

Summary of Discussions from Expert Stakeholder Workshops on the Economics of Hydrogen Technologies

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1. Introduction

As part of the UK Sustainable Hydrogen Energy Consortium (UKSHEC) the Policy Studies Institute (PSI) is undertaking work to explore the feasibility, from a socio-economic perspective, of a range of possible applications for hydrogen and fuel cell technologies in future economies. A key part of this process has been a scoping of the current and projected technical performance levels of various components of hydrogen and fuel cell systems, and an analysis of which factors would be most likely to drive market penetration. PSI researchers produced discussion papers, drawing on reviews of the available literature, which were then submitted for consultation to a range of UK based independent expert stakeholders.

This paper summarises and discusses the outputs from three expert stakeholder workshops, held in April and May 2006. The workshops were based around the following themes: *Portable and Auxiliary Power Unit applications*, *Storage and distribution infrastructure*, and *Fuel Cell Vehicles*. Each workshop was attended by stakeholders with a particular expertise in the relevant sector, and included technology developers, systems integrators, infrastructure providers, market analysts and policy consultants. Participants in each workshop discussed current and projected levels of cost and performance of the relevant technologies, as well as the possible market drivers in each case.

The outputs of these workshops form a major part of PSI's work on the economics of hydrogen and fuel cell technologies; however, other crucial components in possible hydrogen / fuel cell futures are hydrogen production technologies, and the use of fuel cells for stationary power. PSI discussion papers have also been produced on these sectors (Hawkins and Joffe, 2006; Hawkins et al, 2006), and have been submitted for individual consultation to stakeholders in the relevant fields. The outputs of these processes are not discussed here, but will be integrated into a future paper, which will aim to cover in as comprehensive a manner as possible the range of interactions within putative hydrogen / fuel cell energy systems, from a technological transitions perspective, and with insights for policy. All PSI discussion papers can be found on the UKSHEC social science website (www.psi.org.uk/ukshec).

This paper will first review the technical issues of cost and performance, at current and projected levels, as explored by the discussion papers and refined by the workshop discussions. These issues, being somewhat specific to each sector, will be dealt with by discussing the relevant outputs from each workshop separately. In the following sections issues pertaining to market penetration, drivers and technology transfer will be discussed in a more integrated fashion, drawing in insights from all workshops where appropriate.

An important and overarching output of the workshops was that hydrogen, as a fuel, and fuel cells, as potential conversion technologies, were linked but by no means inextricably so- hydrogen could be used to power internal combustion engines (ICEs), just as certain high temperature fuel cells are capable of running on fuels other than hydrogen, many of

them more widely and readily available. Thus in this paper general reference is sometimes made to a hydrogen / fuel cell (H/FC) economy, implying a future economy that makes some use of either hydrogen, fuel cells, or both, taking into account the potential interactions between hydrogen and fuel cells, whilst not associating one inextricably with the other.

2. Technological / performance issues in each workshop

2.1 Portable fuel cells and Auxiliary Power Units

An early market entry point for fuel cell technologies may be in providing small scale or portable supplies of power, often for specialist applications. The provision of electrical power in off-grid situations is a function which fuel cells have a strong potential to fill, particularly as in many such situations alternative power sources are usually expensive, meaning that users may be prepared to pay premiums for the right functionality. In addition fuel cells may be able to attract certain users because of particular beneficial characteristics such as clean and silent operation. Portable fuel cells were defined for the purposes of this workshop by the discussion paper (Agnolucci, 2006a) as including *micro fuel cells*, for providing portable power to electrical devices such as laptops and mobile phones; and *portable generating systems*, where fuel cells are used within a system to provide portable off grid power for larger scale generators, for applications including outdoor leisure activities and military uses. Auxiliary Power Units (APUs) are defined in the discussion paper (Agnolucci, 2006b) as devices which provide onboard electrical power in vehicles, for onboard services energy demand, rather than propulsion. Fuel cells may become attractive in such a role in vehicles with a very high number of high energy onboard functions (such as air conditioning and entertainment systems) and also for providing power needs for overnight stays in heavy duty vehicles- in current practice it is not uncommon to leave the engine idling to provide this energy from the vehicle's battery. In each application, however, fuel cells have competitors, in particular in the case of portable fuel cells, conventional lithium batteries, which are continually expanding in storage capacity; conventional generators, which are considerably cheaper than fuel cell generating systems; and in the case of APUs, the increased efficiency of onboard power provided directly by the engine, combined with increased onboard electricity storage due to hybrid technologies, and the increasing provision of electrical services at truck stops.

Despite these apparent barriers to fuel cell penetration in portable and APU markets, participants in this workshop were enthusiastic about the prospects for fuel cells in these markets, emphasising that despite the higher cost, performance advantages over incumbent technologies were already making them an attractive prospect in certain applications. An area of great interest is powering portable electronic devices, particularly as increased functionality increases the energy demand of such appliances. Military applications, for soldiers' portable power packs or for other field operations, are also considered promising early stage niches, as higher costs will be accepted if the required high specifications are met. Fuel cells have the potential to offer significantly reduced weight compared to current alternatives, and the benefit of silent operation. An important niche for APUs is to provide power for use in motor homes and camper-vans, where again their clean and silent operation may be valued. It is worth noting that fuel cells are already commercially available in such applications, some models carrying them as standard. The prospects for APUs in heavy duty trucks was also thought very promising, although possibly more so in the US, where competition with electrified truck

stops is less intense. The prospects for APUs providing onboard power on planes was also thought by some participants to have potential.

