THE PROSPECTS FOR A HYDROGEN ECONOMY

Note: This paper summarises the work carried out by the Policy Studies Institute (PSI) (much of it in collaboration with colleagues at the University of Salford, whose work is also substantially referenced), and its principal findings, as a result of PSI's membership of the UK Sustainable Hydrogen Energy Consortium (UKSHEC) over the four years 2003-2007.

This work produced numerous working papers (available at http://www.psi.org.uk/ukshec/publications.htm), and a number of journal papers, many of them referenced below, which between them range over a large proportion of the literature on hydrogen as an energy carrier that has been produced to date. This paper is intended to be a convenient entry point into this literature, as well as summarising PSI's contribution to it.

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1. INTRODUCTION

Common to all discussions and projections of ‘a hydrogen economy’ is the widespread use of hydrogen as an energy carrier. Beyond that the projections differ greatly.

The use of hydrogen as an energy carrier requires the development and use of a range of different technologies, some similar to and some quite different from those in common use in current energy systems. Section 2 very briefly introduces and very briefly describes these technologies. Section 3 then discusses some of the hydrogen futures that have been proposed, which envisage the use of different sets of hydrogen technologies, and most of which require that these technologies are considerably developed before the uses become competitive with alternative means of delivering the same energy service. Section 4 explores the economics of the different technologies for hydrogen production, distribution, storage and end-use, with an emphasis on cost but also discussing functionality. Section 5 uses these costs estimates to explore through the use of formal modelling techniques some of the future scenarios that were described in Section 3. Section 6 then relates the scenarios to the literature on technological transitions, considering the pathways by which the different hydrogen futures might come about. Section 7 discusses issues relating to the public acceptability of hydrogen as a major energy carrier, and Section 8 then explores the public policies that might be necessary to bring about the energy transitions described in Section 6, both in respect of public acceptability issues and to supplement the market forces which are unlikely to be sufficient by themselves to engender the widespread use of hydrogen in the foreseeable future. Section 9 concludes.

2. HYDROGEN TECHNOLOGIES

Padró & Putsche (1999) list and survey the economics of the technologies shown in Table 2.1, which include all the key technologies which might be included in a hydrogen economy. However, as the survey by McDowall & Eames (2006a) made clear, there is not a single hydrogen economy, but a range of views as to precisely what technologies, in different combinations, a hydrogen economy might include.

Hydrogen (H_2) is often cited as the most common element in nature, but such citations do not always say that it is also reactive and therefore in nature does not exist in elemental form, but needs to be produced from compounds that contain it. There are a range of means of hydrogen production (some of which are listed in Table 2.1). All have in common that they require energy to produce hydrogen. A key question for any production technology is whether the energy used in producing hydrogen might not be better used to satisfy the demand for energy services itself, and what the energy cost of producing hydrogen actually is for different technologies.

Where the hydrogen is produced by fossil fuels (either through steam methane reforming (SMR) or through electrolysis where fossil fuels are the source of the electricity), carbon capture and storage (CCS) is necessary for hydrogen to be considered a ‘low-carbon’ energy source.

Hydrogen Production	***Hydrogen Transport***	***Hydrogen Storage***	***Stationary Power***	***Transportation Applications***
Steam methane reforming (SMR) Non-catalytic partial oxidation Coal gasification Biomass gasification Biomass pyrolysis Electrolysis	Pipelines Truck transport Rail transport Ship transport	Compressed gas Liquefied gas Metal hydride Carbon-based Chemical hydrides	Proton exchange membrane fuel cells (PEMFC) Phosphoric acid fuel cells (PAFC) Solid oxide fuel cells (SOFC) Molten carbonate fuel cells (MCFC) Alkaline fuel cells (AFC) Gas turbine Stationary internal combustion engine	Hydrogen fuel cell vehicles Hydrogen internal combustion engines Hybrid vehicles Onboard storage Onboard reforming Refueling options

Table 2.1: Technologies Included in the Survey of Padró & Putsche 1999, p.1

Once produced hydrogen may need to be either stored or distributed or both. It may be stored or distributed as a gas or a liquid, or in the molecular structure of a variety of solid media. Means of distribution include pipelines (where it is a gas) and truck, rails and ship transport for hydrogen in all its forms.

Finally, hydrogen may be put to a range of final uses to satisfy the demand for energy services. Some of these involve hydrogen fuel cells (but note that not all fuel cells use hydrogen as their fuel), devices which convert hydrogen to electric power with high efficiency; some of them involve hydrogen being burned in turbines or internal combustion engines. A major category of end use is in vehicles, and one of the most active fields of research and development relates to fuel cell vehicles. Whilst in the past the development of vehicles capable of 'on-board' reforming of hydrogen from conventional fuels was seen as a possible way of avoiding the problems of developing hydrogen infrastructure for vehicles, this approach has in the last few years been largely abandoned by manufacturers due to significant technical challenges (Hughes, 2006). Thus, hydrogen will need to be stored onboard vehicles (either as a compressed gas, a liquid, or in a solid-state form) raising a number of specific technological problems relating to the performance of the vehicle concerned.

3. HYDROGEN FUTURES

Table 3.1 sets out the 'hydrogen futures' which were developed by McDowall and Eames on the basis of their review of the literature (McDowall & Eames 2006a) and an expert workshop (for further details of which see McDowall & Eames 2004).

UK Hydrogen Futures	**Brief description**
Transport only	
Central pipeline	Hydrogen has become the dominant transport fuel, and is produced centrally from a mixture of clean coal and fossil fuels (with C-sequestration), nuclear power, and large-scale renewables. Hydrogen is distributed as a gas by dedicated pipeline.
Forecourt reforming	Hydrogen produced locally from natural gas is the dominant road transport fuel. The existing natural gas network provides the delivery infrastructure, and hydrogen is generated on-site by steam methane

	reforming at the refuelling station.
Liquid hydrogen	Liquid hydrogen produced by nuclear power and large scale renewable installations has become the dominant transport fuel. There is an international market in liquid hydrogen. This is largely a scenario of substitution, with current energy and transport paradigms remaining unchanged.
Synthetic liquid fuels	Renewably produced hydrogen again provides the dominant transport fuel. In this case, however, it is ‘packaged’ in the form of a synthetic liquid hydrocarbon, such as methanol, to overcome the difficulties of hydrogen storage and distribution. The carbon for fuel synthesis comes from biomass and from the flue gases of carbon-intensive industries.
Transport and other energy services	
Ubiquitous hydrogen	Renewably produced Hydrogen is a major energy carrier for heat and power as well as the dominant transport fuel. A hydrogen pipeline grid serves most buildings. Many homes and businesses use fuel cell CHP systems running on hydrogen, and it is common to refuel your vehicle at home. Hydrogen is produced from a mix of larger centralised and smaller-scale distributed renewables and biomass.
Electricity store	Hydrogen, produced through onsite electrolysis, is the dominant road transport fuel, and also plays a vital role overcoming the intermittency problems of a renewables-based electricity system. Hydrogen production is flexible, and can respond to variable electricity supply conditions, easing load-balancing. Since hydrogen is produced onsite it requires no distribution infrastructure. Locally-stored hydrogen provides back-up power for domestic and commercial CHP units at times of peak electricity demand/limited supply.

Table 3.1: UK Hydrogen Futures
Source: Eames & McDowall 2005, p.1

Eames and McDowall subsequently compressed their six futures into four ‘transition scenarios’, which describe both an end point vision and a description of how such an end point might feasibly be evolved to from the present day, drawing on insights from the transition theory literature (see Eames & McDowall 2006). This is discussed further in Section 6 of this paper.

Most elements of the original 6 ‘visions’ or futures have been integrated into the 4 transition scenarios. *Synthetic liquid fuels* and *Electricity store* are much as described in Table 3.1. So is *Ubiquitous hydrogen*, but the Forecourt Reforming future is folded within it as part of the transition to the end point. The Central Pipeline and Liquid Hydrogen futures are amalgamated into a *Central hydrogen for transport* scenario.

Table 3.2 lists the technologies, many of which are also listed in Table 2.1, which would be required for the four ‘transition scenarios’.

From these tables some broad conclusions can be drawn:

- For hydrogen to be ‘low-carbon’ it must be produced from renewable energy sources (electrolysis, biomass gasification/fermentation), nuclear power (electrolysis, thermal, thermo-chemical) or fossil fuels with CCS (SMR, gasification, electrolysis). Where local (‘on-site’) hydrogen production is envisaged, CCS is infeasible. Local SMR is therefore, at best, a transitional technology if hydrogen is intended to contribute to a ‘low-carbon’ economy.

- Most envisaged transport applications depend on fuel cell technology, although the fuel in this case could be methanol rather than hydrogen.
- All transport applications require considerable technical advances with onboard storage before they are likely to become competitive with fossil fuel vehicles (which may be hybrid fossil fuel/electric), at least in mainstream applications.
- The different futures have very different implications for infrastructure, some requiring highly developed hydrogen distribution networks (pipelines, refueling stations), while others can use existing (gas, electricity, road) networks.

UK Hydrogen Future	***Hydrogen Production***	***Hydrogen Transport***	***Hydrogen Storage***	***Stationary Power***	***Transportation Applications***
Transport only					
Central hydrogen for transport	Large-scale electrolysis (inc. nuclear power, renewables, fossil fuels with CCS) Thermal or thermo-chemical production in high-temperature reactors (HTRs) Gasification (coal, waste, biomass, with CCS) SMR (with CCS) Pyrolysis	Pipelines and metering Liquefaction	Stationary bulk storage Chemical or solid-state onboard storage Handling Cryogenic technologies Liquid H_2 storage		Onboard storage (inc. liquid H_2) Hydrogen fuel cell (likely to be Proton Exchange Membrane) vehicles (HFCVs)
Synthetic liquid fuels	Synthetic liquid fuel synthesis, with CCS Renewables				Direct Methanol Fuel Cells (DMFCs)
Transport, other energy services					
Ubiquitous hydrogen	Large and small scale (central and local) production from a variety of sources, inc. small-scale SMR, gas separation/ gasification (coal, waste, biomass, with CCS) Renewables Pyrolysis	Pipelines and metering Liquefaction	Stationary bulk storage	Hydrogen CHP (probably PEM and Solid Oxide Fuel Cells) ‘Smart’ networks (electricity grid and metering)	Onboard storage HFCVs

Electricity store	Renewables for electricity Small-scale electrolysis		Small-scale stationary storage and handling	Hydrogen CHP (probably PEM and SOFC) ‘Smart’ networks (electricity grid and metering)	Onboard storage HFCVs

Table 3.2: Technologies required for different Hydrogen Futures

This listing of technologies permits the identification of the kinds of technological development that are likely to be required for the scenarios to become realistic.

Production

Only for *Electricity store* is small-scale electrolysis a necessary production technology, to allow local renewables to produce hydrogen with their electricity, rather than feed it into the grid. All the other scenarios depend on large-scale centralised production of hydrogen, from electrolysis, high-temperature reactors, SMR or gasification (with CCS where necessary). *Synthetic liquid fuels* then requires the hydrogen to be converted to methanol, but this technology is already well developed. A transitional technology for *Ubiquitous hydrogen* is small-scale SMR (for example, on filling station forecourts), while pipeline infrastructure is being developed.

Transmission and distribution (T&D) infrastructure

Pipelines and metering are necessary for both *Central hydrogen for transport* and *Ubiquitous hydrogen*. Liquid hydrogen technologies could also be applied to both. Neither of the other scenarios require hydrogen T&D infrastructure.

Storage

Only *Synthetic liquid fuels* does not require onboard hydrogen storage (this was the reason this scenario was developed). The other three scenarios also require stationary storage, *Electricity store* on a small scale, the other two on a large scale.

Applications

For transport applications, as already noted, only *Synthetic liquid fuels* does not require onboard storage. All the scenarios require fuel cells, DMFCs for *Synthetic liquid fuels*, and (probably) PEMFCs for the other three scenarios. For stationary power, *Electricity store* and *Ubiquitous hydrogen* require fuels cells for CHP, which could be PEMFCs for residential applications with low heat demand, or high temperature SOFCs for industrial applications. These two scenarios also require ‘smart’ networks for electricity and metering.

This technological characterisation enables the scenarios to be placed in a rough hierarchy in terms of the technologies that are required to make them operational.

- *Synthetic liquid fuels* is stand-alone and only requires the large-scale centralised production of hydrogen from any of the available technologies, plus the development and application of methanol technologies, including DMFCs.
- Large-scale centralised production technologies, plus the development of bulk storage technology and pipeline infrastructure (perhaps with local SMR as a transitional technology), and onboard storage and PEMFCs, would permit the *Central hydrogen for transport* scenario.
- Abundant local renewables plus small-scale electrolysis, plus onboard storage and PEMFCs, plus small-scale storage and SOFCs, would make the *Electricity store* scenario feasible.
- The *Ubiquitous hydrogen* scenario requires elements from all the other scenarios, and may perhaps best be described as *Central hydrogen for transport* plus the application technologies (small-scale storage and SOFCs) of *Electricity store*.

Such a description enables an exploration of the economic implications of these scenarios, based on an investigation of the economics of their necessary component technologies.

4. HYDROGEN ECONOMICS

4.1 Hydrogen Production

Only for *Electricity store* is small-scale electrolysis a necessary production technology, to allow local renewables to produce hydrogen with their electricity, rather than feed it into the grid. All the other scenarios depend on large-scale centralised production of hydrogen, from electrolysis, high-temperature reactors, SMR or gasification (with CCS where necessary). *Synthetic liquid fuels* then requires the hydrogen to be converted to methanol, but this technology is already well developed. A transitional technology for *Ubiquitous hydrogen* is small-scale SMR (for example, on filling station forecourts), while pipeline infrastructure is being developed.

