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A FUEL CELL AND HYDROGEN TECHNOLOGY WATCH BASED ON EMERGING PRODUCTS

FINAL REPORT

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The European Commission is supporting the Coordination Action "HyLights" and the Integrated Project "Roads2HyCom" in the field of Hydrogen and Fuel Cells. The two projects support the Commission in the monitoring and coordination of ongoing activities of the HFP, and provide input to the HFP for the planning and preparation of future research and demonstration activities within an integrated EU strategy.

The two projects are complementary and are working in close coordination. HyLights focuses on the preparation of the large scale demonstration for transport applications, while Roads2HyCom focuses on identifying opportunities for research activities relative to the needs of industrial stakeholders and Hydrogen Communities that could contribute to the early adoption of hydrogen as a universal energy vector.

Further information on the projects and their partners is available on the project web-sites www.roads2hy.com and www.hylights.org

EXECUTIVE SUMMARY

This report is a deliverable of the Roads2HyCom project, a partnership of 29 stakeholder organisations supported by the European Commission Framework Six programme. The project is studying technical and socio-economic issues associated with the use of Fuel Cells and Hydrogen in a sustainable energy economy.

Within the project, several studies have looked at the state of Research and Technology Development, in Europe and elsewhere. The aim of this Technology Watch study has been to identify recent changes to the "accepted wisdom" on Fuel Cell and Hydrogen technologies that could lead to opportunities for the technology to enter the market more quickly. Since these technologies are potentially moving closer to market, this has been done by focussing not on basic technology elements, but on sectors of application. The study has used information from the public domain to highlight the predicted timing and nature of delivery of these emerging technologies, either as fully commercialised products, limited volume products for market trial and extended demonstration, or as prototypes.

The study has found a limited number of products sold on a genuinely commercial basis today (meaning that the value chain trades profitably in supplying the product). In Europe, one manufacturer is supplying a low power leisure power unit on this basis. Alongside this, a small number of industrial-scale combined heat-power systems, buses, cars, two-wheelers and forklifts are made available, mostly to demonstration projects with civic support.

However, this is now a fast-moving arena. By 2015, fully commercialised (meaning fully profitable) products are expected in market-significant numbers in domestic CHP, forklift trucks and small portable applications. In all cases they offer an advantage over incumbent technologies. The success of these products in the marketplace, both in terms of initial sales and proving themselves worthwhile, will be crucial to the future credibility of the Fuel Cell.

In the same time horizon there will be new products in the road transport sector, albeit at very low volumes relative to the sector as a whole. At this time it is unlikely that they will be sold on a profitable basis, although civic authorities may choose to pay a substantial premium (e.g. for buses) to stimulate future demand. Road transport is one of the "ultimate prizes" of the Fuel Cell business – the market transition phase will be decades, and policy for the "greening" of Hydrogen supply are essential as volumes rise significantly in the 2020-2050 period.

In reporting market progress for the Fuel Cell, it has sadly too often been the case that the technology seems to remain permanently in the future. A Technology Watch of this type may be telling a very different story ten years from now; in the meantime it is to be hoped that the promise seen in so many sectors now, is actually realised in products that users appreciate.

ROADS2HYCOM TECHNOLOGY WATCH – FINAL REPORT

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1. Introduction

This report is a deliverable of the Roads2HyCom project, a partnership of 29 stakeholder organisations supported by the European Commission Framework Six program. The project is studying technical and socio-economic issues associated with the use of Fuel Cells and Hydrogen in a sustainable energy economy. Within the project, several studies have been made related to the status of Fuel Cell and Hydrogen technologies. This Technology Watch aims to look at the latest relevant developments by product sector.

Fuel Cell and Hydrogen technologies have been seen for some time as potential key players in a sustainable energy economy. However, these technologies have seen many "false dawns" in terms of past predictions for their arrival in, and uptake by, the market. In reality it remains hard to identify a product whose entire supply chain is trading profitably in these technologies.

Events of recent years, in particular the growing concern over man-made greenhouse gas emissions, the rising price of fossil fuels and continued political volatility in oil-producing regions, have made the potential need for these new technologies stronger than ever. And responding to that need, research continues to yield new developments in what the technologies are capable of.

