et al. [34], a \$1500 government incentive would reduce the payback period of FC APUs for truck drivers to two years, i.e. the time horizon required by the fleet industry. Considering the upfront cost of FC APUs, government support could take the form of capital grants or tax credits for the owners of fleet vehicles. Other potential government interventions are related to the removal of regulatory barriers hindering the development of the fuel used in FC APUs, continued R&D funding, and support for the development of the industry through network building (for example through the UK's Fuel Cells UK).

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References

[1] F.W. Geels, Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study, Res. Policy 31 (8–9) (2002) 1257–1274.

[2] HFP Secretariat, European Hydrogen and Fuel Cell Technology Platform: Deployment Strategy, Brussels, 2005.

[3] A. Farrell, D. Keith, J. Corbett, A strategy for introducing hydrogen into transportation, VIII Biennial Asilomar Conference: Transportation, Energy, and Environmental Policy, Asilomar, CA, 2001.

[4] B. Elzen, R. Hoogma, R. Kemp, Managing the transition to sustainable transport through strategic niche management, VIII Biennial Asilomar Conference: Transportation, Energy, and Environmental Policy, Asilomar, CA, 2001.

[5] R. Kemp, J. Schot, R. Hoogma, Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management, Technol. Anal. Strateg. Manag. 10 (2) (1998) 175–195.

[6] J. Mokyr, Punctuated equilibria and technological progress, Am. Econ. Rev. 80 (2) (1990) 350–354.

[7] J. Schot, F.W. Geels, Niches in evolutionary theories of technical change Paper submitted for publication to Journal of Evolutionary Economics.

[8] H.S. Brown, P.J. Vergragt, K. Green, L. Berchicci, Learning for sustainability transition through bounded socio-technical experiments in personal mobility, Technol. Anal. Strateg. Manag. 15 (3) (2003) 291–315.

[9] M. Hodson, S. Marvin, Understanding transitions to a hydrogen economy(-ies) with and through 'Regions', UKSHEC Social Science Working Paper, vol. 3, University of Salford, SURF Centre, 2004.

[10] A. Smith, Innovation for sustainable development: some lessons from green niches, Conference of the European Society for Ecological Economics, Lisbon, 2005.

[11] C. Christensen, The Innovators Dilemma: When New Technologies Cause Great Firms to Fail, Harvard Business School Press, Cambridge, 1997.

[12] G.S. Lynn, J.G. Morone, A.S. Paulson, Marketing and discontinuous innovation: the probe and learn process, Calif. Manage. Rev. 38 (3) (1996) 8–37.

[13] H. Van Lente, Promising technology: the dynamics of expectations in technological development, Enschede: Department of Philosophy of Science and Technology, University of Twente, 1993.

[14] M. Cohn, Too Cheap to Meter: an Economic and Philosophical Analysis of the Nuclear Dream, State University of New York Press, Albany, NY, 1997.

[15] Toyota, http://www.toyota.com/html/shop/vehicles/ravev/rav4ev_0_home/index.html, 2006.

[16] GM EV1: Lessons Learned, www.gm.com/company/gmablity/adv_tech/300_hybrids/hyb_ev1.html, accessed on January 19th, 2006.

[17] F.W. Geels, From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory, Res. Policy 33 (2004) 897–920.

[18] D. Levinthal, The slow pace of rapid technological change: gradualism and punctuation in technological change, Ind. Corp. Change 7 (1998) 217–247.

[19] P. Agnolucci, P. Ekins. Technological Transitions and Strategic Niche Management: The Case of the Hydrogen Economy International Journal of Environmental Technology and Management (in press).

[20] C.W.I Pistorius, J.M. Utterback, Multi-mode interaction among technologies, Res. Policy 26 (1997) 67–84.

[21] G. Becattini, Sectors and/or districts: some remarks on the conceptual foundation of industrial economics, in: E. Goodman, J. Bamford (Eds.), Small Firms and Industrial Districts in Italy, Routledge, London, 1989.

[22] S. Brusco, The Emilian model: productive decentralisation and social integration, Camb. J. Econ. 6 (1982) 167–184.

[23] C. Camison, Shared, competitive, and comparative advantages: a competence-based view of industrial-district competitiveness, Environ. Plann. A. 36 (12) (2004) 2227–2256.

[24] M.H. Lazerson, G. Lorenzoni, The firms that feed industrial districts: a return to the Italian source, Ind. Corp. Change 8 (2) (1999) 253–266.

[25] R. Kemp, Technology and the transition to environmental sustainability: the problem of technological regime shifts', Futures 26 (10) (1994) 1023–1046.

[26] M. Weber, Transforming large socio-technical systems towards sustainability: on the role of users and future visions for the uptake for city logistics and combined heat and power generation, Innovation 16 (2) (2003) 155–175.