Hawkins & Joffe (2005) have reviewed the literature on the costs of four major hydrogen production technologies, SMR (large and small scale), gasification, pyrolysis and electrolysis (large and small scale). Throughout their review they emphasise the uncertain and contingent nature of their results – the studies reviewed make a wide range of different assumptions about current technologies and how they might develop – but the range of costs they thereby derive is nonetheless instructive and give insights into the relative economics of four transition scenarios discussed in the previous section. Table 4.1 reproduces their range of costs with relevant comments.

Table 4.1: Costs for Various Hydrogen Production Technologies

Four scenarios:

Synthetic liquid fuels (SLF); Central hydrogen for transport (CHT); Ubiquitous hydrogen (UH); Electricity store (ES)

Technology	Transition Scenario	Cost range, US$(2000)/kg$H_2$	Comments
SMR, large scale (>100MW)	SLF, CHT, UH	5.25 – 7.26	Cost highly dependent on natural gas price
			Cost highly dependent on natural gas price
Coal gasification (min.376MW)	SLF, CHT, UH	5.4 – 6.8	Coal price more stable and predictable than natural gas
Biomass gasification (>10MW)	SLF, CHT, UH	7.54 – 32.61 (av. 14.31)	Size ranges from 25-303MW and affects cost
Biomass pyrolysis (>10MW)	SLF, CHT, UH	6.19 – 14.98	Size ranges from 36-150MW; cost reduced by sale of co-products
Electrolysis, large scale (>1MW)	SLF, CHT, UH	11 – 75 (20 – 60 is preferred range)	Size ranges from 2-376MW, but little effect on cost; cost very dependent on assumed price of electricity
Electrolysis, small scale (<1MW)	ES	28 – 133	Size ranges from 0.03-0.79MW, cost very size dependent

4.2 Hydrogen Storage

Hydrogen can be stored as a compressed gas, as a liquid, in a chemical compound, or physically held within structures such as metal hydrides or carbon nanofibres. A major element of the cost of most of these storage modes (and a major consideration in terms of their energy efficiency) is the energy required to get the hydrogen in and out of storage. Table 4.2 shows the cost of a number of means of storage, including liquefaction, gas compression above ground and underground, and chemical and metal hydrides.

In each case the cost of the storage method is dependent on the cost of the requisite energy to get the hydrogen into the required form for storage, as well as on the scale and throughput, and sometimes on the storage medium, that is envisaged. Table 4.2 shows that storage can add anything from \$0.1 to \$4.5/kg to the price of hydrogen depending on the storage means and assumptions about these associated variables.

Table 4.2: Costs for Various Hydrogen Storage Technologies

Four scenarios:
Synthetic liquid fuels (SLF); Central hydrogen for transport (CHT); Ubiquitous hydrogen (UH); Electricity store (ES)

Technology	Transition Scenario	Cost range, US$(2000)/kg H_2	Comments
Liquefaction (>45 kg/h)	CHT, UH	1-1.5	Cost highly dependent on scale, efficiency, cost of electricity

Compressed gas (<1 week)	CHT, UH, ES	0.15-0.6[1]	For stand-alone (i.e. not onboard) storage only. Strong economies of scale
Bulk underground	CHT, UH	0.12-0.3	Costs rise with increased storage time/reduced throughput
Chemical hydrides	CHT, UH, ES	1.5-2.5[2]	Large economies of scale, figures apply to 3.6kt-9mt H_2; onboard storage
Metal hydrides	CHT, UH, ES	0.4-4.5	For storage times of 1-14 days; onboard storage
Methanol[3]	SLF	Na	Cost not calculated; methanol can be produced from other sources than H_2

[1] One estimate is as high as $1.6/kg H_2

[2] Includes some energy and costs which could be regarded as H_2 production

[3] No included in source table, but elsewhere in source

Source: Hawkins 2006, Table 2.10, p.21

4.3 Hydrogen Transmission and Distribution (T&D)

In addition to being stored, with associated cost, hydrogen must often be transmitted or distributed to its place of use. Clearly the means of T&D will be closely related to the means of storage. Pipelines distribute compressed gas, and an extensive pipeline network will store a sizeable quantity of gas (the stored quantity can be increased by increasing the pipeline pressure). Road tankers may deliver compressed gas or liquid hydrogen.

Table 4.3 gives estimates of the cost of various hydrogen T&D technologies. It can be seen that these estimates, like those for different storage technologies, differ by an order of magnitude, ranging from $0.1 to $2, and that the key variables that affect cost are the quantities transported (there are strong economies of scale), and, as would be expected, the transport distance.

Table 4.3: Costs for Various Hydrogen T&D Technologies

Four scenarios:
Synthetic liquid fuels (SLF); Central hydrogen for transport (CHT); Ubiquitous hydrogen (UH); Electricity store (ES)

Technology	Transition Scenario	Cost range, US$(2000)/kg H_2	Comments
Pipeline (compressed gas)	CHT, UH	0.1-1	Cost decreases with size of pipeline (flow-rate) and increases with distance
Tube-trailer (compressed gas)	CHT, UH, ES	0.5-2.0	Cost increases more than linearly with distance
Liquid by road	CHT, UH	0.3-0.5	Includes cost of liquefaction; cost increases more than linearly with distance
Ship (liquid)	CHT, UH	1.8-2.0	Uncertain estimate because no

			ship for liquid H_2 yet built

Source: Hawkins 2006, Table 3.2, p.32

Figure 4.1 indicates the relative cost-effectiveness of the different transport options over different distances with different throughputs. Given the range of geographical and topographical factors which can affect the relative economics of different options in specific locations, the numbers on the axes should be taken as indicative rather than precise; nevertheless in general terms the comparison is instructive. At higher flow-rates and distances, pipelines are cheapest. At higher distances and lower flow-rates, liquid transport is cheapest, with tube trucks being the cheapest at low distances and flow-rates.

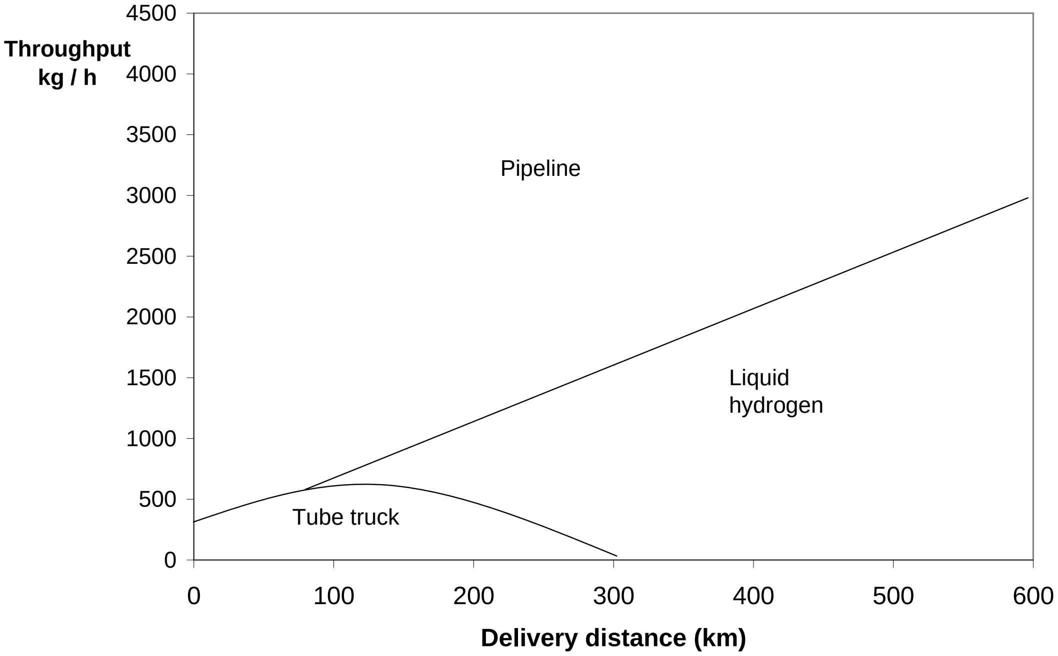

Figure 4.1: Least-cost Transport Options with Distance and Capacity
Source: Hawkins 2006, Figure 3.6, p.31

4.4 Hydrogen Infrastructure

Production and large-scale storage facilities, and T&D equipment, are all part of what is sometimes termed hydrogen ‘infrastructure’, and it can be seen that they can all be important components of the cost of delivering hydrogen to end-users. Another important component of such infrastructure is the network of re-fuelling stations that will be required if hydrogen is to be widely used as a motor fuel. This issue is reviewed in detail by Agnolucci (2007a).

The key issue in this regard is the chicken-and-egg problem that motorists are unlikely to buy hydrogen fuel cell vehicles (FCVs) until there is a well-developed network of filling stations, but energy companies will not provide filling stations until there is adequate demand for them from FCVs. The timing of the provision of this infrastructure could have a major influence on the cost of the delivered hydrogen – Agnolucci (2007a, p.25) reports that there is wide agreement in the literature that the extent of use of infrastructure, called the capacity factor, “is the single most important factor influencing the price of hydrogen”.

Agnolucci (2007a, p.10ff) has identified three approaches in the literature to tackle the issue of timing infrastructure provision.

Whole system incremental approach

This envisages that hydrogen will gradually spread through the economy through a number of different routes, perhaps starting with portable power applications and then moving to stationary distributed power, buses and government fleet vehicles, and only then starting to service commercial and luxury passenger vehicles, followed by ordinary passenger vehicles. At each stage an appropriately targeted infrastructure would be installed, with the gradual investment entailing a natural risk management strategy which keeps the capacity factor high and generates returns for investors prior to each new investment. In addition, provided that there were synergies between the various hydrogen applications, learning about one could spill over into cost-reductions for the next phase. This approach would be most relevant to the transition to the *Ubiquitous hydrogen* future.

However, few experts seem to share an opinion that use of hydrogen is likely to develop in this ‘whole system’. Rather the portable, stationary and automotive sectors are increasingly regarded as separate markets using different technologies (Hughes 2006).

Incremental approaches

This approach focuses only on the transport sector but again is incremental in nature, sequentially targeting different parts of the vehicle market in order to keep capacity factors on an investment relatively high, and generating a return, before moving on to the next stage. Typically it is envisaged that this approach would start with demonstration projects, then move on to providing hydrogen for vehicle fleets and then to different segments of the private passenger vehicle market. This approach would be most relevant for the *Central hydrogen for transport* and *Synthetic liquid fuels* transitions (in the latter the filling stations would be for methanol). Clearly, for this approach to work, FCVs would need to offer advantages for consumers in each phase of market development. While enthusiasts consider that FCVs offer advantages in relation to “environmental performance, quiet operation, rapid acceleration from a standstill, potentially low maintenance requirements and greater design flexibility”, and can generate electrical power for applications outside the vehicle, others question whether these benefits will be adequate to enable FCVs to expand their appeal beyond speciality markets (Agnolucci 2006, p.15).

Step-change approach

Of course, one way of resolving the chicken-and egg problem would be simply to provide large-scale infrastructure in advance of the wide use of FCVs, in the belief that this would follow (developments would be very unlikely to occur the other way round). There is some consensus in the literature that this would require the installation of around 10-15% of the current number of filling stations over around a five-year period (Agnolucci 2007a, pp.16-17), and there has been considerable analysis of the optimal design of a hydrogen re-fuelling infrastructure of this kind, which would be relevant to the transitions to both the *Central hydrogen for transport* and *Synthetic liquid fuels* futures.

The financial risk involved in a step-change approach is considerable – low capacity factors can entail a price of hydrogen of over \$20/kg H_2 for an extended period in order to recoup costs, even though the long-term cost of H_2 with deep market penetration and high capacity factors may be only around \$2.5/kg (Melaina 2003).

4.5 Hydrogen End-Use Applications

While it is possible to burn hydrogen directly as a fuel (as in an internal combustion engine as a direct replacement for gasoline), most projections of widespread future hydrogen use envisage its use in fuel cells. There are four main areas of such applications: auxiliary power units, portable fuel cells, stationary power, and FCVs.

Auxiliary power units (APUs)

APUs are devices for providing additional onboard power for vehicles. Agnolucci (2007b) has carried out a detailed assessment of the economic prospects for fuel cell APUs, which he considers likely to be either PEMFCs or SOFCs[1], across eight kinds of civil vehicle – transits, pick-ups, recreational, specialised utility, refrigeration, luxury passenger and law enforcement vehicles and heavy-duty trucks. Because vehicles in operation can provide significant power from the alternator, and because APUs seem to offer few additional benefits (and at present entail substantial extra cost) compared to this power source, the opportunity for APUs would seem to be restricted to those vehicles which require significant power when idling or stationary, or which have exceptional power demands during use. APUs are also known to be of interest in military applications (particularly because they are silent and evade infrared detection), but information about these is restricted. It should be borne in mind that widespread military deployment may lead to cost reductions and applications that spill over into the civil market, but these possibilities are not further discussed here.

The services provided by fuel cell (FC) APUs may be provided by diesel APUs (the only difference being that the latter are not silent) or, for trucks, by electrified truck-stops (which provide less flexibility for stopping, but a range of additional services which may be highly valued by drivers). Technologically, FC APUs will need to decrease in size if they are substantially to penetrate the market for smaller vehicles, and in cost if they are to compete with diesel APUs and electrified stops. However, a number of scenarios suggest that, with mass production, the cost of FC APUs could become competitive with these rivals. Certainly there is substantial private investment going into these devices, and at least one existing application in a luxury passenger vehicle, which suggests that some manufacturers at least believe them to have a commercial future.