The Roads2HyCom project has addressed the status of technology development in a number of complementary ways, namely:

- Mapping of Fuel Cell and Hydrogen Research and Technology Development Activity in Europe [1.1]
- Development of an interactive, on-line Wiki based encyclopaedia of information on the "State of the Art" of Fuel Cell and Hydrogen technologies [1.2]
- Studies of how future application-specific technology combinations may compete with incumbent technologies and other alternatives [1.3, 1.4, 1.5]
- Development of a set of Research recommendations based on these studies [1.6]

This study complements these others by looking at recent and publically announced future developments by application sector, in the form of a calendar of milestone events or achievements. For each sector, the information is used, along with analysis of relevant technical performance indicators, to seek insight into the future prospects and to validate (or otherwise) conventional thinking on the status of that sector.

2. About Roads2HyCom

Roads2HyCom is a research project that is assessing the European state of the art of Fuel Cell and Hydrogen related technologies relative to infrastructures, resources and the expected needs of early adopters. From this assessment, Roads2HyCom is identifying where research effort is needed to close the gaps and exploit opportunities. Through this work Roads2HyCom, along with the Coordination Action HyLights, is supporting the European Commission and other stakeholders in planning future H2&FC research activities.

Roads2HyCom achieves this goal by three key elements of work:

- **Mapping** of researchers, technology advances, infrastructures, energy resources, potential early adopting communities and their financing mechanisms
- **Analysis** of where the technical State of the Art lies, likely evolutionary scenarios for technology, capacity of future energy resources, and generic classifications of technology adopter ("hydrogen community") and their funding mechanisms
- **Engagement** of stakeholders, from the Commission, HFP and National / Regional governments, to researchers and existing or potential communities of early-adopters, via dialogue, workshops, dissemination and training

An overview of the project structure is provided in Figure 1.

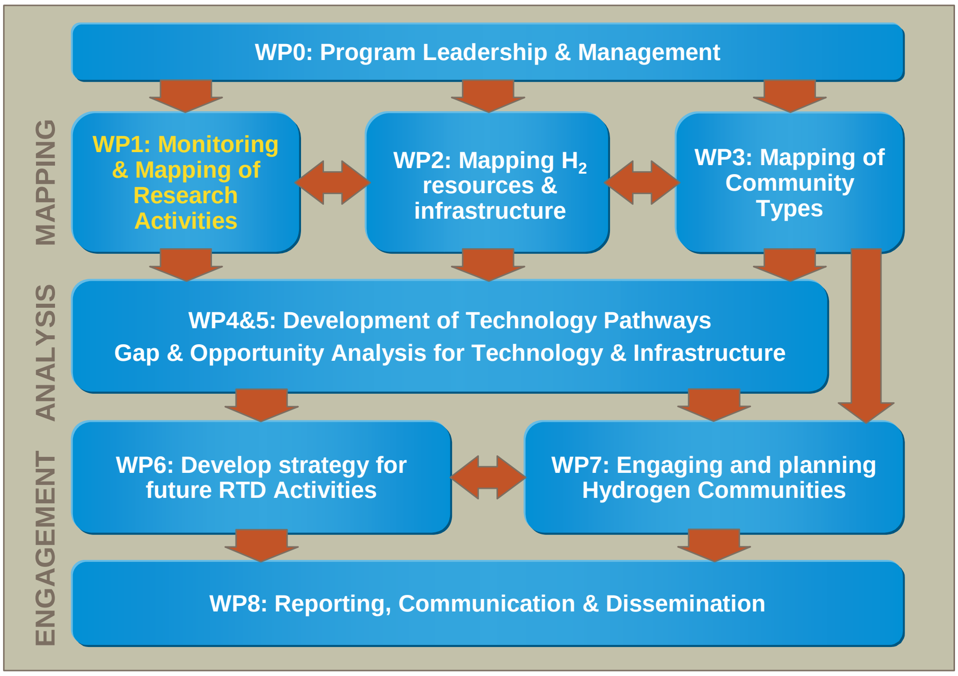

Figure 1: Roads2HyCom Project Work Structure

One of the activities of the Roads2HyCom project has been to create a calendar of R&D milestones, building upon the other R&D mapping exercises conducted by the project. This activity, known as the Roads2HyCom Technology Watch, aimed to identify breakthroughs that could substantially increase the viability of a fuel cell or hydrogen technology, and also breakthroughs in competing technologies (for example, storage of electricity) that could render Hydrogen less competitive as an energy vector. The output from this activity is a series of future time lines that highlight the predicted timing and nature of delivery of emerging technologies, the scope of which includes planned as well as existing programmes.

