Hydrogen Fuel Cells for Stationary Power: Technological Characterisation and Market Assessment

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1 Introduction

Much of the current focus of a possible shift towards H_2 as an energy carrier is on its applications in the automotive sector. However, H_2 can also be used for direct heating and for power production, in which sector its extremely low levels of pollutant emissions could allow greater proximity of power plant to end user, making it suitable for distributed generation. Fuel cells, although generating power through electrochemical rather than combustive processes, nevertheless generate heat, making combined heat and power applications a possibility. Since hydrogen can be produced from multiple sources including carbon-sequestered fossil fuels, renewable energy, biomass, or nuclear power, it has the potential to offer not only decarbonisation but also diversification of fuel supply. Such a scenario may appear increasingly desirable if natural gas supplies become more scarce, insecure and expensive.

However, a scenario involving the widespread use of hydrogen, for power or CHP provision, involves the same uncertainties as those raised by hydrogen transport scenarios; principally, the large structural investments required to transport and store hydrogen, and the large amounts of energy required to produce it in the first place.

Recent research suggests that the widespread use of hydrogen fuel cells for stationary power faces significant obstacles, greater than those faced by automotive applications. For stationary applications, the efficiency losses of the various energy transformations necessitated by a hydrogen chain are particularly challenging, in view of the fact that the initial primary fuel is often itself just as well suited for stationary heat or power production as hydrogen. A report by Eoin Lees Energy, E4 Tech and Element Energy (E4 Tech *et* al, 2004) concludes that ‘generation of electricity from hydrogen leads to thermodynamic losses which are avoided if the primary energy source is used directly for electricity production’, and that it is therefore ‘unlikely that hydrogen fuel will provide competitive CO2 reductions’ in most stationary power applications.. However, it is believed that hydrogen fuel cells could have certain ‘niche’ applications, and that fuel cells operating on low cost and more freely available feedstocks such as natural gas and biogas could also have an important role. Additionally, it has been suggested that fuel cells could be suitable for distributed generation and combined heat and power applications, where their overall efficiency is further improved by capture and use of waste heat.

In this report the various types of fuel cell, and their potential to provide stationary power, are assessed. First, the current state of the technology is characterised, with attention given to the different performance characteristics and costs of the various fuel cell types. Then the potential market opportunities for fuel cells providing stationary power are considered.

Hydrogen can also be used as a fuel in gas turbines and internal combustion engines. This also produces no CO_2 at the point of use, although small quantities of nitrogen oxides are usually emitted. However, compared to the significantly superior electrical efficiency of fuel cells, it is unlikely that the use of hydrogen in ICEs will offer energetic or environmental advantages. Hence, only fuel cells are considered here.

2 Hydrogen Fuel Cells: Technological Characterisation

As electrochemical devices, fuel cells are inherently more electrically efficient than combustion technologies. They are also particularly flexible because they are modular and could potentially be assembled economically in units of varying sizes – from a few watts to at least 10MW. Fuel cells can therefore cover virtually any size of end use requirement, from small appliances to individual homes, large office buildings and on to industrial facilities and merchant power.

2.1 Fuel Cell Technologies

A brief summary of various fuel cell technologies is given in Table 1. Different technologies are suited to different applications. Low temperature fuel cells require external reformers if not operating on pure hydrogen; higher temperature fuel cells can reform fuel internally. A fuel cell system also comprises a fuel cell stack, balance of plant (BOP) and a power conditioner to convert DC to AC.

The desired lifetime (40 000 hours or more compared to 5 000) makes stationary fuel cells much more expensive than automotive equivalents. However the relaxation of other demands (cold start properties, response to dynamic load changes, output heat temperature, size and weight) opens up more technologies, especially solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs) (Erdmann 2003).