The participants were on the whole optimistic that growth in the number of market segments in which portable and APU fuel cells could compete, would continue. Several participants emphasised that the number of potential 'niche' applications for portable and APU fuel cells was so great, that aggregation of these niche areas could eventually encourage widespread production. In other words, in order to achieve significant production volumes it may not be necessary to 'break out of the niche' (see discussion below), as the number of potential niche applications was so large. However, there were equally strong feelings that such applications had the potential to 'go mainstream' as well, if the energy using habits of what are now niche consumers, become more widespread.

Key issues affecting this potential to move from niche to mainstream markets are price, performance, and, particularly in the case of micro fuel cells, the extent of latent consumer demand for increased energy storage. There is uncertainty relating to all these factors, which play out in the inter-relationships between them.

The projections for price and market penetration of fuel cells in portable and APU applications summarised in the discussion papers (Agnolucci 2006a, 2006b) taken from studies such as Darnell (2003) Lutsey et al (2003) Stratonova et al (2003) and others, were perceived in the workshop to be over optimistic. Considerable uncertainty remained over projections of such figures, and the uncertainties were to a large extent interrelated- increased demand would stimulate increased production, investment and technological learning, which would in turn bring down the price and stimulate further demand. Such a process would imply a potential 'snowball' effect, leading some participants to suggest that penetration would ultimately be on the extremes- massive or negligible. Disruptive effects could also be brought about through technical innovations which bring about massive reductions in cost.

Despite the uncertainties, participants remained optimistic about the market pull of the products. It was argued that in many cases, an initially higher price would be accepted by many consumers because of their interest in the additional benefits of fuel cells, such as clean and silent operation, and in the case of electronic equipment, the possibility of vastly superior energy storage capacity. Whilst it is not yet entirely clear whether fuel cells will outstrip ongoing improvements in lithium batteries, participants felt optimistic that whereas batteries were reaching a plateau in their potential for further performance improvements, fuel cells had a much stronger long term potential. Participants were also on the whole insistent that increased mobile energy demand from consumers, for continuing expansion of mobile phone functions, or for longer use of laptops without back up batteries or grid access, was inevitable. The strongest market at the moment for such innovations was identified as being in Asia, though it was felt that demand could spread to the EU and elsewhere.

The workshop discussed whether a large penetration of fuel cells in the portable power and APU markets could improve the prospects for hydrogen and fuel cells in other sectors. Technology transfer might allow commercial success for fuel cells in one sector to transfer to another. However, the participants believed that the increasing fragmentation in the types of fuel cells used in various applications, would make such technology transfer difficult. They were on the whole insistent that the most likely fuel cell technologies in portable and APU applications would be Direct Methanol Fuel Cells (DMFCs) and high temperature Solid Oxide Fuel Cells (SOFCs). SOFCs in particular would allow applications to make use of a fuel that was already available within the given user context. For APUs on board trucks, and portable generating systems, this is likely to be diesel, and in other applications, including camping vehicles, butane, propane, and kerosene. Methanol would be required for DMFCs, and this is being considered as an option for portable electronics- clearly this option begins to introduce questions in terms of provision of the refuelling infrastructure. The use of reformers combined with PEM fuel cells was thought to be too expensive to be considered as an early stage option.

This is in marked contrast to the automotive sector which is ever more strongly focussing on PEM fuelled by pure hydrogen (as discussed below). There is therefore unlikely to be too much direct technological transfer between the portable and APU sector and the FCV sector, although one participant raised the possibility of some shared benefits in membrane and catalyst technologies.

The role of fuel cells in portable and APU applications in contributing to a low carbon or hydrogen / fuel cell economy is therefore somewhat open to question. Their reliance on the whole on conventional fossil fuels mean that, though the absence of combustion delivers extremely low emissions of local pollutants, they will still emit carbon dioxide.¹ It might be argued that even where conventional fossil fuels are used, one might expect some reduced carbon emissions from more efficient use of these fuels; however, the prospects for success of fuel cells in this sector seem largely to rest on continued huge increases in power demand from consumers, which would probably rebound on any efficiency benefits from a carbon saving point of view.

Therefore, at the current state of technology development, it seems unlikely that the portable and APU sectors will make much of a direct contribution to the development of a wider, sustainable hydrogen / fuel cell economy, although they may themselves be very successful. One possible route through which developments in this area could directly transfer to automotive applications would be if developments in DMFCs were so successful that the technology became viable for transport. However, at present only a handful of small vehicles have been built with DMFCs, and it does not seem to be a technology that automotive manufacturers are actively pursuing.

¹ Methanol, however, has the potential to be a low carbon fuel, if it is produced from 'recycled' CO₂ emissions from industry combined with renewable biomass.

2.2 Storage and transportation

This workshop discussed the outputs of two working papers: Hawkins (2006), which presented a literature review of technology and cost characterisation for hydrogen storage and distribution technologies, and Agnolucci (2006c), which discussed the economic and investment issues relating to the build up of hydrogen infrastructure, with particular reference to the transport system.

2.2.1 Technical issues

Some storage and distribution technologies, particularly compressed gas, underground and liquid state storage, and transportation by truck and tube trailer, are considered 'mature', as their current use in providing hydrogen for the chemicals industry allows us to have some knowledge about their costs. However, this kind of specialist use exerts quite different demands on the storage and distribution technologies, whereas if hydrogen was to be used as a transport fuel, the energy density and cost of the infrastructure technologies would have to improve. Such improvements may not yet be being 'pushed' for by manufacturers, given the nature of current usage, so it is possible that there remains the potential for even greater improvements in these 'mature' technologies. Less mature technologies, in particular metal and chemical hydride storage, are considered to have greater potential for improvements, but much uncertainty remains, as it is by no means clear whether such technologies will make it past the laboratory stage. With regard to both mature and less mature technologies, emphasis was laid on the possibility of surprises (such as technological and material developments) which could completely change the picture, and improve prospects for certain technologies.