Portable fuel cells

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[1] The workshop discussions reported by Hughes 2006 (p.6) considered DMFCs and SOFCs to be the likely fuel-cell types for APU applications

Portable fuel cell (FC) systems may be defined as those with a power of up to 5kW and a weight of less that 10kg, and may be divided into micro FCs, intended to replace batteries in portable electronic devices such as computers and mobile phones (DMFCs are currently receiving most interest for such uses), and portable generators (in which PEMFCs and DMFCs are competing), which provide power for camping and other recreational activities, in remote locations or for military purposes. Demand for portable FCs will therefore depend on the demand for the products containing them and on the competing technologies which can also provide the desired energy services. The desired energy services will be increased by the desire for increased functionality, but reduced by energy-saving innovations that allow this extra functionality to be delivered with lower energy use. FC portable generators have the advantage that they are silent, clean and more efficient than diesel generators (the incumbent technology); the only advantage of micro fuel cells over batteries is the potential to supply energy for longer continuous use between recharging.

Undoubtedly there are likely to be some suitable applications for micro FCs, where longer life or increased power are very much valued (e.g. surveillance systems or military applications). However, these are very small markets. For mass commodities, it is not clear that there is strong demand for power characteristics that batteries cannot, or will not be able to, satisfy. Certainly, to penetrate these markets significantly micro FCs will need to reduce their size and cost significantly – the latter by around 10% pa over a five-year period, according to one projection (Darnell 2003, cited in Agnolucci 2007c, p.14).

There are currently few micro FCs on the market; Agnolucci (2007c, pp.19, 21, 22) reports that a number of recent introductions were soon removed from the market, and Nokia has decided against an early introduction of FCs in its mobile phones. However, a number of other major manufacturers (e.g. Casio, Sanyo, Toshiba, NEC, Hitachi) remain active in developments in this area (although they are also developing competing technologies). Agnolucci’s (2007c, p.24) conclusion is that micro FCs are never likely completely to replace batteries, but may capture market-share for those users who value extra energy storage highly and are prepared for some extra cost, size and inconvenience to achieve it. The size of this market share will depend on the extent to which FC technology development is able to reduce the gaps in these characteristics between FCs and batteries.

With regard to portable generators, the potential market is much smaller than for micro fuel cells, and is likely to be concentrated at the lower end of the power range (25-200W). Some products have been available for some time “without generating much interest” (Agnolucci 2007c, p.18), and a market breakthrough would seem to require significant technical improvement (reduced size and weight) and cost reduction (comparable to micro FCs, i.e. 10% pa over five years).

For portable applications as a whole, the major competition is currently between PEMFCs and DMFCs. According to Jollie (2004, p.5) “the latter is winning, particularly in the high profile consumer electronics market”.

Stationary power

Fuel cells (FCs) generate power and heat, which opens up the possibility of them being used as sources of stationary power on a relatively small scale and, perhaps, of Combined Heat and Power (CHP), which would increase their energetic efficiency. High temperature FCs are capable of operating directly on hydrocarbon fuels as well as pure hydrogen, and therefore have greater potential for providing stationary heat and power from more readily available fuels. However, FCs which run on hydrogen require the hydrogen to be produced from other energy sources, as described above, and normally it will be preferable (in terms of both energy efficiency and cost) to use these other sources to generate electricity directly rather than via hydrogen production. It is for these reasons that a report by E4 Tech et al. (2004) largely rules out the use of FCs fuelled by pure hydrogen for stationary power production.

However, on the basis of their review of the literature, Hawkins et al. (2006) consider that FCs, including those fuelled by pure hydrogen, could find niche applications for stationary power, for example for back-up power for essential services, in remote off-grid situations or where there is surplus renewable energy to produce the hydrogen. They may also find application in small-scale or domestic CHP.

A range of different FCs could be used for stationary power, operating at either high (molten carbonate (MC) FCs and SOFCs) or low (PEMFCs, phosphoric acid (PA) FCs, and alkaline (A) FCs) temperatures, with the former able to generate power also from their waste heat, and the latter able to use their heat for space or water heating. Those operating at high temperature (MCFCs, SOFCs) can reform hydrogen from other fuels internally (but will then produce carbon dioxide emissions), while PEMFCs, at a lower temperature, require a source of pure hydrogen. At present, PAFCs are offered commercially at sizes of 20-200kW and MCFCs at sizes of 250kW and above. PEMFCs, with most prospects for technical development, are entering the market at 1-5kW and 75-250kW, and SOFCs are expected commercially at around 200kW. AFCs are only suitable for specialist applications (e.g. spacecraft) (Hawkins et al. 2006, p.4).

Fuel cells are currently three to five times as expensive as diesel and gas engines and gas turbines, indicating the kind of cost reductions that will be required for them to compete effectively with these other small-scale sources of power. However, they are the subject of substantial R&D expenditure from both private and public sources, so that some cost reduction may be confidently expected. How much is, of course, uncertain.

Fuel cell vehicles (FCVs)

FCVs are estimated to be 2-3 times more efficient than conventional gasoline vehicles, and 1.5-2 times more efficient than diesel-electric hybrids. If hydrogen is produced by SMR (without CCS) and transported by pipeline, this increased efficiency is estimated to yield a ‘well-to-wheels’ reduction in carbon dioxide emissions of 30-60% compared with conventional gasoline vehicles (although diesel electric hybrids have been estimated as able to deliver comparable savings) (Hawkins & Hughes 2006, p.20). All futures that involve the widespread use of hydrogen as an energy carrier envisage the mass diffusion of FCVs. The prospects for this technology are therefore critical to whether hydrogen will be widely used or not.

Unlike with the other applications of fuel cells reviewed above, PEMFCs are the clear leader in FC technology for FCVs, and the cost of FCs is the most important element in the overall cost of FCVs. Hyways (2006, cited in Hawkins & Hughes, 2006, p.5) give the current cost of the fuel cell system for a passenger car to be over €4,000/kW (with $50-60/kW required for a family-sized passenger car), while IEA (2005, cited in Hawkins & Hughes, 2006, p.8) puts the cost much lower, at US$1,826/kW. The US Department of Energy (DoE) perceives that, to be competitive with the internal combustion engine (ICE), the fuel cell system cost would have to be in the range $30-45/kW, so an enormous cost reduction is required. Most of this cost reduction is envisaged to be achieved through the economies of scale associated with mass production (of the order of 500,000 vehicles per year), and the DoE has a target to achieve the $30/kW cost by 2015. The review of studies by Hawkins & Hughes (2006, Table 1, p.7) suggests that the mass production of even current technology could achieve a cost of $28-181/kW. The IEA (2005) estimate with production of only 4,000 vehicles per year, but technical advance in respect of materials, power density and other technology, is $103/kW, possibly falling to $50/kW with even more technical progress. There is, therefore, still a very great deal of uncertainty as to how the required cost reduction for competitiveness with ICEs is to be achieved.

Of course the FC is only part of the costs of the FCV, which also requires an electrical drivetrain, control electronics and hydrogen storage, with, perhaps, a complete redesign of the vehicle itself. Each of these elements introduces new uncertainties into the cost projections. In the review of studies of vehicle costs (Hawkins & Hughes 2006, Table 4, p.13), one study from 2002 suggests that the cost of a hydrogen FCV in 2007 would be $36,500. The range of costs for 2015-2030 is $18-34,000. In some cases these are projected to be competitive, in others to cost 15-20% more than comparable ICE vehicles. These estimates are based on FC costs of $35-75/kW, and so clearly assume either mass production or substantial technical progress or both.

Perhaps the area in which technical progress is most required is hydrogen storage. Hawkins & Hughes (2006, p.14) write: “No current technologies are capable to meeting the storage requirements set by US DoE targets for satisfactory performance of hydrogen vehicles”. It should be acknowledged that these targets are designed to deliver performance levels of equivalence to a standard mainstream ‘family’ vehicle, while some FC industry stakeholders argue that roll out in carefully identified ‘niche’ markets could begin before such exacting standards are met (Hughes, 2006). Nevertheless, without such performance it is unlikely that any kind of mass penetration of vehicle markets by FCVs will be perceived possible, and without such perception no mass production of FCVs, required to bring down their cost, will take place. As Hawkins & Hughes (2006, p.15) report: “The reviewing committee of the FreedomCar programme reported hydrogen storage to be one of the ‘greater risks for reaching the programme goals in 2015’, stressing that the area needs a ‘breakthrough discovery as the forerunner of development and innovation.’ (NRC, 2005, p.68)”.

There is also the whole chicken-and-egg issue in respect of mass production and infrastructure, referred to above, the full dimensions of which are now apparent. It is clear that FCVs will never even approach cost-competitiveness with ICE vehicles without mass production (at least 500,000). However, it is not clear how they will achieve this level of sales until the cost (and therefore price) reductions of FCVs have taken place. Nor is it clear either that such sales will take place until the requisite infrastructure to service the vehicles is in place, or who will provide the finance for the huge investment in infrastructure that would be required. Possible policies and strategies that may resolve these difficult transition problems are discussed below.

The issue of transitions in respect of FCVs is made even more difficult because, unlike some other applications in which FCs offer extra performance qualities, which may command a premium price, as noted by Agnolucci (2006d), even the most optimistic advocates of FCVs do not suggest that they will do more than match ICE vehicles in mechanical performance (though FCVs may produce less vibrations and noise, and require less maintenance). Their prospective benefits nearly all involve public goods (fewer local emissions, potentially lower carbon emissions, reduced dependency on oil). One possible exception to this (perhaps of most interest to fleet owners with predictable travel demands) is that FCVs could be 'plugged into' the grid at times of peak power demand and premium-rate electricity costs, and earn thereby an income stream (although the economic attractiveness of this would be highly dependent on the cost of hydrogen). Another potential attraction for fleet owners might be the ability to swap fuel cell stacks in and out of vehicles, in order to perform maintenance on the stack whilst keeping the vehicle on the road.

Other driver concerns explored by Agnolucci (2006d) are infrastructure requirements (affecting the convenience and required time for re-fuelling), costs, safety and image. If infrastructure is to be provided incrementally, as seems likely (see below), then FCVs are likely to start in fleets (e.g. buses, delivery vehicles) which return to depots each night, and which can be re-fuelled there, or with company cars and urban vehicles, which have a known route or operate in a certain area where filling stations are available. Leaving aside the cost of the FCV itself, and potentially lower maintenance costs, cost benefits from their use, especially when oil-based motor fuels but not hydrogen are subject to taxation, may derive from their greater fuel efficiency. However, fuel efficiency does not seem to be a significant concern for drivers of ICE vehicles, and it is not clear why FCVs should be any different. It is possible that the image of a well-designed FCV in an environmentally aware, technologically conscious society could be attractive. Safety, however, is more a risk factor for FCVs to be managed by the industry than a perceived benefit.

Other possible applications for fuel cells in vehicles are in boats, trains and aeroplanes (Hawkins & Hughes 2006, pp.22-23), and they may spur the development of fuel cells, but they have received much less attention than FCVs for road transport.

Conclusions on Applications

A variety of different kinds of fuel cells are already commercially available in portable micro-electronic applications, as APUs and for stationary power. Whether they will become the dominant technology in any of these fields, and whether the FC concerned will use hydrogen or some other fuel, is still unclear. What is clear is that these applications in themselves offer few benefits beyond those to their private producers and users (though they may stimulate technological developments that have public benefits, such as FCVs). They are not likely to get significant support from public support from public policy and will need to succeed in market terms.

FCVs are different, and have significant potential public benefits, in terms of reduced local emissions, potentially reduced carbon emissions (depending on the mode of hydrogen production) and reduced dependence on oil for transportation. They are therefore the hydrogen application that generates easily the most public interest and support. However, the discussion above makes it clear that the private consumer advantages of FCVs compared to ICE vehicles seem thin, while the technical and economic challenges to be overcome for them to come anywhere near ICE vehicles in terms of cost and basic performance are very great. It is hard to avoid the implication that, if their development and deployment are to be as rapid and widespread as has been envisaged in some of the 'roadmaps' that have been produced (e.g. DoE 2002), then public policy will need to play a decisive and determined role over the long-term. Some of the possible aspects of that policy support are discussed below (see Section 9).

5. MODELLING THE HYDROGEN SCENARIOS

The development of the increased use of hydrogen in an energy system may be modelled in a number of different ways. Key issues to consider are the fact that:

- Primary fuels may be used to produce other energy carriers (e.g. electricity) as well as hydrogen, and these or electricity may be used to service energy demands directly – there is therefore competition for these other sources of energy, which should be taken into account by not losing sight of the whole energy system;
- The spatial dimension of, especially, hydrogen infrastructure development is important in respect of its costs;
- Hydrogen-related technologies are both complex and immature, and it is therefore desirable both to represent them in models in adequate detail and to capture the dynamics of their possible development.

Joffe & Strachan (2007, p.4) have categorised the way that different models deal with these issues in terms of optimisation vs. 'scenario-based' models (the former optimises against some variable, normally energy system cost, perhaps under some constraint, e.g. reduced carbon emissions, while the latter concentrates more on the pathway, or 'story-line' entailed in reaching certain outcomes); spatial vs. non-spatial models; and models which impose competition for primary energy sources exogenously, e.g. by setting prices, and those which seek to model it explicitly.

An optimisation model of the whole energy system (i.e. it models the competition for resources explicitly) that has been used on a number of occasions to model the development of hydrogen as an energy carrier is the MARKAL model. Joffe et al. (2007) describe its use, and the different ways the model approaches the issues above and others, in the UK, US and the Netherlands.

The UK model (described in Strachan et al. 2006) has been used to model as far as possible the four scenarios described in Section 3 (Table 3.2), using the data briefly reported in Section 4, which is set out in much more detail in the UKSHEC Working Papers which are referred to there. The most important task in modelling hydrogen as an energy carrier is to capture the roles in which hydrogen may be preferable to other energy carriers, on grounds of cost, environmental impact (local or global emissions), security of supply or technical performance. An example of the latter is hydrogen's potential role in energy storage – onboard vehicles, for portable or back-up power, or for surplus electricity, in preference to batteries – as discussed in more detail above.