	PAFC Phospheric acid fuel cell	**MCFC** Molten carbonate fuel cell	**SOFC** Solid oxide fuel cell	**PEMFC** Proton exchange membrane fuel cell or **SPFC** Solid polymer fuel cell	**AFC** Alkaline fuel cell
ELECTROLYTE	Phosphoric Acid	Molten Carbonate Salt	Ceramic	Polymer	Potassium hydroxide
OPERATING TEMPERATURE	200°C	650°C	600 – 1000°C	40 – 80°C	65 – 220 °C
FUELS	Hydrogen (H_2) Reformate	H_2/CO/ Reformate	H_2/CO_2/CH_4 Reformate	H_2 Reformate	H_2 Reformate
REFORMING	External	External/Internal	External/Internal	External	External
OXIDANT	O_2/Air	CO_2/O_2/Air	O_2/Air	O_2/Air	O_2/Air
POISONS	CO, NH_3, CL_2, S_2	CL_2, S_2	S_2	CO, NH_3, CL_2, S_2	C
ELECTRICAL EFFICIENCY (% HHV)	40-50%	50-60%	45-55%	40-50%	60%
COMMERCIAL STATUS	Most mature, offered commercially between 40-200kW	Offered commercially in 250kW and MW classes	Expected commercially in stationary market. Demonstrated in 200kw range.	Entering stationary market 1-5kW, also available in 75-250kW range	Only specialty applications (spacecraft, submarines etc)

Table 1: Summary of fuel cell technologies. From (EG&G Technical Services 2004; Halliday *et al* 2005).

Various types of fuel cells are commercially available or in development, and can be broadly categorised as high temperature or low temperature fuel cells. Fuel cells with a lower operating temperature are often more susceptible to contaminants within the gas, and as such are designed to run on pure H_2. This would either be provided by a hydrogen transportation infrastructure, or by onsite reforming of hydrocarbons such as natural gas. Fuel cell types such as direct methanol, molten carbonate and solid oxide fuel cells, because of their high temperature of operation, are less susceptible to contaminants, and are able to reform fuel internally, making them suitable for direct use of hydrocarbons.

2.1.1 Low temperature fuel cells

Phosphoric acid fuel cells (PAFCs) are the most mature fuel cell technology, but with least room for further improvement or cost reduction. They were originally singled out for development due to low their low-temperature operation and tolerance to reformed hydrocarbon fuels, and found early niche markets in uninterruptible power supplies (UPS). UTC installed around two hundred 200kW PAFC fuel cells, however they have recently stopped manufacturing them in favour of proton exchange membrane fuel cells (PEMFCs) which have better prospects for cost reductions. Current costs are reported between US$3000-$4000/kW. To compete with diesel, UPS systems need to cost $1000/kW (Halliday *et* al, 2005) or less (Strachan, 2004).

Alkaline fuel cells (AFCs) require oxygen, rather than air as the oxidant, as the cell degrades when operated in the presence of CO_2. As such, they are likely only to fill small niches and therefore not benefit from the large scale investment and deployment to reduce costs and benefit from technical development. Such niches may include the use of regenerative systems for storage of electricity, e.g. in stand-alone power systems, where oxygen can be produced, stored and used in parallel with hydrogen. However, costs would have to reduce substantially in order to compete with other electricity storage options, many of which have significantly superior round-trip efficiencies.

Proton exchange membrane fuel cells (PEMFCs) give an order of magnitude higher power density than any other type, except advanced aerospace AFCs. Consequently they are the main candidate for automotive applications, and their development is being driven by the transport sector. This may result in more extensive technical development and cost reductions than might otherwise occur and as such, PEM is also likely to be the long-term choice for power generation from sources of pure H_2.

PEM fuel cells run on H_2 and air, operating at a temperature of approximately 80 °C, allowing a short start-up time, which is useful for vehicles. This low operating temperature puts some restrictions on the applicability of PEM fuel cells for CHP, although they have a high electrical efficiency, and are capable of adjusting to variable power demands; a characteristic which could also be useful for load following in small scale domestic applications.

PEM fuel cells are sensitive to contamination of the H_2 stream with carbon monoxide (CO), which permanently damages the membrane and leads to a loss of performance. It is therefore imperative that supplies of H_2 for these fuel cells are pure. This will be the case for H_2 produced for the automotive sector, as these will also use PEMs, and also for H_2 produced via electrolysis, e.g. in a stand-alone power system based on renewable electricity (H-SAPS, 2004a).