[27] S. Russell, R. Williams, Concepts, spaces and tools for action? Exploring the policy potential of the social shaping perspective, in: K.H. Sørensen, R. Williams (Eds.), Shaping Technology, Guiding Policy: Concepts, Spaces and Tools, Edward Elgar, Cheltenham, 2002.

[28] R. Hoogma, R. Kemp, J. Schot, B. Truffer, Experimenting for Sustainable Transport: the Approach of Strategic Niche Management, Spon Press, London, 2002.

[29] C. Fischer, America calling, A Social History of the Telephone to 1940, University of California Press, Berkley, 1992.

[30] S.J. Liebowitz, S.E. Margolis, Network externality: an uncommon tragedy, J. Econ. Perspect. 8 (2) (1994) 133–150.

[31] B. Lane, Optimising implementation strategies for fuel cell powered road transport systems in the United Kingdom PhD Thesis, Faculty of Technology, Open University (2002).

[32] G. Schaeffer, Fuel cells for the future: a contribution to technology forecasting from a technology dynamics perspective PhD Thesis, University of Twente, Netherlands (1998).

[33] R. van den Hoed, Driving fuel cell vehicles. How established industries react to radical technologies PhD Thesis, Delft University of Technology (2004).

[34] C.-J. Brodrick, T.E. Lipman, M. Farshchi, N.P. Lutsey, H.A. Dwyer, D. Sperling, I. Gouse, S. William, D.B. Harris, F.G. King, Evaluation of fuel cell auxiliary power units for heavy-duty diesel trucks, Transp. Res., Part D Transp. Environ. 7 (4) (2002) 303–316.

[35] Arthur D. Little (ADL): Conceptual design of POX SOFC 5 kw net system final report to the department of energy national energy technology laboratory January 8, 2001 (2001).

[36] F. Baratto, U.M. Diwekar, D. Manca, Impacts assessment and trade-offs of fuel cell-based auxiliary power units Part I System performance and cost modelling, J. Power Sources 139 (2005) 205–213.

[37] P. Lamp, J. Tachtler, O. Finkenwirth, S. Mukerjee, S. Shaffer, Development of an auxiliary power unit with solid oxide fuel cells for automotive applications, Fuel Cells 3 (3) (2003) 146–152.

[38] J. Zizelman, S. Shaffer, S. Mukerjee, Solid oxide fuel cell auxiliary power unit: a development update, Fuel Cell Power for Transportation 2002, Detroit, MI, Society for Automotive Engineers Technical Paper Series, 2002.

[39] K.S Kurani, T.S Turrentine, R.R. Heffner, C. Congleton, Prospecting the future for hydrogen fuel cell vehicle markets, in: D. Sperling, J.S. Cannon (Eds.), The Hydrogen Energy Transition, Elsevier Academic Press, Burlington, MA, 2003, pp. 33–58.

[40] E. Meissner, G. Richter, Vehicle electric power systems are under change! Implications for design, monitoring and management of automotive batteries, J. Power Sources 95 (2001) 13–23.

[41] N. Lutsey, C.-J. Brodrick, D. Sperling, H.A. Dwyer, Markets for fuel–cell auxiliary power units in vehicles: preliminary assessment, Transp. Res. Rec. 1842 (2003) 118–127.

[42] P. Agnolucci, Economics and market prospects of fuel cells used in Auxiliary Power Units Int. J. Hydrogen Energy (submitted for publication).

[43] K.-A. Adamson, Calculating the price trajectory of adoption of fuel cell vehicles, Int. J. Hydrogen Energy 30 (2005) 341–350.

[44] F. Stodolsky, L. Gaines, A. Vyas, Analysis of technology options to reduce the fuel consumption of idling trucks, Report ANL/ESD-43, Argonne National Laboratory, Argonne, IL, 2000.

[45] Fleet Owner, Turn idle time into cash. a how-to handbook on trading engine idle time for profit, Special Industry Report Produced by the Fleet Owner Magazine, 2003.

[46] Truck Research Institute (TRI), Commercial Driver Rest Area Requirements: No Room at the Inn, Truck Research Institute, Alexandria, Va, 1996.

[47] US EPA, Truck Stop Electrification Codes and Electrical Standards; Notice of Data Availability [FRL-7783-3] — Summary of Comments, US EPA, Washington, D.C, 2005.

[48] W. McDowall, M. Eames, Report of the September 2005 UKSHEC hydrogen transitions workshop, UKSHEC Social Science Working Paper, vol. 11, Policy Studies Institute, London, 2005.
[49] W. McDowall, M. Eames, Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: a review of the hydrogen futures literature, Energy Policy 34 (2006) 1236–1250.
[50] H2 Wales, A vision of the hydrogen economy in Wales: placing Wales in a position to take full advantage of the hydrogen economy University of Glamorgan Hydrogen Research Unit, 2004.
[51] Fuel Cells Canada, Industry Canada, and PriceWaterhouseCoopers: Canadian Fuel Cell Commercialisation Roadmap, Fuel Cells Canada, Ottawa (2003).

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