Figure 5.1 gives a simplified schematic representation of the hydrogen module in the UK MARKAL module, indicating the technologies which are discussed in more detail in Section 4. Production options are represented at large and small scales, including electrolysis and SMR at both scales, and with and without CCS for the large-scale carbon-emitting production technologies. Transmission and distribution (T&D) means include central and local pipeline networks, compressed gas via tube trailers and liquid hydrogen using road transport. End-use technologies include stationary and vehicle applications (but not portable applications, many of which do not use hydrogen as a fuel and those that do are likely to remain relatively small scale compared with the other applications).

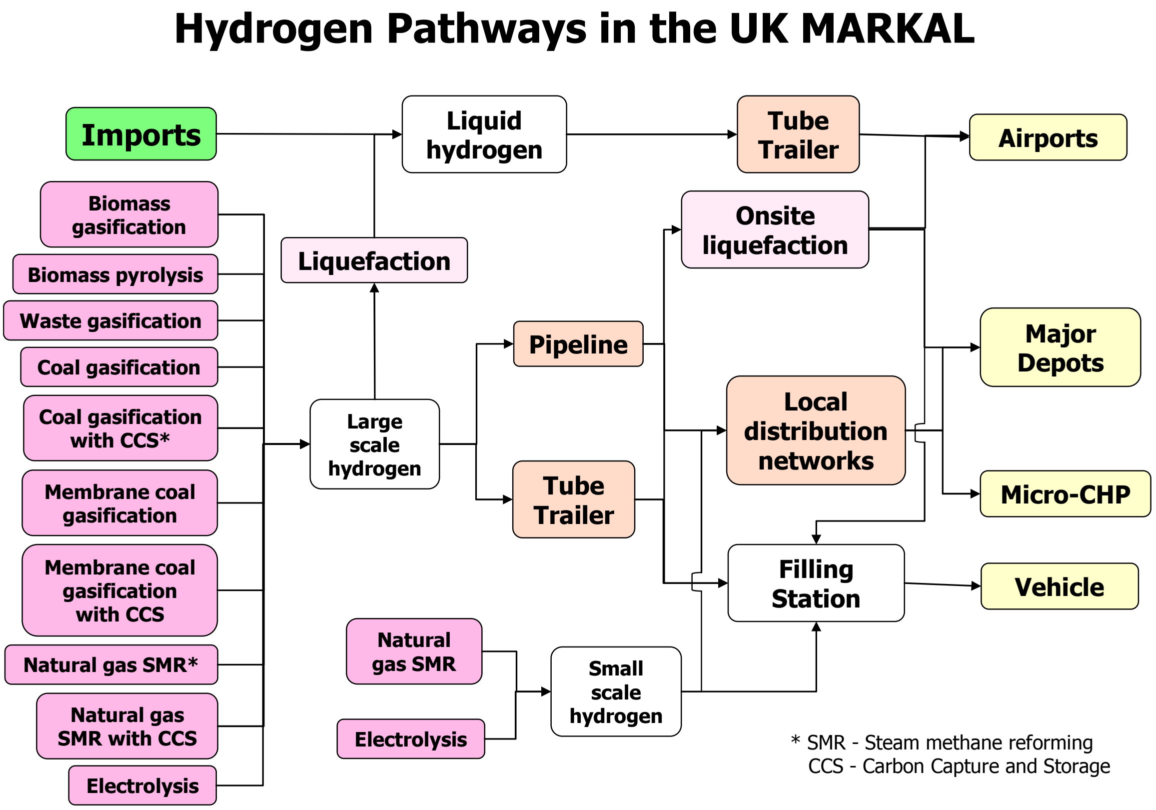


Figure 5.1: Structure of the Hydrogen Module in the UK MARKAL Model
Source: Balta-Ozkan et al. 2007, p.6

The crucial relationship in respect of distribution options between throughput and distance (illustrated in Figure 4.1) is represented in the model as shown in Table 5.1, in which different end-use applications are assumed to require different combinations of flow-rate and distribution distance. They also require hydrogen in different forms – air transport would require the greater energy density offered by liquid hydrogen, while 2-wheelers (with low range) and rail transport (large storage space) would need only compressed gas. The other transport modes could take it in either form, so that liquid hydrogen could either be distributed as such, or could be produced at local liquefaction sites from centrally-produced compressed gas transported by pipeline or road, or locally produced gas. Local production is assumed not to need a distribution network as it is close to demand.

		Distribution Distance	
		Short (50 km)	**Long (300 km)**
Flow rate	**High (100 t/day)**	Air, rail, ship	Heavy goods vehicles (HGV)
	Low (15 t/day)	Bus, Two-wheeler	Car, light goods vehicles (LGV), micro-generation

Table 5.1: UK Hydrogen Distribution Network by Transport Mode
Source: Balta-Ozkan et al. 2007, p.7

An important aspect of the representation of technologies in MARKAL is how their costs and performance change over time, especially those which, like hydrogen and fuel cell technologies, are immature and might be expected to improve substantially as they are more widely deployed. The model uses technology vintages to capture these changes, with new vintages with different performance assumed to be introduced in particular years. The model will ‘choose’ these new vintages in preference to competing technologies, where it may not have chosen older vintages, if their performance has improved sufficiently to make them competitive when they are introduced.

The Base and Reference Scenarios

First the MARKAL model was run with no constraints on carbon emissions (the Base Scenario) and then constrained to produce a 60% reduction in carbon emissions from 2000 levels by 2050 (30% by 2030), but with no technological constraints (the Reference Scenario). The Base Case therefore delivered the minimum energy system cost under the defined overall technological assumptions, and the Reference Case the minimum energy system cost to reach a 60% reduction target.

The MARKAL model delivers a very large amount of data as results of scenario runs. For each scenario, Balta-Ozkan et al. (2007) reports primary and final energy demand, sectoral and end-use sectoral (in which the emissions from the power sector and hydrogen production are allocated to four end-use demand sectors based on their use) CO_2 emissions, hydrogen production and use, fuel use in the transport fleet, electricity generation mix, total system cost, and the marginal and average cost of CO_2 abatement. Only a small proportion of these results can be reported here.

Interestingly, as shown in Figures 5.2 and 5.3, hydrogen is used in the transport sector, first for HGVs, then for buses, LGVs and cars, from about 2020 even in the Base Scenario, and also in the Reference Scenario, by 2050 comprising 15% of final energy demand, or about 70% of the fuel used in road transport. However, while the Base and

Reference Scenarios use about the same amount of hydrogen, the hydrogen is produced very differently, shifting from gas and coal (Base) to gas and coal with CCS, and then electrolysis once the CCS capacity is used up, and substantial imports (Reference) under the impact of the carbon constraint.

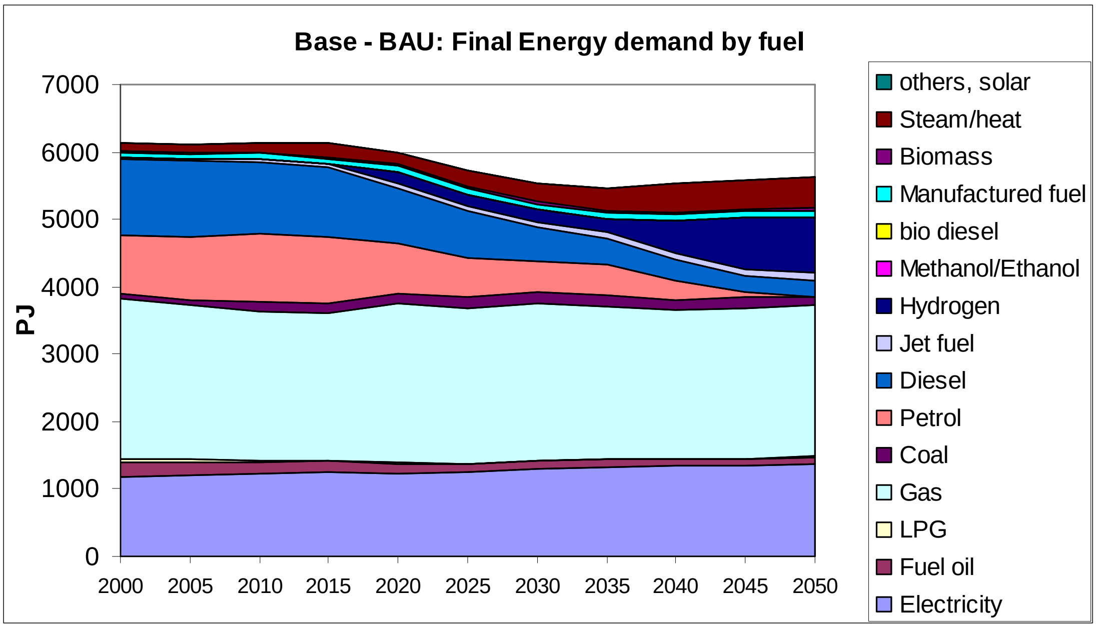


Figure 5.1: Final energy demand – Base Scenario

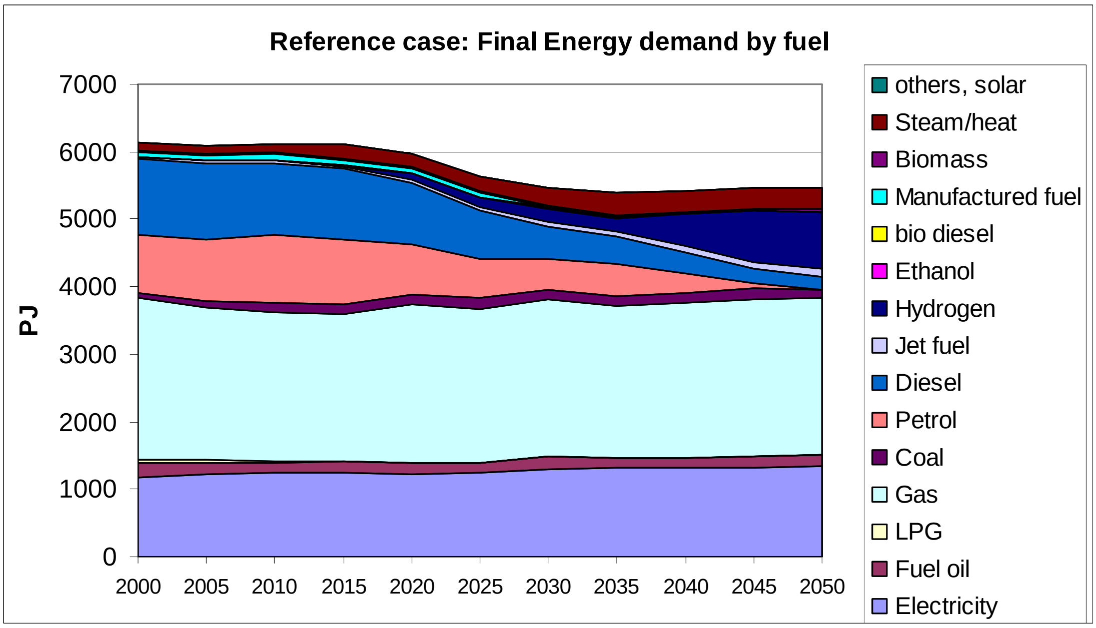


Figure 5.2: Final energy demand – Reference Scenario

Electricity Store

The purpose of the electricity store scenario was to capture the possibility of hydrogen being used to store electricity from intermittent renewables, in order to buffer fluctuating demand in the electricity system. Adequate modelling of this scenario requires more detailed modelling of electricity demand during the day than the day/night differentiation of the standard MARKAL model. This is currently being extended to divide the day into five time slices, but the extension has not yet been completed so that this scenario was not modelled.

Central Hydrogen for Transport (CHT)

This was defined as hydrogen (all used in the transport sector) as comprising 20% of final energy demand (in the Reference Scenario transport fuel use varies from 22-31% of final energy demand over 2000-2050). However, as noted above, even in the Reference Scenario hydrogen comprised 15% of final energy demand, so that the difference between the CHT and Reference Scenarios is quite small. The main result of the extra hydrogen demand in CHT is a change in the fuel mix, with less electricity use (as rail transport shifts to hydrogen), but more use of gas in electricity generation (as co-generation and district heating expands), and less nuclear, renewable and imported electricity.

Figure 5.3 shows the transport sector fuel demand in the CHT Scenario. Only Car Diesel and Rail Electricity remain significant non-hydrogen fuel uses.

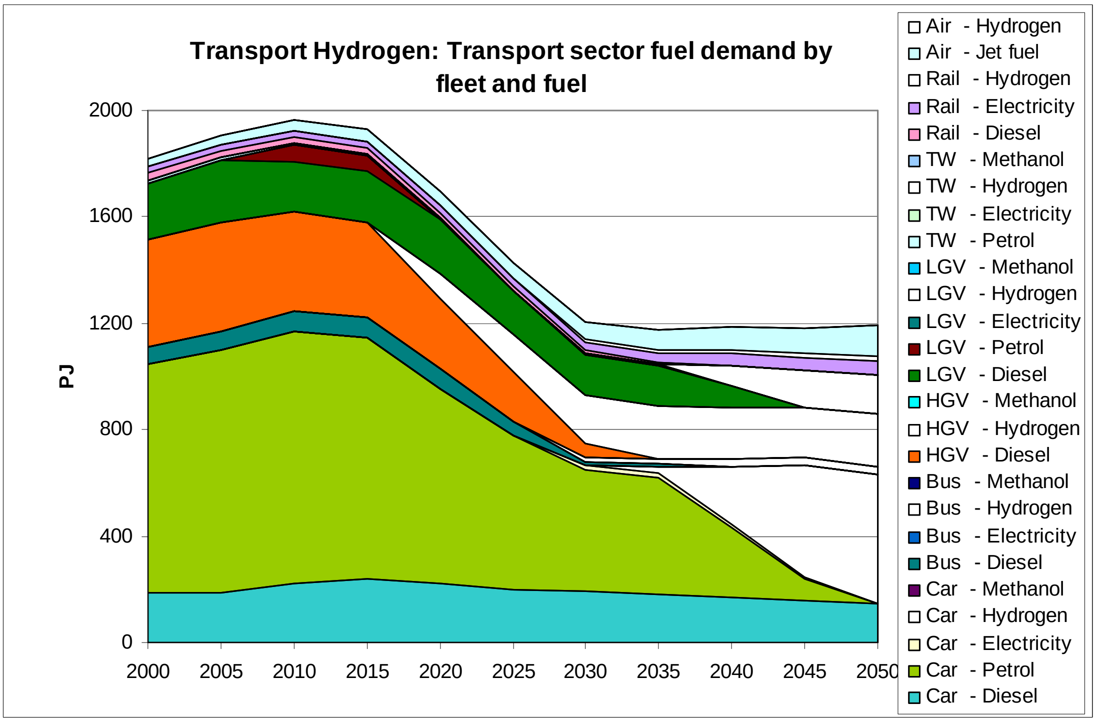


Figure 5.3: Transport Sector Fuel Demand by Fleet - CHT Scenario

Ubiquitous Hydrogen (UH)

In the UH Scenario, hydrogen is assumed to deliver 50% of final energy demand (three times the level of hydrogen use compared to the Reference Scenario), with 60% of the hydrogen being used in heat and power generation, mainly as microgeneration in the service sector, substituting for gas, and the rest in transport.