2.1.2 High temperature fuel cells

Molten Carbonate Fuel Cells (MCFCs) were originally developed for use directly with coal (which now looks unlikely) although they can be operated directly on natural gas, syngas (CO and H2) and other light hydrocarbon fuels. The focus of MCFC development has been stationary and marine applications, where the relatively large size and weight of MCFC and slow start-up time are not an issue (EG&G Technical Services 2004). Their high temperature operation eliminates the need for noble metal catalysts, but the extremely corrosive electrolyte requires the use of expensive steels.

Solid oxide fuel cells (SOFCs) use a ceramic solid electrolyte, which reduces corrosion and liquid management problems. They must operate at high temperatures (600-1000° C) to achieve conductivity, which also allows internal reforming of a variety of fuels, but places stringent (and generally expensive) requirements on their materials. If pressurised, the exhaust gas of an SOFC can fire a gas turbine. According to Siemens, who have demonstrated 220 and 300kW plants, this combined approach should achieve electrical efficiencies of 55% at capacities of 250 kW, around 60% at 1 MW, and 70-80% efficiency above that (Siemens, 2006). At the other end of the scale, recent advances in planar SOFCs allow lower temperatures (~700° C as opposed to 1000° C previously) which may reduce costs and make SOFCs scalable down to sizes of one or two kW (EG&G Technical Services 2004). SOFCs are less developed than PAFCs, but are generally thought to have good market potential (Halliday *et al* 2005). Their ability to process a range of fuels is considered a key advantage, and experiments have shown SOFCs maintaining good efficiencies while processing biogases such as landfill and sewage gas, despite their variable hydrocarbon content (Staniforth and Ormerod, 2001). This potential to recycle freely available, but otherwise waste gases, could be attractive both from an environmental and an economic standpoint.

2.2 Costs of Fuel Cells

2.2.1 Capital costs

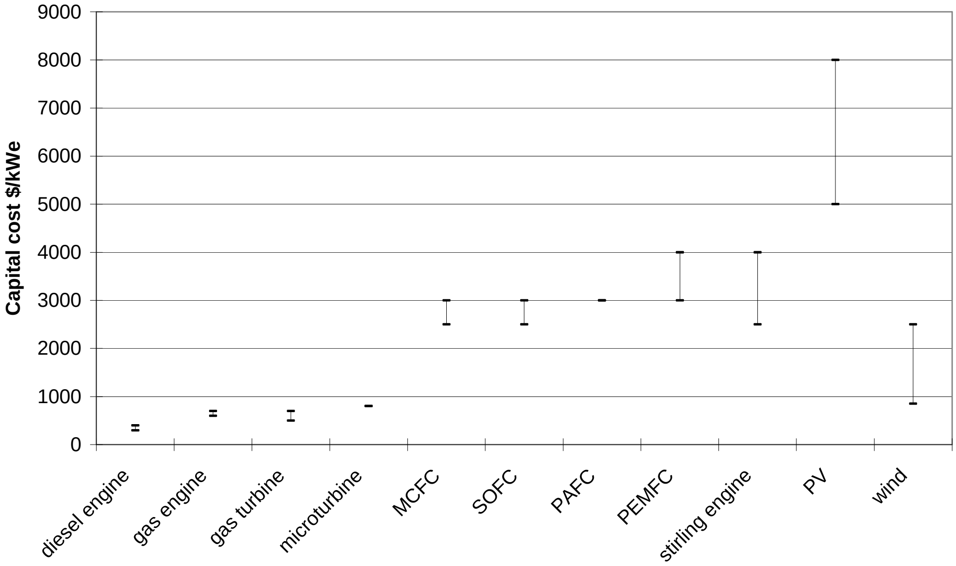

Figure 5: Capital cost ranges of DG technologies (Strachan, 2004).