The biggest changes in gaseous storage and delivery might come in the delivery pressure. Infrastructure providers who currently deal with hydrogen are used to storing and delivering it at a pressure of 200 bar. Vehicle manufacturers are likely to design storage tanks for higher pressure gas, potentially up to 700 bar, in order to increase the driving range of the vehicle. A higher delivered pressure of hydrogen would result in greater costs for infrastructure providers, therefore some kind of compromise would be likely to be found.

Hydrogen pipeline costs are currently uncertain. They are expected to be higher than gas, but economies of scale and learning by doing could eventually make the cost difference very small. The location of the infrastructure is an important consideration, given the impact which topography has on the cost. This emphasises the importance of a geographically sensitive approach to considering hydrogen infrastructure costs.

2.2.2 Integrated view

The infrastructure paper presented comparisons of a range of different storage and transportation methods. A major piece of feedback on this process was that costs at any part of the process of production, transportation and storage, should be considered in relation to the rest of the chain. For example, the cost of compressing hydrogen for distribution depends on the starting pressure, or the pressure at which the hydrogen is

produced. The costs of liquefaction for distribution will be viewed differently depending on whether the end use technology requires hydrogen in liquid or gaseous form. The liquefaction process also removes some impurities, which may be considered a factored in cost- depending on how crucial the purity of hydrogen is for its end use applications.

Given the interactions between the various components of the system, a technological or other breakthrough in one area could radically alter the picture, not just in terms of overall viability, but also production-to-end use route choices and specific system dynamics. For example breakthroughs in compressed gas storage might render developments in solid state storage unnecessary; or a reduction in the cost of liquefaction could encourage the development of vehicles utilising on board liquid storage.

2.2.3 Regional perspective

Regional incremental developments based around public transport infrastructures were seen as the most viable routes for early stage H₂ infrastructure development. This allows the infrastructure provider to supply to a demand that is predictable and guaranteed. Buses, with their relatively fixed drive cycles, are ideal applications from the infrastructure provider point of view. If asked to consider how an infrastructure for private light duty vehicles might develop, most participants imagined an incremental development of filling stations spun out from the infrastructure provided for buses, allowing the infrastructure provider to remain as close as possible to 100% utilisation at all times, which was considered an important factor in reducing the costs of investment. On the vehicle manufacturing side, by contrast, incremental infrastructure development poses a problem to companies set up only for large scale manufacture- their ideal production levels would far overshoot what could be supported by the initial infrastructure. Under the incremental scenario, therefore, small specialist companies, accustomed to low production levels would be the most likely to provide the first private light duty vehicles (LDVs).

The location, quantity and, crucially, *predictability* of demand has a big impact on infrastructure of choice- liquid and tube truck options are relatively small incremental investments, and flexible in responding to changes in demand. Pipelines are inherently less flexible, but for large volumes of demand can be the most economic option. Therefore, what is most economical is almost certain to change as the infrastructure develops. It was therefore proposed that early stage incremental infrastructure could be designed to be modular and moveable, so that it could be easily expanded, replaced or relocated as demand profiles change.

Much of the requirements for hydrogen infrastructure will be related to the kinds of hydrogen vehicles that are being marketed, and consumers' perceptions of what they should be used for. For example, if hydrogen vehicles are supposed to support long distance travel, the infrastructure needs will be different to vehicles designed to operate within a city. Infrastructure needs could be further simplified if it was considered that the vehicle would only be used for a limited number of specific journeys. For example, commuting vehicles could be serviced by refuelling facilities situated at workplaces.

It was also observed that the increasing use of ‘smart’ technologies such as satellite navigation could alter consumers’ perceptions of how much infrastructure is required.

2.3 FCVs

This workshop discussed the outputs of two papers: Hawkins and Hughes (2006), a literature review-based technological characterisation of fuel cell vehicles; and Agnolucci (2006d), an economic analysis of the market prospects for fuel cell vehicles.

2.3.1 Performance and costs, current and projected

Following a ‘no-go’ decision on on-board reforming by the US DoE in 2005, research and development in automotive fuel cells is now almost entirely focussed on PEM cells fuelled by pure hydrogen.

The US DOE has set commercialisation targets for FCVs for the year 2015, and most of the large manufacturers have responded by predicting commercialisation by this year. Despite the lack of clarity regarding how realistic these promises are, (and the arguably strong reasons to be sceptical about them), an interesting output of the FCV workshop was that participants agreed that it would be possible, at least in theory, to bring performance and cost to the required levels to achieve at least low volume commercialisation within the next decade. Whether this in fact happens, or gets close to happening, is highly dependant on the extent of investment from large manufacturers, which will both influence and be influenced by the extent of market pull and the strength of policy incentives that are put in place. The reciprocity of this relationship will be discussed in greater detail below.

There are key uncertainties relating to how FCVs will commercialise in the future, and current cost projections may be misleading. For example, the TIAX (2005) study forecasts the cost of fuel cell stacks based on the current construction of stack architectures, but at the so far unattained production level of 500,000. However, if stacks were produced on such a scale, the stack architecture would have to be completely overhauled to facilitate the process. Therefore conclusions which can be drawn from studies such as this were felt to be minimal.