Most of the extra hydrogen is produced by electrolysis (see Figure 5.4), with nuclear power being the electricity source. The greater efficiency of microgeneration in producing heat and electricity combined means that final energy demand in the service and residential sectors declines by 8% and 14% (due in this case to increased take up of insulation) respectively. But the thermodynamic inefficiency involved in using electricity to produce hydrogen, which is then itself used to produce electricity, means than overall primary energy demand in UH increases by 14% over the Reference Scenario.

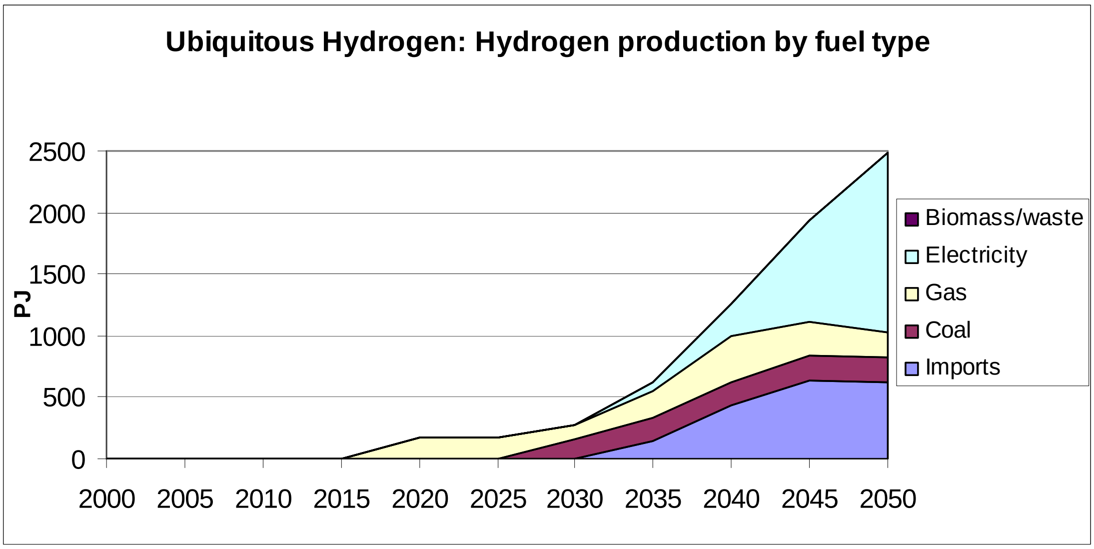


Figure 5.4 Source of Hydrogen Production – UH Scenario

Synthetic Liquid Fuel (SLF)

For this scenario some extra methanol technologies are added to those in the model and these are taken up to a small extent in both the Base and Reference Scenarios, substituting for some hydrogen, indicating that the costs of these technologies are comparable to those based on hydrogen. In the scenario itself, methanol is assumed to comprise 20% of final energy demand by 2050 (the same as the level of hydrogen penetration assumed in the CHT Scenario), being used first in LGVs, then cars and HGVs. Nearly half the methanol is produced from natural gas, with most of the rest coming from imports and hydrogen, with the latter mainly being produced from coal with CCS, and some from biomass, which switches out of power generation. Nuclear power reaches similar levels to those in the UH Scenario, when it was extensively used for electrolysis for hydrogen production, but in this case is used in the residential and service sectors for heat production. This switching between fuels is a common characteristic in MARKAL when assumptions are changed and a number of different technologies can be used to satisfy different final energy demands.

Comparison between Scenarios

The next few figures illustrate the various differences between the scenarios, with Figures 5.5 and 5.6 showing the differences in the share of different fuels in primary and final energy demand in 2050. The blue blocks show the Reference Scenario, the red lines the range of variation across the three other scenarios. Figure 5.5 shows that the share of renewables, gas and nuclear in primary energy demand tend to increase in some of the scenarios, while those of coal and oil tend to be reduced, and imported hydrogen is very variable. In contrast, Figure 5.6 shows that the share of gas in final energy demand is reduced in all the scenarios, while those of the other fuels is very variable.

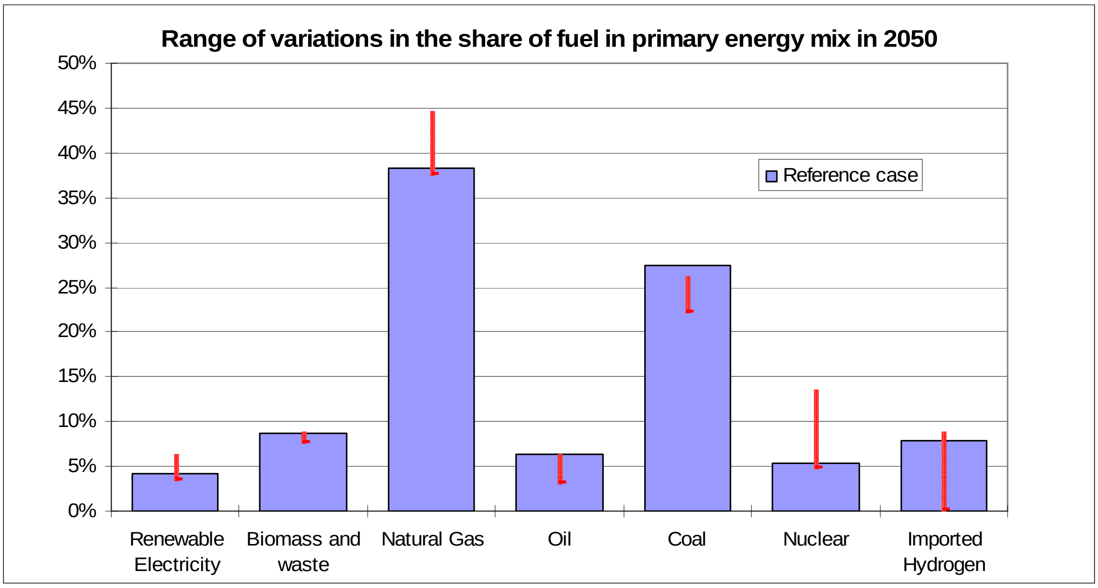


Figure 5.5 Changes in Primary Energy Demand across the Scenarios in 2050

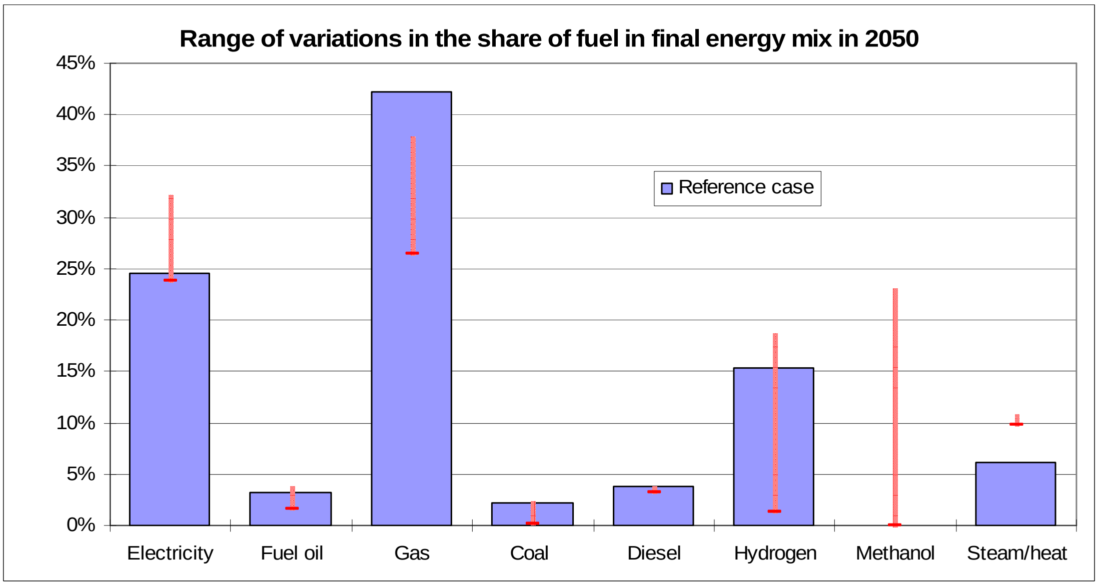


Figure 5.6 Changes in Final Energy Demand across the Scenarios in 2050

Figure 5.7 shows the differences in the sources of power generation for the scenarios in 2050. In the Base, with no carbon constraints, coal predominates. In the Reference, with 60% carbon reduction, coal CCS and nuclear are the largest sources. This is little changed in CHT, because there is little change in the hydrogen requirement, but in UH greatly increased nuclear power is required to produce the additional hydrogen. In SLF gas re-enters the generation mix.

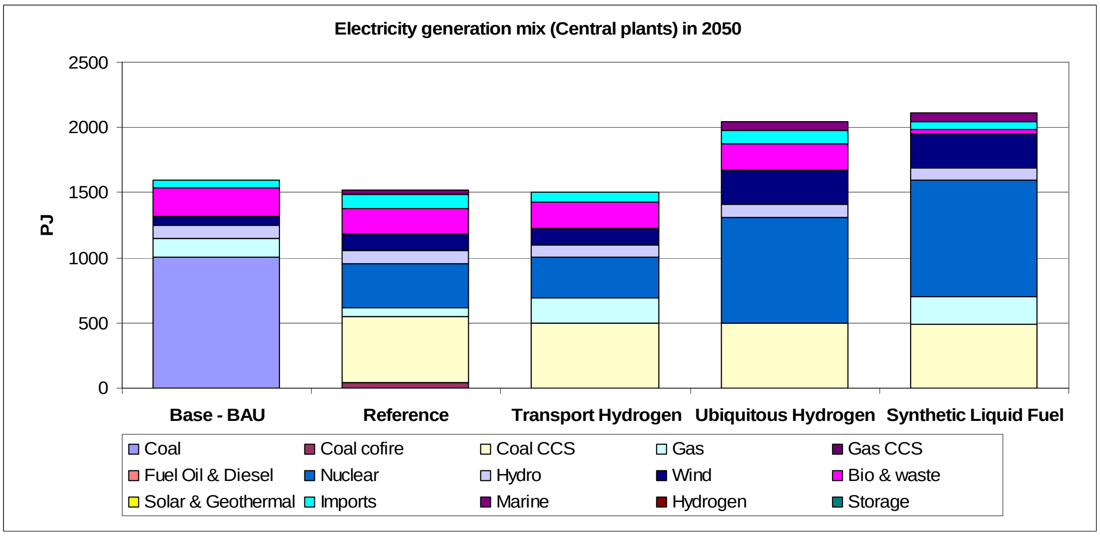


Figure 5.7 Electricity Generation Mix across the Scenarios in 2050

Finally, Table 5.2 shows the range across the scenarios of the energy system cost increases and the marginal costs of carbon abatement in 2050 for the different scenarios. The energy system cost of the UH scenario is 11% above that in the Base, compared to only 2% for CHT (because the Base had nearly as much hydrogen as CHT). Comparing SLF and CHT, in which methanol and hydrogen respectively are extensively used in transport and account for 20% of final energy demand, the extra cost of SLF is significantly above that of CHT, showing that the cost of methanol production is substantially above that of hydrogen. Perhaps surprisingly, in UH the marginal cost of carbon abatement only increases to £77/tCO2, from £61/tCO2 in CHT. But this extra marginal cost across a large increase in hydrogen use results in significantly higher overall system costs.

Increase above Base of:	**Reference**	**CLT**	**UH**	**SLF**
System cost (£)	£4.6 bn	£6.3 bn	£35.3 bn	£23.8 bn
System cost (%)	1.4	2	11	7.4
Marginal CO2 abatement cost (£/tCO2)	54	61	77	140

Table 5.2 Costs Increases from the Base Scenario for Different Scenarios in 2050

Conclusions on Scenarios

The MARKAL scenarios reported above generate cost-efficient mixes of energy technologies out to 2050 on the basis of the cost and other assumptions that are fed into the model. As shown above, hydrogen is introduced into the transport sector of the UK energy system from about 2020 even in the Base Scenario, which indicates that such introduction is cost minimising on the assumptions made. However, it should pointed out that the cost assumptions fed into the model assume very considerable technological development in relation to hydrogen, on the basis of some of the aspirations for such development that have been incorporated into various hydrogen technology roadmaps. It should be pointed out that for this technological development to take place, it is likely both that substantial research and development budgets (considerably higher than those currently in place) will need to be committed, and that these budgets are successful in achieving fundamental technical breakthroughs in such areas as hydrogen onboard storage. Without such breakthroughs the penetration of hydrogen vehicles into the transport sector will simply not be able to take place. The breakthroughs will need radically to improve on both current costs and current performance. As E4Tech (2004, p.98) puts it: “All (promising UK hydrogen) chains face significant cost and performance improvement challenges, particularly in fuel cell vehicles.”