Fuel cell type	System size (kW$_e$)	Internal reforming	Equipment cost (2003 $/kW$_e$)	Total installed cost (2003 $/kW$_e$)	O&M costs (cents/kWh)	Electrical efficiency (%), HHV	Total CHP efficiency (%), HHV	CO2 (g/kWh)
PAFC	200	No	4600	5200	0.97	36	72	515
PEMFC	10	No	4950	5500	1.42	30	69	617
PEMFC	200	No	3220	3800	0.98	35	72	531
MCFC	250	Yes	4450	5000	0.80	43	65	431
MCFC	2000	Yes	2850	3250	0.55	46	70	404

SOFC	100	Yes	2970	3620	1.15	45	70	413

Table 2: Prices and efficiencies for commercial or near-commercial fuel cell CHP systems. From (NREL 2003). 'Total installed cost' include labour (~6% of total), project construction and management, engineering fees, and contingency (~6% together).

Figure 5 shows a summary of typical capital costs for fuel cells, compared to other DG technologies, based on a review of current literature (Strachan, 2004). Table 2 shows another set of estimates of fuel cell CHP costs and performance, based on manufacturer's targets for market entry systems (NREL, 2003).

The costs in Table 2 are generally around $1000/kWe higher than Figure 5. However, cost per kW comparisons should be made with caution since they depend on a number of factors, including the overall size (large installations tend to benefit from economies of scale) the application (e.g. back-up electricity vs continuous stationary power) and the auxiliary equipment included (Table 2 includes power conditioning equipment and isolation breakers suitable to allow grid interconnection).

Also, as fuel cell production is not fully commercialised there is significant uncertainty as to market entry costs. Commercially available 5kW PEMFCs from Plug Power, aimed at extended back-up for telecommunications, cost $15 000 ($3 000/kW) (Cropper *et al*, 2003), but it is not known what their lifetime would be in continuous operation. Geiger and Cropper (2003) report Japanese manufacturers aiming to market small PEMFCs for stationary power at $4200/kWe by 2005, with other Japanese manufacturers having public targets of $1 650/kW by 2010.

PureCell 200 is a 200kW PAFC unit built by UTC Power. Current costs are approximately $4,000/kW, and total installed costs approach $1.1million or $5,500/kW. UTC did focus briefly on PEM due to expected cost reductions, but found durability a problem.

Lokurlu (2003) reports current costs of PEMFCs as $12 300/kWe; Erdmann (2003) reports $12 000 - $24 000 /kWe, and the DTI quotes a current price of fuel cell CHP as $12 500 - $62 300 /kWe (DTI 2002). James *et al* (1999) projected future manufacturing costs of stationary PEM stacks as being $433-$156 /kWe at an annual production level of 100, dropping to $165 - $82 /kW at an annual production level of 10 000.

For SOFCs, Hawkes & Leach (2005) note that although literature on the costs range from $300/kWe to $20 000/kWe, most estimates are in the range $700 to $1 300 /kWe. Colson-Inam (2004) write that tubular SOFC stacks presently cost about $1000-1500/kW, and planar designs about $600-800/kW. For large SOFC-turbine hybrids, Rolls Royce claim to have achieved $300/kW (Fuel Cell Today 2001).

Most of the costs reported have been for fuel cells reforming natural gas. For such systems, about 25-40% is for the stack subsystem, 25-30% for the fuel processing subsystem, 10-20% for the power and electronics subsystem, and 10-20% for the thermal management subsystem and 5-15% for ancillary systems (DTI 2002; NREL 2003). Therefore, hydrogen-only systems could see a reduction in capital costs, since less catalyst would be needed, and stack degradation would not be as great. In particular, low temperature fuel cells would not require a pre-reforming system attached to the stack. However, a fuel cell operating on pure hydrogen could potentially face far higher fuel costs than one running on hydrocarbon fuels. The question of which cost dominates will be key, and the direction of technological development of stationary fuel cells may therefore be strongly affected by any significant cost reductions in hydrogen production methods.

2.2.2 O&M costs

Table 2 estimates O&M costs for fuel cell technologies, including maintenance labour, an annual fuel pump overhaul, condenser cleaning, and air and water filter replacement. According to the compilers of the table, "details of maintenance contracts are not generally available, but appear to be priced between 0.7 to 2 c/kWh" (NREL 2003). Similarly the DTI (2002) report a target range of 1-2c kWh, but add that "O&M costs will only emerge over time". They also agree that an annual maintenance visit will probably be needed, with a major overhaul including stack replacement every fifth year.