Significant cost reduction may come about through increased integration of cells, reducing the number of component parts, and facilitating mass production. The cost of the balance of plant (BOP) could be significantly reduced, particularly if manufacturers have sufficient incentive, due to increasing certainty of demand, to design parts specifically for fuel cells, rather than using designs ‘borrowed’ from other technologies. Standardisation is an important process for cost reduction in general- currently components must be designed to be compatible with a wide range of systems, making them more expensive. Incremental improvements in cost and performance can be expected, but there is also a possibility of step change improvements, for example if cheaper materials can be developed and used.

The extent of any such improvements is strongly dependent on the attitudes of car companies to investing in the necessary research and development.

2.3.2 Niche transport applications

The role of the niche application in this process is crucial, as it gives a technology a chance to establish itself in order to begin to make progress down the learning curve. There are numerous possibilities for niche applications within the vehicle sector. Although the debate around the viability of fuel cell vehicles frequently focuses on how close they are to meeting the equivalent performance standards of mainstream vehicles (such as driving range), workshop participants observed that manufacturers are increasingly designing to specific niche requirements. This allows performance in certain areas (for example, storage) to be 'frozen', in order to maximise performance in the areas most crucial to the specific application. One such example is in warehouse applications such as forklift trucks, where requirements such as durability over rough ground can be less stringent, but where attributes such as low emissions, longer running time and fast refuelling are particularly prized. Due to these specific conditions, fuel cells already appear to be commercially viable in forklift truck applications. Another niche application suggested in the workshop was for boats, in particular recreational tourist boats such as London's 'Thames Clippers' - conventionally these vessels are highly polluting, but their highly predictable drive cycles would generate a relatively unfluctuating demand for fuel. Moreover, due to the onboard space, weight and volume of hydrogen storage would be much less of an issue than for cars. Currently there is comparatively little activity on hydrogen / fuel cell powered boats from manufacturers, although indications are that it may be a growing area.

Such applications may produce useful market entry points for fuel cell technologies - however, if successful, penetration into wider markets could still remain challenging.

2.3.2 Larger markets

Private urban commuting vehicles

Given that large manufacturers are simply not set up to manufacture in anything other than large volumes, they are unlikely to find ways of producing low volumes of specialist products, which would be crucial in an early stage of development with low demand. Therefore it is the smaller, specialist companies, which have a different attitude to risk and are more able to manufacture at low volumes, which seemed to be the most likely candidates to produce early market entrants.

It was proposed that the earliest private fuel cell vehicles to come to market would be mopeds. A key market to focus on would be style conscious urban commuters, and early fuel cell models would be marketed as 'lifestyle choices', avoiding direct price comparisons with existing models. The strategy likely to be most successful would be to concentrate on rolling out the vehicles in a few very tightly defined geographical areas, such as capital cities. This was the strategy for the SMART car, and would complement well the incremental regional focussed infrastructure strategy described above. There was

some optimism for the prospects of a fuel cell vehicle on the grounds that the motivations behind car purchasing decisions are not entirely logical in a strictly functional sense. Presentational, aesthetic and image related aspects are as much part of the decision to buy a car as its price and basic functionality. By appealing along such lines it was felt FCVs should attempt to establish their own niches, avoiding price comparisons with conventional models. Workshop participants observed that such factors could be a major influence on consumers, but did not raise the issue of environmental motivation as a potentially strong driving force behind purchasing decisions.

Buses

Because of the serious risk in making large investments in infrastructure before a definite demand is established, from the infrastructure provider point of view, buses and public transport projects are considered highly favourable for early hydrogen developments, as they can potentially provide a guaranteed and steady demand for hydrogen. However, the interest of vehicle manufacturers in providing the buses is difficult to gauge. The EU CUTE project has on the whole reported successful performance of its buses in the various cities involved. However, according to workshop participants, the London hydrogen project has so far found it difficult to generate interest from manufacturers in providing the 10 buses needed by 2010. This may be due to technical reasons- it was proposed that there are currently still problems building a reliable single 200kW stack. Consequently buses tend to use multiple stacks which cannot benefit so easily from simplification of BOP as it would apply to a single stack. It was also suggested that for most automotive companies, the production volumes for buses would not justify the investment. Although more specialist HDV companies might be more suited to this market, participants observed that the HDV industry is 'boom and bust' in nature, meaning that companies either don't have the money or the time to invest in fairly long term projects, particularly where there is some uncertainty. Related to this, despite the strength of the mayor's 2010 commitment, it is possible that the industry is still sceptical that this commitment will be secure in the long term. This is an issue which government, both local and national, should attempt to address, through developing clearer and long term policy signals relating to the role of transport in tackling climate change.

Fleet vehicles

Companies which operate fleets of vehicles are more sensitive to the impact of operational costs than the average consumer. Consequently, incentives impacting on running costs, such as exemptions from congestion charges and fuel tax breaks may be considered as being more effectively aimed at vehicle fleets than individual consumers.

For individual consumers however, up front investments are much more apparent when making purchasing decisions than long term running costs. In either case, if policy and fiscal incentives such as duty rebates on certain fuels, or on vehicles, were to have a strong effect, it would be important that they should be seen as permanent enough to generate consumer and manufacturer confidence.

Transition technologies

The role of transition technologies was discussed at the workshop. Hydrogen ICEs, or vehicles running on alternative gas fuels such as compressed or liquid natural gas (CNG or LNG) or hythane (a hydrogen / natural gas mix) may be seen to offer an acceptable transitional route to penetration of hydrogen / fuel cell vehicles, for example through facilitating the incremental development of hydrogen infrastructure, or through encouraging consumer familiarity with gaseous fuels. However, concerns were raised at the workshop that technological lock-in to these technologies could occur before the transition to more environmentally benign technologies occurs. From a policy point of view, the benefits of encouraging early introduction of transition technologies should be carefully weighed up against a later deployment of more advanced technologies.