The Base and other scenarios should therefore not be interpreted as what is likely to happen, much less as what ‘will’ happen, but rather as possible futures containing various levels of hydrogen usage on the assumption that profound technical advances are made in a number of areas of hydrogen technology. It is still very much an open question as to whether these advances will in fact materialise.

6. HYDROGEN TRANSITIONS

In the most detailed analysis yet carried out of the most appropriate hydrogen strategy for the UK, E4Tech et al. (2004) identify six hydrogen chains as particularly relevant to the UK context. These are shown in Table 6.1, together with the areas which E4Tech et al. suggest need to be addressed in order for practical realisation of these routes to hydrogen utilisation to be achieved.

Hydrogen Chains	Areas to be addressed
	1. Fuel cell road vehicles including storage*
	2. Other hydrogen and fuel cell vehicles*
	3. Hydrogen pipelines*
	4. Road transport of hydrogen*
	5. Refuelling infrastructure*
Biomass gasification	Biomass and waste supply
	6. Biomass gasification to hydrogen
	7. Hydrogen integration in biomass systems
Nuclear electricity	Nuclear electricity
Renewable electricity	Renewable electricity
	8. Hydrogen integration with renewable energy
Novel H2 technologies	9. Electrolysers**
	10. Novel hydrogen production technologies
Natural gas with CCS	11. Natural gas reforming
	12. Hydrogen integration in natural gas systems
Coal with CCS	13. Coal gasification to hydrogen
	Carbon capture and storage (CCS)**

* Common to all chains
** Common to 2 chains

Table 6.1 Hydrogen Chains Appropriate for the UK and Areas to be Addressed for them to Become Viable
Note: The chains have been placed opposite the areas to which they are most closely related, but note that some areas are relevant to more than one chain, or to all chains. The numbered areas are those which are referred to in Section 9.
Source: E4Tech et al. 2004, p.102

Table 6.1 may give the impression that the principal task to be accomplished for the establishment of ‘a hydrogen economy’ (defined here as a (national) economic system in which hydrogen is the energy carrier which delivers “a substantial fraction of the nation’s energy-based goods and services” (NRC & NAE, p.11)) is the development of a range of different technologies, and there is no denying the essential role of technological development in this process. However, this is very much only part of what is required.

The current, largely fossil-fuel based, energy system in industrial countries is mature, pervasive, reasonably efficient in its satisfaction of a wide range of demands for energy services (heat, light, power, mobility), and has an extensive infrastructure which is long-lasting and has been developed over many years with very large investments. For the hydrogen economy to come about, there will need to be an extensive transition away from the fossil-fuel economy. For this transition to occur in a largely market-based economy, hydrogen technologies must compete effectively with the fossil-fuel alternatives. In particular, “devices that use hydrogen (e.g. fuel cells) must compete successfully with devices that use competing fuels (e.g. hybrid propulsion systems)” and “hydrogen must compete successfully with electricity and secondary fuels (e.g. gasoline, diesel fuel and methanol)” (NRC & NAE 2004, p.17). In addition to competing successfully economically, any transition to hydrogen would need to be supported by political and cultural factors if it is to come about.

There is now an extensive literature analysing past technological transitions, and speculating about the conditions and processes which may bring them about in the future. Agnolucci & Ekins (2007 forthcoming) describe three theories of technological transition involving innovation chains (Foxon 2003), the co-evolution of societal subsystems (Freeman & Louça 2001) and the multi-level interaction between landscape factors, technological regimes and niches (Geels 2005).

Using the Geels multi-level approach, Eames & McDowall (2006) developed four ‘transition scenarios’, which were briefly mentioned in Section 3 and modelled as described in Section 5. Eames & McDowall (2006) combine the multi-level approach with further thinking on thinking on transitions by Berkhout et al. (2004) and Hisschemöller et al. (2006).

Berkhout et al. (2004) develop a 2x2 typology for thinking about transitions, combining the dimensions of low/high coordination (or purpose or intention) with the use of resources that are internal or external to the regime. The transitions in the four quadrants are therefore characterised by the extent that they are purposive or largely uncoordinated, and make use of internal or external resources (e.g. ‘emergent transformation’ is a transition involving low coordination and external resources).

Eames and McDowall combine this typology with Hisschemöller et al. (2006)'s four types of governance:

- *Governance by policy networking*, through which public and private actors cooperate informally to achieve change
- *Governance by government*, through which change is promoted by the institutions of the state
- *Governance by corporate business*, through which change is promoted by big business
- *Governance by challenge*, through which innovation is driven by fostering challenges to vested interests, that promote innovation

Figure 6.1 shows how Eames & McDowall (2006) map the two typologies onto each other.

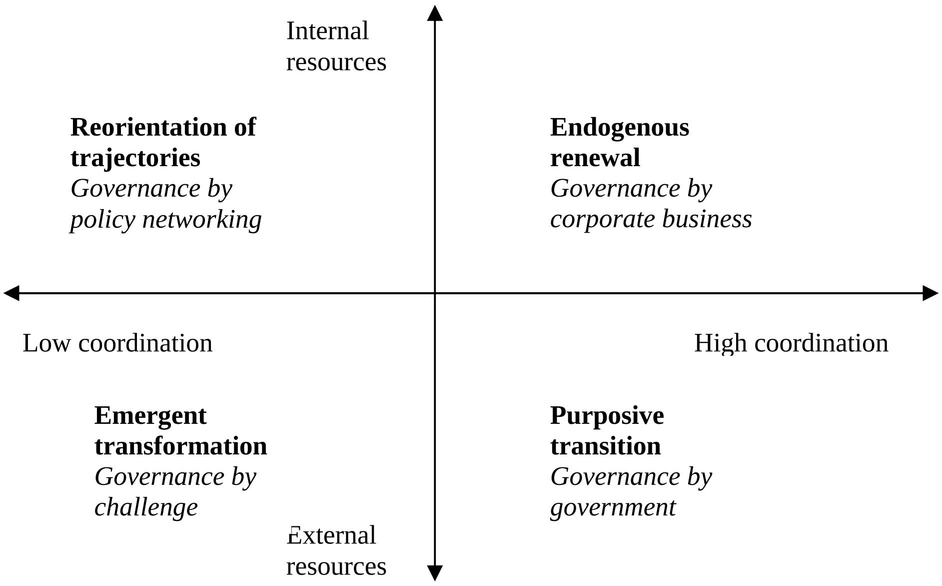


Figure 6.1: Four Types of Transition Distinguished By Coordination and Source of Resources
Source: Adapted from Berkhout et al. (2004, p.67), Eames & McDowall 2006, p.33

Eames & McDowall (2006) then locate their four hydrogen 'transition scenarios' within this framework, as shown in Figure 6.2, with 'coordination' interpreted as 'guiding vision', and 'resources' as 'actors/institutions'.

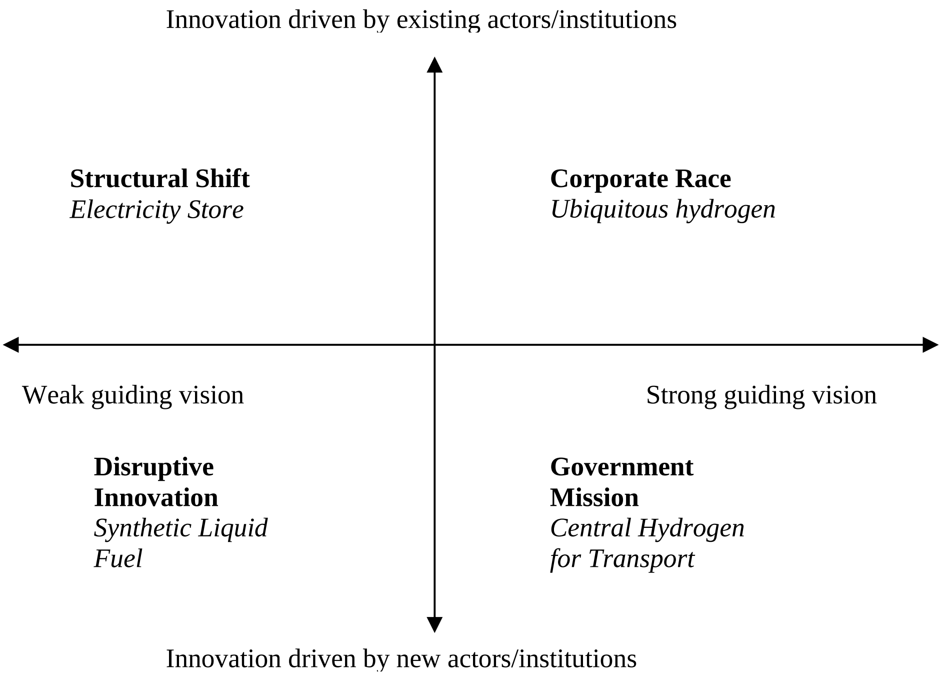


Figure 6.2: Four Hydrogen Transition Scenarios
Source: Eames & McDowall 2006, p.5

Table 6.2 summarises the 'stories' which Eames & McDowall (2006) construct to go with their transition scenarios,

	Structural Shift	**Corporate Race**	**Government Mission**	**Disruptive Innovation**
Dimensions	Innovation driven by existing actors/institutions Weak guiding vision	Innovation driven by existing actors/institutions Strong guiding vision	Innovation driven by new actors/institutions Strong guiding vision	Innovation driven by existing actors/institutions Weak guiding vision
Drivers	Strong UK Government and social concern for climate change and energy security Greater social awareness of need for demand reductions Societal rejection of nuclear and CCS	Strategic positioning of big auto and big oil in the face of climate change and energy security concerns High demand for and volatile supplies of oil and gas lead to increasing prices	Strong UK/EU government concerns over climate change and energy security Societal acceptance of nuclear and CCS and greater social trust in science and technology	Emerging climate and energy concerns Emphasis on building competitive markets and high innovation Social preference for liberalised markets and consumer sovereignty
Key technologies	See Table 3.2	See Table 3.2	See Table 3.2	See Table 3.2
End vision	**Electricity Store**	**Ubiquitous Hydrogen**	**Central Hydrogen for Transport**	**Synthetic Liquid Fuel**

Table 6.2: Summaries of Four Hydrogen Transition Scenarios
Source: Eames & McDowall 2006, p.7

What is apparent from Table 6.2 is that there are both differences and similarities across the characteristics of the different scenarios, and that different stories for the scenarios are possible (for example, the UH scenario could be driven by government, and the CHT by business; or the drivers could be combined, with the transport component of UH being driven by business, but the technology then being taken into the residential and commercial sectors by innovative new small companies acting in ‘policy networks’ with government.

What is also apparent from the different scenarios, and especially the different technologies through which they are realised, is that they are likely to vary greatly in attractiveness to different groups of people, an issue that is explored further in Section 7.

Under any of the governance perspectives described above, one way in which a technology may become widely diffused is to become established in a niche or niches, and expand into the mainstream. Indeed, it has been suggested that what has been called strategic niche management (SNM) “may be the only feasible way to transform environmentally unsustainable regimes”, although they accept that a this may need in addition policies such as taxes and regulation (Kemp et al. 1998, p.191). Agnolucci & Ekins (2007 forthcoming) explore the issue of SNM in relation to the hydrogen economy.

McDowall (2004) identified seven current niches for hydrogen technologies, which might provide the basis for hydrogen’s expansion: portable power for electronic and small electrical equipment; auxiliary power units (APUs) in vehicles; fuel cells for stationary power, for back up or in remote locations; fuel cells to propel niche vehicles; hydrogen-fuelled internal combustion vehicles; hydrogen/hydrocarbon fuel blends; and various demonstration projects and experiments. In an assessment of one of these niches, Agnolucci & McDowall (2006 in press) conclude that an increased use of APUs powered by hydrogen fuel cells could indeed support the development of a hydrogen economy more generally. Even if they were methanol or solid oxide fuel cells, increased use could generate useful experience with fuel cells generally, and could give consumers a taste for more onboard power, which could help the establishment of fuel cell vehicles.

On the other hand, Agnolucci & Ekins (2007 forthcoming), while they accept that current hydrogen niches, and their expansion, should not be ignored, consider that the fundamental technological and economic challenges facing core hydrogen applications such as fuel cell vehicles are more likely to be successfully addressed by the kind of major ‘technology push’ policies focused on R&D than by the promotion, or strategic management, of relatively peripheral niches such as APUs. This issue of policy support is revisited in Section 8.

7. PUBLIC ACCEPTABILITY OF HYDROGEN

It is apparent from the descriptions of the possible hydrogen futures presented in Table 3.1, and of their technologies in Table 3.2, that they are likely to elicit a wide variety of different public responses. To explore this issue, an innovative multi-criteria mapping of the futures was carried out with a small group of experts in the field (McDowall & Eames 2006b), and focus group work was undertaken with members of the public with less knowledge of the issues. This section reports this work.

Multi-criteria mapping (MCM) is a technique developed by Stirling (1999) with the aim of making explicit the value judgements, perspectives and assumptions which cause people to arrive at different appraisal conclusions about the same situation. In this case, 15 experts in energy and hydrogen, from very different backgrounds, explored the six different hydrogen futures descried in Section 3. They were invited to specify and weight for relative importance their own criteria (grouped under environmental, economic, social, energy security, other) and, for each of the six futures, to score its performance against each criterion, on both optimistic and pessimistic assumptions, thus generating a range of performance scores on each criterion, to reflect uncertainty. The experts were also asked to score a Status Quo scenario consisting of broadly current conditions in which hydrogen plays a negligible role.