Some estimates include a stack-replacement fund as an O&M cost, since current stacks typically suffer an average 10% reduction in performance (cell voltage, power and efficiency) over 5 years (NREL 2003). This is not included in Table 2.

In the longer term, a reduction in O&M costs is likely as technologies mature and developments are made to improve membrane durability.

2.2.3 Future and target costs

Table 3 gives NREL's projected costs and performances circa 2020. O&M costs are significantly higher than those given in Table 2, since the stack replacement fund could not be dissagregated. This fund recovers 50-80% of the stack value over 4-5 years and represents about 70% of the total O&M cost.

Fuel cell type	System size (kW)	Internal reforming	Total installed cost ($/kW)	Operating and maintenance costs (cents/kWh)	Electrical efficiency (%)	Total CHP efficiency (%)	CO_2 emissions (g/kWh)
PEMFC	10	No	2,200	1.9	35	72	531
PEMFC	200	No	1,700	1.2	38	75	517
MCFC	250	Yes	1,650	2.0	49	75	378
MCFC	2,000	Yes	1,400	1.4	50	72	372
SOFC	100	Yes	1,800	1.5	51	72	363

Table 3: Projected costs and performance for fuel cell CHP circa 2020. Data (NREL 2003), O&M includes a stack replacement fund which could not be dissagregated, but contributes around 70% of the O&M costs (NREL 2003)

The numbers in Table 3 are somewhat higher than the aspirational targets both within the US and the UK. The US DoE has targets to develop a distributed generation PEM fuel cell system operating on natural gas or LPG that achieves 40% electrical efficiency and 40,000 hours durability at $400-$750/kW by 2010. The UK DTI mentions a target range of $900-$1,200 /kWe (DTI 2002), and a recent UK Fuel Cells Roadmap recommends targets of $2,400 /kW for commercialization of stationary systems by 2008, and $400/kW for SOFC by 2010 (Fuel Cells UK 2005 Figure 5.8).

Halliday *et al* (2005) quote Johnson Matthey, as forecasting fuel cells to be economically viable at a cost of US $4,000 for niche, stand-by and back-up power applications, $1,000 to $2,000/kWe for off-grid locations and with a target of $400 - $1,000/kWe for widespread applications. Hawkes & Leach

(2005) estimate domestic SOFC cell stacks being economical at costs below \$450/kWe (plus a basic fixed cost of \$600 per stack).

3 Market opportunities

The market for H_2 as an energy vector is presently very small, although expected to become significant in the period to 2030. Substantial quantities are produced and used in industry, most commonly in refineries for the production of low-sulphur fuels. By far the most common technology for H_2 production within industry is reforming of natural gas, with a market share of around 95% (US DOE, 2005), although electrolysis is sometimes used where natural gas is unavailable or there is surplus electricity available[1].

The use of H_2 for power generation is not likely to be a major option for the short to medium-term, for reasons both of costs and the overall efficiency of primary energy resource use. Like electricity, H_2 is an energy carrier that is clean at the point of use but that must be generated from primary energy resources. Due to the capital costs and energy losses associated with the conversion, both electricity and H_2 are inherently more expensive (per kWh) than the primary resource from which they were produced.

However, there are a number of specific situations in which H_2 might be a viable option for power generation; these are described in the following sections. Additionally, fuel cells may also find viable applications in the absence of a fully developed hydrogen infrastructure, through onsite or internal reforming of hydrocarbons.

3.1 Combined Heat and Power (CHP)

The principle of combined heat and power is that the heat generated in power production, instead of being treated as a waste product, should be captured and used directly, greatly improving the overall efficiency of the unit. The system obviously depends on a potential end user with a need for heat being situated relatively nearby. In residential areas its growth has been limited by two factors: economies of scale in combustion power plants making small scale applications unviable; potential for increased localised pollution from a closely situated power plant being unacceptable to residents.

Fuel cells generate heat while producing power, the grade of heat dependent on the type of fuel cell. Being inherently modular, they experience no loss of efficiency at small scales, and they have very low emissions at point of use- these aspects make them potentially very suitable for small scale residential CHP applications.