However, it was also stated that in general, precedents for alternative fuels and alternative fuelled vehicles are not strong. Despite favourable duty and running costs of LNG and CNG, uptake has been extremely slow.

Other cleaner vehicle technologies may not be considered as transition technologies, as they lead in a different direction to hydrogen. Biofuels, and continuing incremental improvements in the efficiency of gasoline vehicles including hybrid electric technology, might delay and even avoid totally FC development, particularly as they may be seen to offer nearer term more cost effective emissions savings on a CO₂/£ basis. There is some conflict here between a long term and short term planning approach, between greater rewards now or in the future.

3. Key system issues and concepts

3.1 Niches and technology transfer

The concept of market niches has been identified by various authors as being central to theories of technological transition (see for example Geels, 2002; Hoogma et al, 2002; Eames and McDowall, 2006). In theory niches allow the protected development of technologies, which can then spill out into other market spaces. The role of niches also emerged strongly within workshop discussions as being important to hydrogen / fuel cell technology development, as there are particular applications where certain operational characteristics of hydrogen / fuel cell technologies may be highly valued by certain users.

Clearly to have success with a niche marketing strategy it is important to address the product to a very specific section of the market. There is also potential for effectively *creating new niches* by selling fuel cell products into specifically targeted markets appealing to the preferences of a particular kind of consumer, which current incumbents may not target, thus avoiding competition and therefore price comparison altogether. For example, pioneering FCV companies are likely to market their vehicles as alternative 'lifestyle choices', rather than aiming to make them indistinguishable from the standard incumbent ICE vehicles.

The theory of technological transfer suggests that niches give technologies a protected market space in which their overall performance can be improved, and crucially, their cost can be brought down due to increasing production. If this happens, there is a much greater opportunity for the technology to transfer to applications in wider, mainstream markets.

The extent to which this technology transfer can occur with fuel cells was an important area of discussion in the workshops. A major conclusion was that due to the variety of fuel cell technologies being used, and the different applications for which they are being designed, there are ever more increasing divergences in the technological parameters of each kind of appliance. This divergence means that the potential for technology transfer between fuel cell niches within the various sectors is highly restricted. As has been observed, for example, niches developed within the portable power market are unlikely to yield significant benefits to the development of fuel cells in automotive markets, as the types of fuel cells as well as the fuels used in each market are now almost always different.

Within a particular market sector however, the links between niches, and thus the potential for technology transfer, are clearly much stronger. The efficiency, silent operation and low pollution levels of portable fuel cells mean that certain niche users may prefer them to conventional technologies despite high cost. A significant cost reduction, and some key performance improvements, such as weight and volume reduction, would allow them to penetrate in wider markets.

On the other hand, efficiency and low pollution levels may be particularly attractive in certain niche transport applications, for which users may pay higher premiums. Key performance improvements such as vehicle range, stack durability and cost reduction, possibly assisted by policy incentives, could see the technologies appeal to consumers in a wider range of applications within the automotive sector.

It was observed in the workshops that standardisation will be a key factor in bringing down the costs of technologies. It is also likely that increased standardisation will aid technology transfer, as it will imply technologies with high performance in enough key areas (ie weight and volume of hydrogen storage, power, transient response, durability, etc) to meet the needs of a variety of applications.

From the perspective of consumer demand, in order for a niche technology to spill over to wider markets, there has to be a latent potential demand for that application within a broader group of consumers, which is ready to be realised as soon as the cost falls enough. An example of this brought up within the workshops was the latent consumer demand for increased portable power. Similarly, the need for urban commuting transport is a significant area of potential consumer demand, which could be realised beyond an initial niche market if the cost of the technology became viable.

3.2 Integrated nature of system

As has been described under the infrastructure discussion, a functioning hydrogen / fuel cell system would operate with a high degree of integration, with each stage in the chain highly responsive to developments and technological shifts taking place at other stages. As has been described, technical demands of end use technologies relating to the physical state and pressure at which hydrogen is required, affect the comparative economics of the various production and distribution routes. Because of these whole chain linkages, technical improvements which see a particular technology come to dominate at one stage in the chain, greatly affect which technologies remain viable at other stages. The integrated nature of the system must be kept strongly in mind when designing policies to encourage implementation- incentives for certain technologies must be backed up with incentives likely to support the appropriate chain. Policy makers should also be aware of the potential for success or failure in any of the technologies, and how this could alter the viability of other components in the chain.

3.3 Circular demand / supply, cause and effect

The time frame for commercialisation of the various applications of fuel cell technologies was deemed to be uncertain, and dependent to some extent upon the attitudes of the manufacturing companies. In portable, APU and FCV markets the time frame of commercialisation is not critical to large companies which have a large portfolio of projects. Many of these companies have fuel cell prototypes, but the extent to which they will push to be the first to bring these to market is far from clear. It is likely to be the smaller companies which are specialising more and thus have a different approach to risk, which would be the first to bring the technology to the market.

When and whether large scale production will come about is an area of great uncertainty, but the workshops identified three key driving forces in this process: demand, investment and innovation, which impact upon each other in an ongoing circular fashion, as represented in Figure 1. This circularity is rooted in the premise that the positive effect of a learning curve is dependent on the number of units sold- however if increasing numbers of units cannot be sold due to a high cost and lack of demand, progress down the learning curve will not be made. Conversely, if the price becomes acceptable to a significant number of consumers, the increased demand will stimulate increased production volumes, and progress down the curve will be much faster. Government policy can have a role in directing taxes and incentives to render technologies financially attractive to the consumer, despite high manufacturing cost. This, for example, may help FCVs to broaden their initial niche market- where their high price might have limited their appeal to a narrow niche, incentives could widen their appeal to a wide enough consumer base to generate real economies of scale, which would in turn generate greater manufacturer confidence, investment, and increasing economies of scale, producing lower cost and in turn, greater demand.