In the event, there was considerable overlap between the criteria chosen by each expert, but considerable differences between both their weighting of these, and the scores they allocated to each hydrogen future. Figure 7.1 shows the range of weights allocated by the experts to each of the groups of criteria, with the range of importance given to economic criteria varying the most.

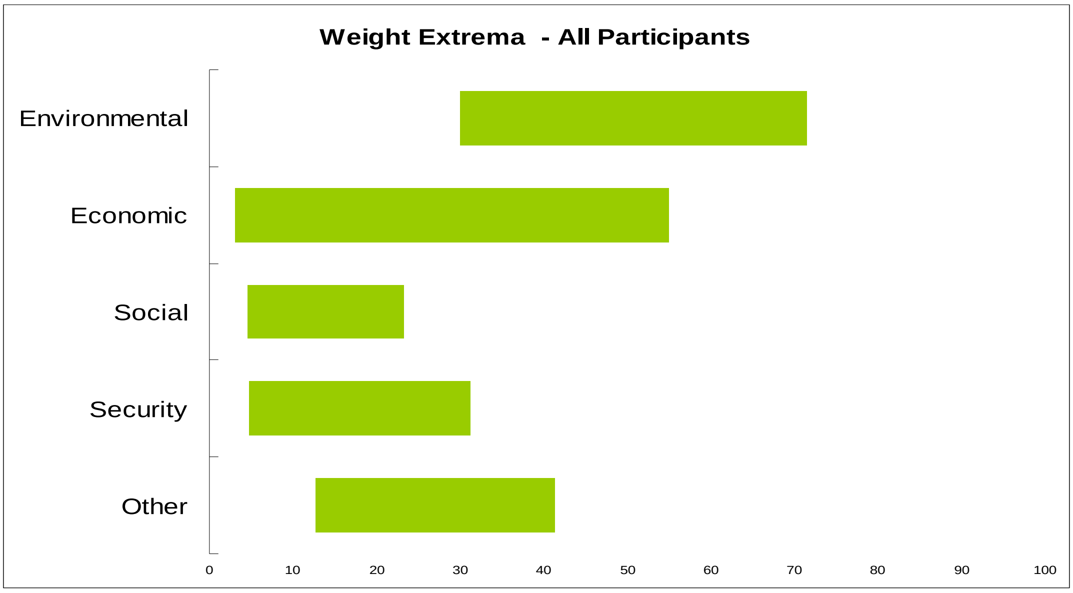


Figure 7.1 Criteria Weightings
Source: McDowall & Eames 2006b, p.31

Figure 7.2 shows the final weighted score for the participants in the exercise, with the dark blue bars showing the range of the average, and the light blue the range of the extremes, of the optimistic and pessimistic scores.

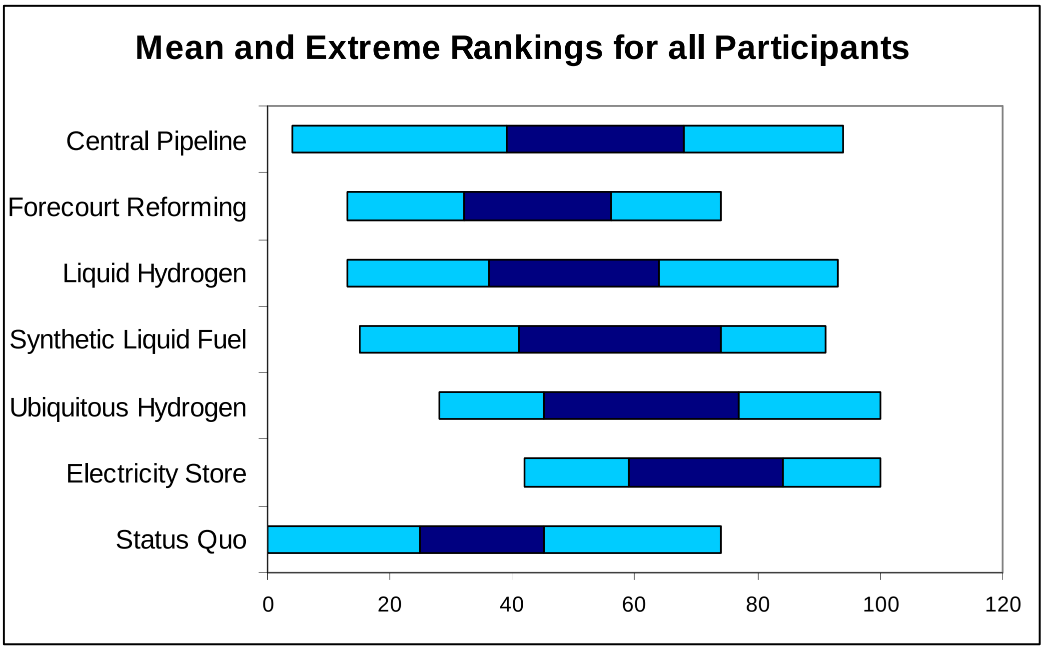


Figure 7.2 Final Weighted Scores for all Participants
Source: McDowall & Eames 2006b, p.33

Figure 7.2, showing the mean and extreme weigthed scores for all participants, shows that Electricity Store had the highest average optimistic score, that the Status Quo was generally not favoured, and Central Pipeline was subject to the greatest variation of opinion about its overall performance. No one hydrogen future was preferred by all participants. Most uncertainty was expressed about Synthetic Liquid Fuel.

Much of the power of the MCM method lies in its ability to get behind the reasons for the scores that are given by the different participants. Crucial in the appraisal were disagreements about the acceptability of nuclear power (one expert refused to score any scenario in which this was the source of the hydrogen), the relative desirability of centralised and decentralised energy systems, and perceptions of economic and political feasibility.

The conclusions drawn by McDowall & Eames (2006b, pp.54ff.) from this exercise are that hydrogen is not automatically a ‘sustainable’ technology (indeed, different people interpret this word differently); that the desire to reduce carbon emissions is the main reason why it is favoured; but that there is significant uncertainty about the cost and performance, and the desirability, of many of the elements of different futures. How these elements are put together is therefore likely to be a key issue for their general public acceptability.

Ricci et al. (2007) describe research that used focus groups to explore public attitudes to hydrogen in three areas that have some practical manifestations of hydrogen technologies: Teesside, which has a history of industrial hydrogen production and a local pipeline; South Wales, which has projects to generate hydrogen from biomass; and London which has a European demonstration project on hydrogen buses.

The focus groups explored four sets of attitudes of relevance to hydrogen: those towards the environment and willingness to consider environmentally beneficial behaviour change; those towards hydrogen and other new energy technologies; criteria by which they would evaluate hydrogen technologies; and attitudes to public engagement in decision-making about such technologies.

The research confirmed many of the points that have been found in previous work:

- On behaviour change the difficulty of connecting local actions with global effects; the tendency to blame others for problems; a value-action gap; the importance of habits, norms and convenience, and of infrastructure and institutional ‘lock-in’; the difference between behaviour as consumers and as citizens, and the importance of collective change processes; and on the importance of fairness and of guidance and information from trusted sources.
- Despite some initially negative associations with hydrogen, prompting safety concerns, people seemed to be in general prepared to accept hydrogen technologies as they do any other. They would have to be safe, convenient and reliable to use, and offer comparable performance for comparable cost with respect to competing technologies. There was a general expectation that, if rolled out, hydrogen technologies would in the event be brought up to the required safety standards; however this apparent trust in ‘the system’ contrasted with a marked distrust of several of the key actors – industry, business, the Government – who would be responsible for this. There was interest in the details of the whole hydrogen chain, and particularly the comparative sustainability of various production methods, including fossil fuels and nuclear power. Whilst there was no widespread rejection of any particular aspects of the hydrogen chain, support was highly conditional on understanding the ‘context’ and the ‘bigger picture’..
- There was ambivalence on public engagement. At one level people wanted to be engaged, but only if it concerned issues in which they were interested or which had direct bearing on their lives. There was recognition that many people would not want to be involved in engagement on hydrogen.

Bellaby et al. (2007) explore the challenging policy implications of these public attitudes to hydrogen. First, it is not too soon to start public information and engagement exercises to familiarise people with various aspects of hydrogen technologies. Second, it is clear that a combination of public and private research, development and demonstration projects will need greatly to improve the cost and performance of hydrogen end-use applications to levels that the public have come to expect, while establishing sound safety features and procedures. Third, market stimulation measures will probably need to make use of the full range of policy instruments, such as taxation of carbon-intensive alternatives to hydrogen, while being careful not to alienate public opinion. And fourth, public acceptance of hydrogen and the policies required to support it would only be won if it was clear what the public benefits of the technologies were and how they were being achieved.

8. POLICIES FOR HYDROGEN TRANSITIONS

The current costs and technical performance of hydrogen technologies such as fuel cells mean that, as discussed above, their use is presently confined to small niches or demonstration projects. On the evidence to date, market development and forces alone are unlikely to enable these technologies to break out of these relatively limited uses. Indeed, there is no literature that suggests that the hydrogen economy will come to exist in the foreseeable future, if ever, without substantial and long-term public support. Even with the political will to give that support, the nature of what is being attempted should not be underestimated. It is unprecedented. Writing about the US, NRC &NAE (2004, p.17) state: "In no prior case has the government attempted to promote the replacement of an entire, mature, networked energy infrastructure before market forces did the job. The magnitude of the change required if a meaningful fraction of the U.S. energy system is to shift to hydrogen exceeds by a wide margin that of previous transitions in which the government has intervened." The same would be true for other industrialised countries. To attain such a shift, strong public policy is likely to be required, applied consistently and systematically over an extended period.

Public policy, of course, needs to be justified in terms of the public benefits that it delivers. In respect of hydrogen these potential public benefits are of four kinds. Two relate to air emissions, one to energy security, and one to economic development. The potential air emission benefits are that, at the point of use, the use of hydrogen either in fuel cells or in combustion produces only water. Where this use substitutes for the combustion of fossil fuels (e.g. petrol/diesel in vehicles, coal in power stations), this means that the use of hydrogen can reduce emissions of carbon dioxide, and therefore contribute to climate change mitigation, and of local pollutants such as the oxides of sulphur and nitrogen, and therefore help to improve air quality. The delivery of these benefits is of course dependent on the means of production of the hydrogen (i.e. these means would have to involve low or no emissions themselves).

The potential benefits of energy security derive from being potentially able to substitute hydrogen for imported fuels (such as oil) that may suffer constraints in their supply, either because of scarcity or from political factors. Again, the delivery of these benefits will depend on the means of production of the hydrogen – for example, producing it from natural gas through SMR will do nothing to reduce dependence on imported gas.

A fourth possible perceived public benefit from the development of hydrogen technologies is economic. Some regions and countries which perceive that hydrogen technologies are likely to become important in the future consider that they will benefit economically from this development if they have created a local, regional or national capability in these technologies. Strictly, this is more a private benefit to the firms and employees concerned, but societies as a whole also stand to gain from successful technological developments of this kind, and in fact it is such industrial considerations that currently seem to be driving much of the current public support for hydrogen, as will be seen below. Of course, should hydrogen technologies fail to develop as foreseen such benefits will fail to materialise and the public subsidies that have been committed to them will be effectively wasted.

Because of the importance of achieving technical improvements in hydrogen technologies, that deliver any or all of new functionalities, performance improvements and cost reductions, most public policy support for hydrogen is devoted to research and development (R&D). Hughes (2007) found that research in hydrogen technologies is mainly organised, coordinated and funded internationally and nationally. Important internationally are the International Partnership for a Hydrogen Economy (IPHE) and the work of the International Energy Agency (IEA), and the European Union (EU), while outside Europe individual countries with major hydrogen research programmes include the US, Japan, S. Korea, Canada and Iceland, the last of which has a target to convert its economy entirely to hydrogen by 2030.

EU funding goes to support a number of research and demonstration projects, including the CUTE project which has deployed 33 fuel cell buses in nine cities, and networks and initiatives such as HyWays which is developing a hydrogen roadmap for the EU as a whole. There is also a public-private collaboration called the European Hydrogen and Fuel Cells Technology Platform, which has ambitious targets for fuel cell commercialisation in a range of uses, including vehicles.

An important source of EU funding for hydrogen activities at the sub-national level is through the European Regional Development Fund (ERDF), which is accessible to less prosperous EU regions, or those undergoing industrial restructuring. It is clear from Hughes (2007) that interest in hydrogen at a sub-national level, in the UK at least, is driven to a large extent by the desire for economic development and regeneration, rather than purely for its wider public benefits. Because economic development and regeneration is highly location specific, it is not therefore surprising that different regions in the UK which have aspirations towards ‘a hydrogen economy’ have very different perceptions of what such an economy in their area would comprise, and how they might seek to move towards it. Hughes (2007), drawing heavily on work by Hodson & Marvin (2005a,b,c), contrasts the differences in approach to this issue being taken in London, Teesside, Wales and Scotland. However, two conclusions emerge from all of the regions studied. The first is the importance of the regional level (in England provided by the regional development agencies, in Wales and Scotland by the national governments) in providing impetus to activities on the ground. The regional level is large enough to be able to include a variety of relevant actors and interests, but small enough to be able to take account of local contexts, skills and enthusiasms. The second is for the need for these regional activities to be supported by and related to a clear national vision, policy framework and funding provision. As will become clear, it is this national-regional linkage which, in the UK, seems to be largely missing.

As seen in Section 6, the Strategic Framework for hydrogen in the UK developed by E4Tech et al. (2004) identified six hydrogen chains as most promising in the UK context. However, all these chains were oriented exclusively towards the use of hydrogen in transport, and specifically in FCVs. This is in contrast with the main thrusts towards hydrogen coming from Scotland, Wales and Teesside, none of which are concerned with FCV development, and with “the significant entrepreneurial activity in the UK from small companies developing stationary and portable fuel cells” (Hughes, 2007, p.17).