Solid oxide and molten carbonate fuel cells produce process heat of 260-370° C, suitable for most thermal uses, including industrial applications. Lower temperature cells, such as PEMFCs, produce less high grade heat which limits their application for cogeneration, however it is claimed that they can be used to provide water and space heating in domestic situations (WADE, 2003).

In planning CHP applications, it is important to consider how the heat to power ratio (HPR) of the device fits the heat and power demand of the users. CHP can follow a heat-lead or an electricity-lead strategy, according to the HPR profile of the application.

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[1] An example of surplus electricity being available is hydro generation in Canada, which has large amounts of rainfall at certain times of year and can therefore produce more electricity than required to meet demand.

In general in climates like the UK, domestic buildings have a higher demand for heat than electrical power. Also, thermal demand varies less rapidly than electrical demand, heat is much easier to store, and therefore thermal demand is more easily modulated. These factors favour a heat-lead strategy at the domestic scale. In this strategy CHP is designed to match part, or all, of the thermal load, with extra electrical demand met by the grid. Excess electricity could potentially be exported to the grid, although there are currently technical barriers to connecting a low-voltage variable supply to the distribution grid, and little economic incentives as excess power is of low (or zero) value to utility companies since it is likely to be off-peak and variable.

The prevailing electricity infrastructure and institutional arrangements favour larger, more centralised power generators, meaning electricity-lead strategies tend to be more applicable at larger scales, for example a commercial power generator using waste heat to supply a district heating scheme. However, this general separation of strategies is not set in stone and the best strategy depends on the specific situation including the technology being deployed, the relative electricity and fuel costs, and the institutional arrangements.

The use of absorption cooling – using heat to provide cooling capacity, can increase the viability of CHP schemes, especially in buildings with large cooling demand e.g. air-conditioned offices.

The average HPR for a UK dwelling is estimated at 4 by the DTI (DTI, 2004), and by Halliday *et al* at around 3 (Haliday *et al*, 2005). This suggests that even for domestic applications, high temperature fuel cells may provide a better heat and power match; however, PEM fuel cells would be better suited to cope with the variability inherent in both diurnal and annual heat and power demand. Industrial applications could make use of the very high grade process heat of SOFCs.

It appears that in the main, the most likely candidates for CHP are the high temperature fuel cells, such as SOFCs and DMFCs. These are capable of running directly on hydrocarbons; therefore while there is some potential for fuel cells to feature in scenarios for distributed generation and cogeneration, it is unlikely that pure hydrogen will be the fuel of choice.

3.2 Niche applications

As H_2 is, in general, more expensive than primary energy resources, there are few situations in which its use for stationary power generation[2] would be economic in comparison to direct generation of electricity from the primary resource.

Some situations have been identified in which H_2 might potentially be used for power generation, described below.

3.2.1 Primary resource is remotely located

In a situation in which the primary energy resource is located where there is no existing electricity transmission infrastructure (or insufficient transmission capacity) or where there are surplus renewable energy resources, the resource could be used to produce H_2 rather than electricity. The H_2 could then be transported to a population centre and used either as a transportation fuel or for stationary power generation, ideally in a Combined Heat and Power (CHP) system, thereby maximising energy utilisation.

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[2] The use of hydrogen use in fuel cells for vehicle propulsion produces electricity to drive the electric power train, but that is outside the scope of this report.

One example of such a situation could be offshore wind resources, such as those off the coast of Scotland. Areas where the wind resource is large tend to be sparsely populated, precisely because of the local climate. On the island of Unst, in the Shetland Islands off the coast of mainland Scotland, a pilot wind-H_2 scheme was established (described in (Baker and Carter, 2005)), which could be scaled up to serve all of the inhabitants' energy needs as well as potentially exporting H_2 to mainland Scotland.

Iceland is keen to develop a H_2 economy, due to its large renewable energy resource (geothermal and hydro) and the expense of importing oil to its remote location. Iceland meets 100% of its electricity demand from renewable resources, at only 2 cents / kWh (Solomon and Banerjee, 2006). It therefore has strong potential to produce low cost hydrogen. As the country's most significant oil consumer, the transport sector remains the primary target for hydrogen conversion, nevertheless stationary power applications would also have the potential to develop in such an environment. The Euro-Hyport study is investigating the feasibility for the export of H_2 from Iceland to the European continent.