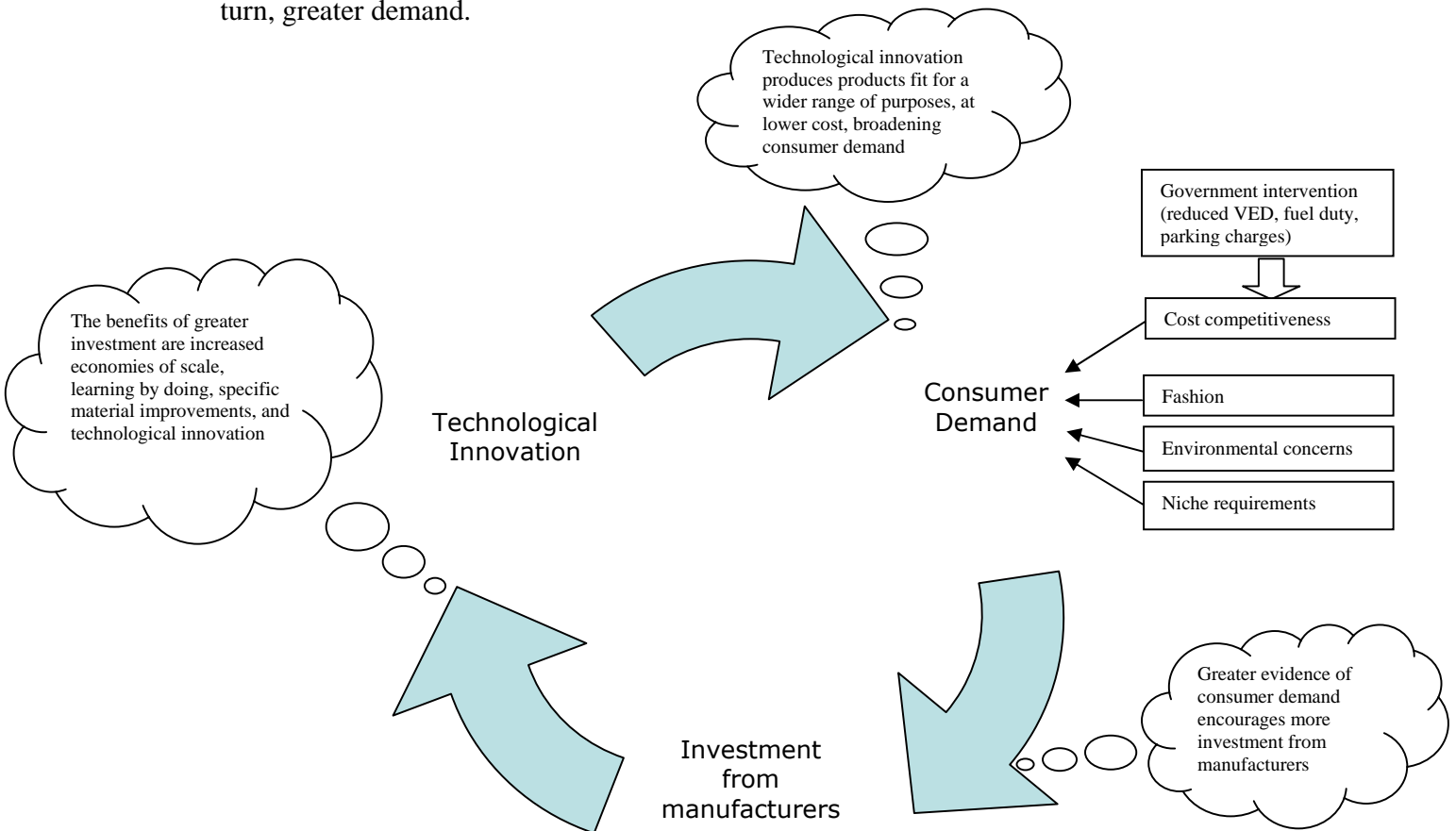


Figure 1: The Circle of Demand, Investment and Innovation

3.4 Uncertainties inherent in considering technological transitions

A major conclusion from the workshops was that this three stage process admits considerable elements of uncertainty at all stages. There is significant uncertainty surrounding the extent of consumer demand for hydrogen / fuel cell products, and the different fuel cell technologies elicited contrasting views on the sensitivity of consumer demand to price in respect of them. Some participants in the APU and portables workshop expressed views that users would be motivated to buy such products purely based on their performance in certain applications against incumbent technologies, rather than by any fascination with owning a new technology for its own sake- moreover it was generally felt that such technological fetishism need not be relied upon, as the technologies have the potential to better incumbents in these specific applications. In the case of vehicles however, it became harder to imagine how the private benefits, in purely functional terms, of a fuel cell vehicle could outweigh the performance of petrol ICEs. Thus participants in this workshop were more inclined to discuss the benefits of fuel cells in terms of less 'logical' consumer motives, such as fashion and an attraction to new technologies for their own sake (although workshop participants did not raise environmental concern as being likely to be a major motivating factor for the individual consumer). Participants in this workshop in particular emphasised that much of the decision making behind car purchases is not strictly logical in a functional sense. Factors such as presentation, image associations, and aesthetics can play a much larger role in car buying decisions than what the consumer actually needs. Fuel cell vehicles could be potentially be made to have increased private benefits compared to conventional ICEs, through policy engineering designed to stack the economics in their favour, such as congestion charging, parking charges and road pricing that are weighted in favour of low polluting vehicles.