As Hughes (2007, p.34) later puts it: “High level policies and roadmaps should provide an aspirational drive to encourage local and regional actors to implement projects, supported with funding, whilst remaining flexible to regional interpretations of what a hydrogen or fuel cell economy means in each local context.” UK policies and roadmaps would seem to leave quite a lot to be desired in this regard.

E4 Tech et al. (2004) identify 33 measures to address the barriers to the development of hydrogen technologies in the UK, grouped according to the current ability of the UK to address them, alone or in international collaboration. Table 8.1 lists these 33 measures. The numbers refer to the numbered areas to be addressed in Table 6.1. Many of these measures require the commitment of substantial resources. Their successful implementation would also require committed and knowledgeable actors and institutions at the regional and local levels. Perhaps the first policy priority is to connect the national perception of the priority of these measures (as opposed to others) with the realities of actors and institutions on the ground.

Table 6.1 confirms the point made above that a major focus of public policy support should be research, development and demonstration projects. However, of themselves, these are unlikely to mobilise the really large investments from private sources that will be necessary for the mass diffusion of hydrogen technologies in terms of both applications and infrastructure and applications. This will require substantial policy measures of market enablement and incentives (such as feed-in tariffs, carbon pricing and fuel duty exemptions) that private investors believe to be long-term. It is probably still too early for such measures – the markets to which they will need to be applied (e.g. FCVs) are still characterised by technologies that need further fundamental development. But policy makers should keep in mind both the need for such measures in due course, and the desirability of targeting them appropriately and differently in line with the different developments at regional and local level.

CREATE STRONG UK POSITION ALONE **Major Barriers** 1 Stimulate market for low-carbon transport in UK 4 Include road transport of H2 in UK demonstrations 5 Demonstration of refuelling stations **Other Barriers** 3 Identify and focus UK pipeline capabilities 3 Evaluate and demonstrate undersea UK pipeline from UK remote renewables 7 Develop UK biomass policy to include H2 8 Conduct feasibility studies on H2 integration with renewable electricity 8 Policy development for H2 and renewable electricity 8 Demonstration of H2 with renewable electricity in the UK 11 Deploy large transformers and integrate with CCS in UK 13 Demonstrations of coal gasification with CCS	**UK LEAD IN INTERNATIONAL ACTIVITIES** **Major Barriers** 1 Lead international R&D effort on H2 onboard storage **Other Barriers** 5 Create strong UK systems analysis position 10 Lead RD&D in non-nuclear novel H2 production
NEED TO BUILD UK EXPERIENCE **Major Barriers** 2 Deployment of H2 and other FC vehicles **Other Barriers** 3 Demonstrate urban pipeline network to supply refuelling stations in UK 3 Demonstrate trunk pipelines in UK 5 Cooperate in refuelling codes and standards development 7 Conduct UK systems studies and demonstration of biomass to UK 12 Plan for future natural gas demand for H2	**UK COOPERATION IN INTERNATIONAL ACTIVITIES** **Major Barriers** 1 Cooperate in international R&D efforts on fuel cell stacks 1 Participate in international FCV design, demonstration and integration activities **Other Barriers** 2 Participate in international development efforts for other H2 and FC vehicles 6 Participate in international R&D and demonstration on biomass gasification to H2 7 Develop EU biomass policy to include H2 9 Cooperate in international electrolyser R&D within areas of UK strength 9 Cooperate in international electrolyser demonstrations 10 Participate in international novel nuclear to H2 RD&D 11 Demonstrate and commercialise reformers for energy applications in UK 12 Cooperate in studies and demonstration of H2 use in pipelines 13 Conduct R&D on coal gasification, CO2 separation, polygeneration, and biomass co-firing

Table 8.1 Measures Required to Develop UK Hydrogen Options

Source: E4Tech et al. 2004, p. 107

Although one of the two key axes in the UKSHEC transition scenarios splits the scenarios according to whether they are characterised by a ‘strong’ or ‘weak guiding vision’ (see Figure 6.2), nevertheless each of the scenarios is driven by decisive action on the part of at least one major actor, and, it could be argued, all are crucially dependent on strong government. In *Government Mission* it is explicitly the government which takes imposes strong policies to specifically bring about a hydrogen transition. *Corporate Race* is driven by large commercial interests, motivated by a growing culture of corporate social responsibility, but it is unlikely that this would be powerful enough unless it were also supported by government policy. The other two transitions are characterised by a ‘weak guiding vision’, but even in these cases the notable absence of action in one area is compensated for by action from a large actor in another area. In *Structural Shift* there are no specifically hydrogen directed policies, but it is nevertheless strong action on the part of government in terms of demanding high renewable energy targets, which indirectly drives the need for hydrogen as an energy regulator. *Disruptive innovation* is the transition which is least obviously driven by specific directed actions of government, with direct hydrocarbon fuel cells emerging for transport uses from portable niches. However, even here the developments in fuel cell technology which enable the transfer from portable to automotive markets imply some significant levels of R&D on the part of companies within the automotive supply chains, and the government is again broadly responsible for directing a move away from carbon intensive fossil fuels through enforcing emissions reductions, incentivising renewable transport fuels and stimulating the ‘policy networks’ and markets through which the knowledge generation and market development comes about.

9. CONCLUSIONS: PROSPECTS FOR A HYDROGEN ECONOMY

There are many possible hydrogen economies, but the emergence of any of them will require substantial and sustained public policy support

There are many technologies which can produce hydrogen, many that can store and transport it, and many applications in which it can be used. Moreover, these technologies can be combined in many different ways to bring about a range of different hydrogen futures. It is not yet at all clear what combination of what technologies, if any, will deliver the private and public benefits that will be required for the mass diffusion of these technologies into society. Fundamental improvements in both cost and performance across the whole range of hydrogen technologies are still required for them to compete effectively in end-use mass markets and to deliver the low emissions and energy security for which they are widely advocated. Achieving these improvements will require a greater commitment of public and private investment than has yet been forthcoming, and, in due course, long-term and credible strategies of market incentivisation and enablement through determined public policy interventions. Given this investment and the current state of development of various hydrogen technologies, it is quite possible that hydrogen could play a major role in the energy economy of the mid-century and be associated with major profitable new industries, as well as delivering large-scale environmental benefits.

Not all hydrogen futures will be regarded as sustainable and desirable by everyone, so that public understanding and engagement will be required for them to gain public acceptance

Elements of possible hydrogen futures that may be contentious include its production from nuclear power, huge onshore wind farms, or fossil fuels with carbon capture and storage. Public familiarity and attitudes on safety, and the ability of hydrogen technologies to meet desired standards of cost, convenience and performance, are also likely to be important for its widespread diffusion. It is necessary for the public to be informed about and engaged in the potential and implications of hydrogen technologies, and to be engaged in their early manifestations in different regions, if the diffusion of these technologies is to proceed smoothly when they are ready for mass marketing.

The transition to a hydrogen economy will require more than strategic niche management

Hydrogen and fuel cell technologies are currently highly uneconomic, except for certain niche applications, where their market potential is greater. However, such applications, either because of their limited market size, or because any potential advantages of hydrogen or fuel cell technologies within them depend on large increases in energy demand, are unlikely on their own to represent a significant transition to a more sustainable energy economy. They may however provide a ‘stepping stone’ to lowering costs of technologies through increased production. However, due to the variety of technical specifications which different fuel cells are responding to, there are significant technical distinctions between the technologies being used in the various niche applications. This imposes significant barriers on the potential for major technological transfer from niche to mass market, as it has been characterised in numerous case studies in the literature. Thus in addition to the work of small to medium companies in designing fuel cells for niche applications, a major transition to the use of sustainable hydrogen energy in mass markets, will require some significant and concerted efforts on the part of large scale actors, including governments and major companies in the energy, automotive and other related sectors.

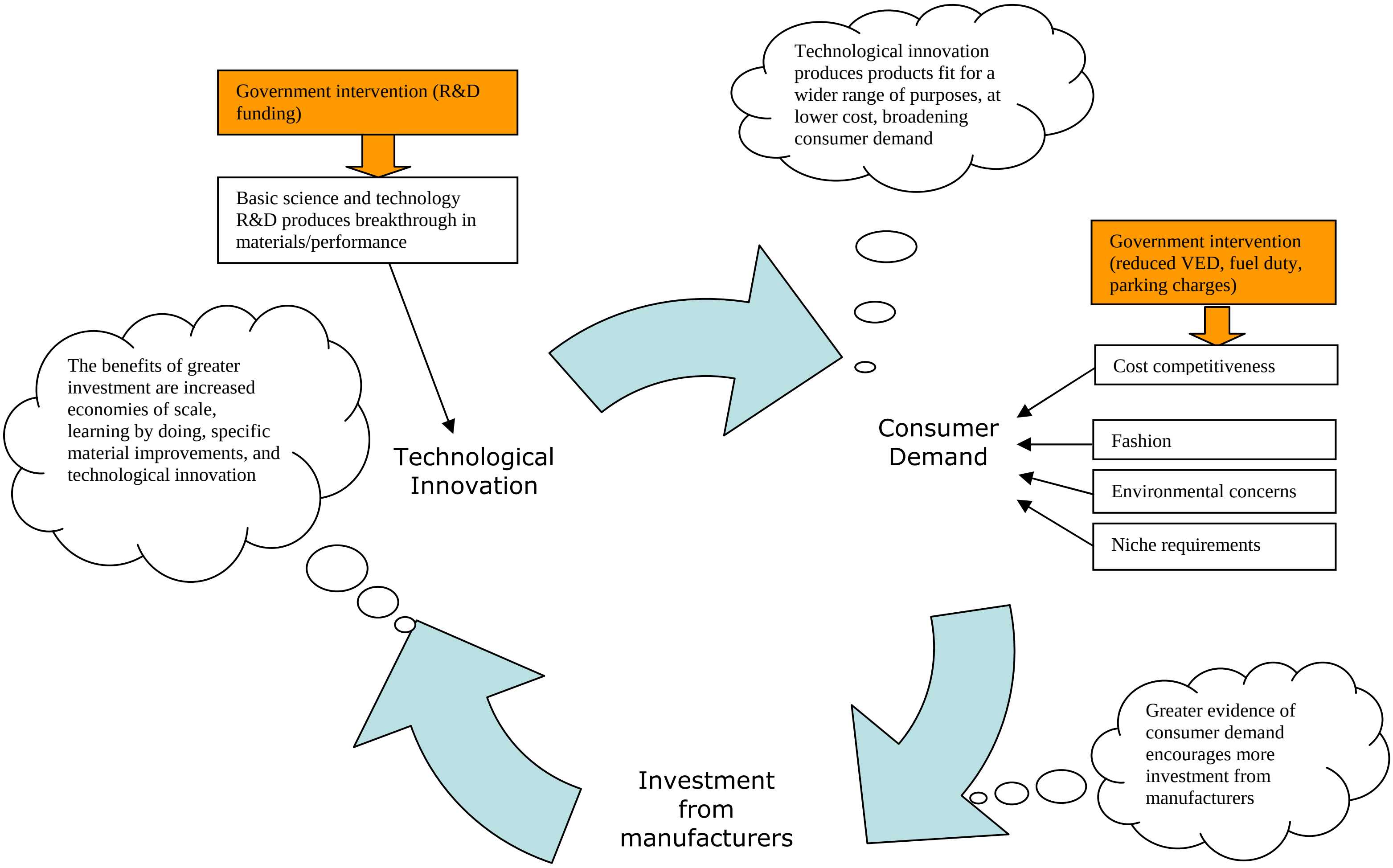
National policies towards hydrogen should support regional hydrogen strategies and local activities.

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.

Different groups in different regions have different reasons for regarding hydrogen as potentially beneficial and wish to develop it in their regions in different ways. National roadmaps of hydrogen development should be sensitive to, and seek to support, these different regional aspirations, while providing an overall vision and rationale for moving towards a hydrogen economy which is both consistent with and makes wider sense of these different regional developments.

Public policy to stimulate the hydrogen economy should seek to promote the establishment of a virtuous circle of demand, investment and innovation in a coordinated way

When and whether large scale production will come about is an area of great uncertainty, but it is clear that the establishment of a hydrogen economy will require multiple reinforcing interactions between demand, investment and innovation, as shown in Figure 9.1 (adapted from Hughes 2006).



Technological innovation produces products fit for a wider range of purposes, at lower cost, broadening consumer demand

The benefits of greater investment are increased economies of scale, learning by doing, specific material improvements, and technological innovation

Greater evidence of consumer demand encourages more investment from manufacturers

Figure 9.1: The Circle of Demand, Investment and Innovation

The circularity in Figure 9.1 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 higher manufacturing cost (as shown in the right-hand orange box). 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.

Of course, government interventions of this kind are only likely to be effective once the technology has already reached the position of being only marginally less economic than competing alternatives, at which point such consumer focused incentives can tip the scales in its favour. A comparable example is the effect of exemptions from congestion and parking charges on encouraging the use of low-range electric vehicles in London. In the case of hydrogen, however, before the technologies can approach the levels of cost where consumer incentives can begin to take effect, significant technical breakthroughs are needed, as has been discussed. Therefore, government intervention is also crucial in the promotion of basic technological R&D (as shown by the left-hand orange box). Nonetheless, the long term confidence of manufacturers to invest in developing the technologies will be strengthened by the knowledge that the kind of consumer incentives represented by the right-hand orange box *will be in place* once the technologies do begin to approach the competitive range of costs. Thus, in order to generate confidence within the industry, and to set this virtuous cycle in motion, government must be seen to make positive interventions at both of these key points in the cycle. As described above, this may well require coordination between the national level, as the likely location of R&D funding programmes, and the regional level, as the likely location of various specific consumer incentivisation policies.

Policy measures should be coordinated to avoid giving conflicting signals both to consumers and potential manufacturers. Policies must also be constructed with long term future pathways in mind, and with some sensitivity to the key areas of uncertainty. 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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