Similarly, one possible source of large-scale H_2 production is from solar energy in deserts. For example, the Sahara desert could potentially provide huge quantities of renewable H_2, shipped to Europe in liquid form at a cost of US$7-9/GJ (Ogden and Nitsch, 1995).

In such scenarios, the cost of hydrogen fuel becomes competitive when the primary energy is in excess of local demands, and is therefore not at a premium. When hydrogen fuel becomes more affordable, fuel cells naturally become more attractive as the most efficient technology for converting the fuel. This is particularly the case if the availability of primary energy does not coincide with demand (see section 3.2.3).

3.2.2 Carbon capture and storage

In order to capture and store CO_2 most cheaply, this should be done on as large a scale as practicable, using technologies that allow a large proportion of the CO_2 to be captured and transporting the CO_2 as short a distance as possible (IEA, 2002). In practice, this may mean a few large plants that produce energy from fossil fuels or biomass, located near to sites for CO_2 storage.

However, such a large-scale approach may conflict with other aims of energy policy that encourage smaller-scale power generation near to the point of consumption to minimise transmission losses and utilise the heat in a CHP system. One way to meet both objectives might be to produce H_2, or syngas[3], on a large scale near to sequestration sites and then transport this via pipeline to areas of heat and power demand for use in CHP on a smaller scale.

As part of the UK's Carbon Abatement Strategy (UK DTI, 2005), £25m (€35m) was allocated in June 2005 for fossil technologies associated with carbon capture and storage. This may involve a coal gasification project with sequestration of the CO_2 and production of H_2 which would be used for power generation of up to 800 MW (BBC News, 2005).

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[3] Synthesis gas, known as syngas, is the product of processes such as gasification and is generally a mixture of H_2, CO_2, carbon monoxide (CO), water and sometimes methane. Depending on the proportions of H_2 and CO, syngas can be quite energy-dense. If necessary, the CO can be converted to H_2 using the water gas shift process, which requires the addition of water vapour: $CO + H_2O \Rightarrow CO_2 + H_2$

3.2.3 Availability and demand for energy resources do not coincide

While conventional thermal power generation is schedulable to coincide with demand for electricity, many sources of energy cannot be scheduled to produce energy only when required. These energy sources are generally renewable and fall into two categories: predictable sources, such as tidal and – in some climates – solar, and unpredictable sources, such as wind and wave.

This situation offers an opportunity for the use of H_2 for electricity storage. While with current technology conversion to H_2 and back to electricity does not provide a particularly good round-trip efficiency[4] compared to some other electricity storage options, H_2 does provide greater flexibility as it can be used for transport or in a CHP system. Research efforts also proceed to increase conversion efficiency.

Using H_2 in this way may particularly apply to island systems that are predominantly reliant on intermittent renewable resources. The Hydrogen Stand Alone Power Systems (H-SAPS[5]) project under the EU Altener program examined many of the issues for such systems. The recommendations of this study (H-SAPS, 2004b) included:

- undertaking targeted analysis of potential markets, focusing on portable applications, H-SAPS, grid islanding, large wind/H_2 systems and residential units;
- setting cost targets for each component of the stand-alone system;
- review existing regulations that discourage ‘islands’ within a grid system; and
- focused research on areas where there are critical barriers.

The study identified a number of critical barriers, presented in prioritised order:

- High costs of both electrolyser and fuel cell solutions
- Low energy efficiency of the hydrogen energy system - especially critical for small systems
- Development of easy-to-use and energy efficient gas and electricity control systems
- Short lifetime warranties and little lifetime experience for PEM electrolysers and PEM fuel cells.

3.2.4 Back-up / off-grid power

Essentially replacing diesel generators, this application would see H_2 used as back-up for essential services, e.g. in hospitals, and also for off-grid applications. In addition to the potential to decarbonise such forms of power generation, there may be other important benefits, such as the reduction in local pollution and noise.

While H_2 fuel cells could be used for portable applications such as consumer electronics, the focus in this area is currently on the development of direct methanol fuel cells (DMFCs).