As has been described, increased investment will be a big influencing factor on technological change. However, there is also some uncertainty as to where and how quickly technological change could happen. Workshop participants stressed that most of the technologies concerned are not 'mature', and expressed confidence that some 'step change' improvements in technologies could be brought about with significant investment. A key technological change could dramatically alter the viability of a particular technology- however, precisely where such step changes could occur remained an area of uncertainty in the workshops.

4. Policy making

Within the APU and portable workshop the role of government policies was not greatly stressed- rather the emphasis was placed on the degree to which the private benefits of the technology could bring about market penetration unaided. The FCV workshop however focussed much more strongly on the role of government in incentivising change, with participants commenting that a ‘step change in incentives’ was required. Therefore the policy incentives discussed in the workshops, listed here, relate predominantly to vehicle applications.

There are different policy options available, which could have different impacts in terms of the kinds of technologies and applications which are incentivised, leading in turn potentially to different routes of technology development. The effect of policies should be considered in this forward looking manner, as different kinds of policy directions could lead to quite different outcomes.

4.1 Heavy duty vehicles- Public Procurement

Several participants emphasised that a crucial first step for fuel cell vehicles will be the build up of public vehicles within regional spaces, particularly cities, as such a strategy would improve infrastructure logistics and demand risk management. This implies a potentially strong role for local authorities which exert some influence on the local public transport system. London, which is something of an unusual case in that the mayor’s office has a particularly significant role in procuring public transport vehicles through Transport for London, was seen to be a leader in this regard, in the UK.

Workshop discussions reiterated the importance of a strong long term signal to the success of procurement activities. Manufacturers require a certain level of confidence that the demand for the technology is in place for the long term, before investing in developing it. The GLA has publicised a commitment to 70 hydrogen vehicles on London’s roads by 2010, however this alone does not yet appear to have stimulated a significant increase in activity from manufacturers.

4.2 Incentives for light duty vehicles

Another, slightly different emphasis to early stage deployment, though not necessarily incompatible with a public transport focus, is to focus on incentives that may encourage purchase of passenger vehicles. The point was strongly made in the FCV workshop that the first small scale vehicles would be low range urban commuting vehicles. It is therefore worth considering how policies might offer incentives to the individual consumer for the use of such vehicles within, and on journeys to and from urban centres.

Exemption from Low Emission Zone charges could be an important instrument, particularly as such schemes usually focus on urban areas, and would thus coincide with the most promising early market for fuel cell vehicles. The workshop also raised road

pricing schemes, and a more radical approach of restricting access to certain roads for high emission vehicles, combined with the ability to trade emissions in order to gain access.

It was also mentioned that the objectives of the various policies should be clarified in order not to conflict with one another- for example there seems to be some confusion as to whether the priority of the London congestion charge should be local emissions, carbon emissions, or traffic congestion. This has significant implications for hydrogen, as shall be discussed below. The workshop suggested that the various schemes should be linked up into an 'intelligent system' making use of telemetric technologies, and a trading system.

Another type of business incentive mentioned in the workshops was the possibility of using planning laws as an instrument to increase the attractiveness of low carbon vehicles. For example, when companies apply for permission to build new premises, they could be allocated additional parking spaces for low carbon vehicles only.

The prospect of reduced running costs, which may be the combined effect of the kinds of measures described, may make hydrogen vehicles more attractive to companies operating fleets of vehicles within urban areas. Fleet owners tend to have a longer term view of costs, and may be attracted by reductions in running costs despite higher capital costs.

For individual consumers however, the impact of capital cost tends to appear far more significant than operational costs, which are seldom considered by consumers in as much detail. Therefore, the operational benefits would have to be fairly clear cut to encourage general consumers to purchase the vehicles. However, the workshop described mechanisms such as purchase grants as being more likely to be seen used in the US. Such policies, which are aimed directly at reducing the burden of capital investment for the individual consumer may have a greater impact on incentivising the purchase of fuel cell vehicles by individual consumers.

4.3 Supply side investment incentives

As well as providing incentives on the demand side, incentives for the companies which are likely to produce hydrogen / fuel cell technologies might facilitate greater investment in the technologies. Workshop discussions consistently emphasised the important role of small and medium scale enterprises in early stage technology development, as the large scale companies are not set up to manufacture at the low production levels that would be required at the early stages. Consequently, it might be inferred that any business and investment incentives which are developed with a view to incentivising hydrogen / fuel cell development, should be constructed to be favourable to small and medium scale enterprises. Larger companies would be more likely to join at the later stages, when production numbers justified their investment.

4.4 Extent of government intervention to ensure key policy objectives are met

It was observed in the workshops that even assuming a hydrogen supply chain could be generated in something close to market conditions, the market might not choose the supply chain which most closely met key policy objectives, such as diversity of supply and carbon reduction. Therefore, increased use of hydrogen that met both of these key objectives may require some significant policy intervention.

All measures are likely to be technology blind- however, due to the significantly higher cost of hydrogen / fuel cell technologies compared to other potentially low carbon but nearer term options, such as hybrids and electric vehicles, if measures were really to incentivise hydrogen technologies they would have to be weighted to give increased incentives to very low carbon options. It was observed in the workshops that policy makers may be tempted to favour measures which give equal incentives to near term incrementally improved technologies, which would provide more immediate benefits in terms of CO₂ reduction / £. However, such policies might not allow the development of potentially more radical technologies, which could lead to a less than optimal solution in the long term.