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[4] Round-trip efficiency is defined as the proportion of the electricity supply entering the storage system that is available upon exit. In the case of H_2 as an electricity store, the round-trip efficiency would be in the region of 40-50%, only around half that from the most efficient technologies.

[5] http://www.hsaps.ife.no

3.2.5 Availability of surplus energy

H_2 is currently produced as a by-product in a number of industrial processes, mainly the production of ethylene, chlorine and acetylene via electrolysis. At present, this is generally mixed with natural gas and used for thermal processes

In future, where H_2 is being produced for the transport sector in a plant with a large capacity, it is likely that there will initially be insufficient demand from transport to fully utilise the plant’s production capacity. In some situations, such as where H_2 is being produced from waste, there is good reason - and likely fiscal incentive - to operate the plant at full capacity, which may lead to surplus H_2 being available for power generation, until displaced by transport demand. This linkage between stationary and transport sectors could help break the typical problem of low initial demand threatening the viability of production and infrastructure investments, accelerating the move to H_2 in both sectors.

3.3 Future developments

The development of other fuel cell technologies, for example in the transport sector, could influence how quickly stationary power reaches the market. There is some potential for PEM fuel cells to be used for stationary as well as automotive power- moreover, developments in hydrogen production technology and infrastructure would benefit both sectors.

Geiger & Cropper (2003) note that manufacturers are moving away from domestic market as current costs are too high and stack lifetimes too short. As result, an early focus for manufacturers has been on uninterruptible power supplies (UPS), which require shorter lifetimes and can demand a price premium. Here fuel cells are already thought to be cost competitive with incumbent technology (Adamson and Jollie, 2004) and commercial versions are available. However, interest in the domestic market might be again picking up (Adamson and Jollie, 2004).

Some of the strongest drivers for stationary fuel cell power development may come from applications which do not require pure hydrogen. High temperature fuel cells, in particular SOFCs are capable of internal reforming of syngas enabling them to generate power directly from natural gas, and even biogas such as that emitted from sewage farms and landfills. The generation of energy from fuel which is ‘freely available’ may lead to a more economically and energetically efficient process. It is possible, therefore, that some fuel cells may find market applications before pure hydrogen is available to power them.

4 Conclusion

The market prospects for hydrogen fuel cells in distributed CHP applications are currently limited by the high capital costs of the units. This is evidenced in part by the fact that manufacturers are currently concentrating their efforts on niche applications such as uninterruptible power supplies, where a premium can be demanded. The quick start up capability of PEM fuel cells would be useful for load following in small scale domestic applications, and this technology looks likely to benefit from future cost reductions as a result of the research being devoted to it for automotive applications. However, the requirement of PEM cells for pure hydrogen means that domestic applications would be heavily dependent on a hydrogen infrastructure, which currently looks some way off.

The higher operating temperatures of solid oxide and direct methanol fuel cells allow greater potential for CHP applications, in industrial as well as smaller scale applications. They can also be used in combined cycle gas turbine applications: Siemens Westinghouse have demonstrated that the exhaust gas of an SOFC can be used to improve the electrical efficiency of the stack to up to 80% at large scales.

Where high temperature fuel cells are appropriate, the fuel of choice is likely to be a hydrocarbon such as natural gas or biogas, for reasons both of economic and energetic efficiency. Although fuel cells operating on hydrocarbons emit carbon dioxide, there are still environmental benefits from their use. Fuel cells are inherently more efficient at producing electrical energy, so should produce CO_2 savings over conventional combustion of natural gas. Additionally, if fuel cells can be run on biogas, they not only save energy by recycling a waste product, but also prevent the venting to the atmosphere of methane (CH_4), a gas whose greenhouse strength is 26 times that of CO_2 (Staniforth and Ormerod, 2001).

In the near term, it seems unlikely that fuel cells running on pure hydrogen will find widespread market applications for stationary power production. However, opportunities for hydrogen fuel cells look more encouraging for certain niche applications, in particular for back up or off grid power, or as an energy carrier for scenarios where the primary resource is remotely located, or the availability of the resource does not coincide with demand. Examples of where hydrogen could be used to store excess energy include nuclear power stations during times of low demand, and in locations with abundant renewable resources.

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