Moreover, the variety of hydrogen WTW chains available introduces a complexity into the coordination of low carbon technology policies. For example, dispensation could be made within a low emission charging zone for the exemption of hydrogen powered vehicles. Whilst the impact of this measure would be unequivocal in terms of local pollution, depending on the production route of the hydrogen powering the vehicles, the overall effect on carbon emissions could be a negligible reduction, or even a net increase.

In summary, a major output of the workshops was that policies need to be carefully coordinated to avoid giving out mixed messages. This involves coordinating the various incentives and penalties that could potentially be imposed on individual consumers, and rationalising the various aims towards which such measures could be directed. These measures should also be considered in the light of other signals sent out to the manufacturing industry, both to companies who might be able to provide public transport vehicles and infrastructure, who require the confidence of long term signals of procurement intentions, and to the small scale companies who could potentially provide the first private vehicles, for whom favourable business conditions and the incentivisation of the potential consumer market will be important.

5. Conclusions

Bringing key issues from all the workshops together, the following aspects emerge as being pertinent to all of them, and identify key linkages between all areas.

5.1 Regional-specific rather than generalised approach to the ‘Hydrogen Economy’

Various outputs of these workshops suggest that considering the hydrogen economy as a transition that will happen to a large area or to ‘society in general’ is far less meaningful than considering it as something that will take place in specific applications, at specific locations or within specific regions. Briefly, these outputs are as follows:

- **Technology:** The first market entrants would be manufactured at low production volumes, by small innovative companies and to limited market segments
- **Infrastructure logistics:** An incremental approach, initially on a region by region basis, was identified as the only feasible approach to infrastructure build up
- **Infrastructure costs:** It is problematic to compare costs and performance levels of storage and distribution technologies without the context of the production method and end use technology. This requires an understanding of where and for what purpose the hydrogen is being produced

As McDowall and Eames (2006) have noted, ‘there is no single, shared vision of a ‘sustainable hydrogen economy’’. Studying the feasibility of hydrogen economies in specific regions would help to avoid the uncertainties implied by this conclusion. It could lend greater clarity to issues of public acceptability, which is highly inter-related with regional values and identities. It would also deliver a far greater degree of rigour to discussions about the feasibility of future hydrogen economies, which, as was observed in one of the workshops, can be somewhat sabotaged by proponents of opposing view points choosing the most extreme illustrative examples.

5.2 Policy making under Uncertainty

Coping with uncertainty when scoping hydrogen / fuel cell futures emerged as a significant issue within all workshops. This was commonly identified at the technology development level, where participants stressed the possibility of major improvements in areas of performance hitherto undiscovered. However, discussions frequently related such improvements as affecting and being affected by the extent of consumer demand, as depicted in Figure 1. In this context uncertainty was frequently characterised in ‘all or nothing’ terms, where if the technology reaches the necessary level, its growth will be huge, while if it doesn’t reach this ‘critical mass’, penetration will be negligible. The ranges of uncertainty are huge- they are far too significant to ignore, but at the same time the ranges are so great as to diminish the meaningfulness of sensitivity analysis.

As Figure 1 also shows, the workshops (and particularly the FCV workshop) observed that government policy incentives may be crucial in setting this cycle in motion, by

stacking the economics in favour of these new technologies in order to make them more desirable to consumers.

However, it might be observed that there is another key uncertainty here relating to how much intervention in these matters it will be possible for any government to make. Policies which incentivise some technologies usually have to penalise others, and the impact of socio-political and cultural factors on the strength of policies which are considered politically acceptable, should not be underestimated. As Anable et al (2006) observe, transport ‘appears to be the least acceptable area of policy for the public with respect to tackling climate change’ and ‘financial penalties are the least supported’ within this sector.

Within this context, the question again arises as to what degree of intervention will be tolerated by the political system, business interests and the public at large. The success of hydrogen and fuel cells, the extent and speed of their penetration, and their success, if they do penetrate, in meeting low carbon and supply diversity policy objectives, being heavily dependant on the extent of policy intervention, are therefore equally dependent on the acceptability of strong policy intervention to society in general. This is a key uncertainty which must be considered in planning for hydrogen / fuel cell transitions.

5.3 Policy coordination

The workshops offered several conclusions relating to policy implementation and coordination. A variety of policy instruments were discussed, but a key point was that the various measures should be coordinated to avoid giving conflicting signals both to consumers and potential manufacturers.

Given the relevance of a regional approach to hydrogen / fuel cell development, there should be coordination between policies which operate at the regional level and national level incentives. The most likely potential public benefits of hydrogen / fuel cells are decarbonisation and reduction of local pollution. The latter would be more likely to speak to a local agenda, however the former could be a crucial long term goal within the national context. The extent to which these different objectives should be prioritised or combined needs to be coordinated. Policies should also be sensitive to the integrated nature of hydrogen production, storage, distribution and end use systems, and view a potential system as an integrated whole.

Policies must also be constructed with long term future pathways in mind, and with some sensitivity to the key areas of uncertainty that were identified in the workshops. Some judgement must be exercised in the balancing up of the relative benefits of near term, low cost carbon reduction, against longer term, more expensive but potentially deeper cuts. Policy should attempt to account for the uncertainties related to technology development and the extent of public acceptance of measures designed to incentivise this development. The impact of policy decisions should be viewed in the context of long term development, with an understanding of the different kinds of technologies and infrastructures different policies might be tuned to promoting, what kinds of transitions

will be possible through these pathways, and what end goals might be achieved by each route.

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