The Technology Watch activity has been conducted mainly by Ricardo UK with support from other Roads2HyCom partners, in particular RWTH Aachen, JBRC Prague and CoreTec Ventures.

Roads2HyCom is an Integrated Project funded under the European Framework Six Programme. The project brings together 29 partners from a broad cross-section of areas including energy and hydrogen supply, transport industries (surface and air), stationary power (buildings, industry), engineering and socio-economic research, finance and community expertise. Further information about Roads2HyCom, including project reports and on-line tools, can be found on the project website www.roads2hy.com.

3. Objectives and Methodology

The aim of this Technology Watch study has been to identify recent changes to the "accepted wisdom" on Fuel Cell and Hydrogen technologies that could lead to opportunities for the technology to enter the market more quickly. Since these technologies are potentially moving closer to market, this study has focused on sectors of application (referring if necessary to basic research breakthroughs that affect the sector), rather than on the status of fundamental research[1].

The study has used information from the public domain to highlight the predicted timing and nature of delivery of these emerging technologies. Planned as well as existing development and research programmes have been included. Information on recent concepts, prototypes and products has provided an indication of Fuel Cell and Hydrogen technology readiness in each application sector. The study has also drawn on information gathered in other work tasks of the Roads2HyCom project.

Hydrogen is an energy vector, in that it must be produced from a primary energy source before it can be used. If technologies that use hydrogen as a fuel are to become commercially successful, then the technologies behind the hydrogen infrastructure to support that technology must also be successful. Therefore the Roads2HyCom Technology Watch included technologies from across the hydrogen energy chain, as illustrated in Figure 2.

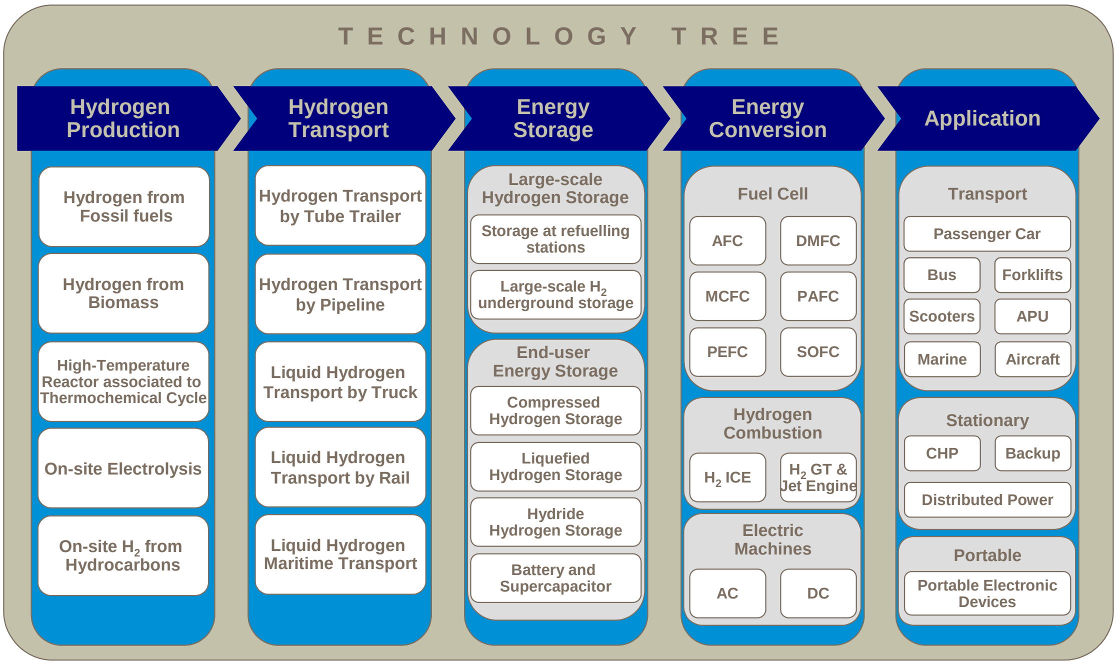

Figure 2: Examples of hydrogen technologies across the hydrogen energy chain

[1] Information on the State of the Art can be found on the Roads2HyCom Hydrogen and Fuel Cell Wiki (www.ika.rwth-aachen.de/r2h)

Fuel cells are the main family of technologies that use hydrogen as a fuel. However, some types of fuel cell can run of other fuels, for example Solid Oxide Fuel Cells (SOFC) can utilise natural gas. Therefore Roads2HyCom has also watched the development of infrastructures for other energy vectors such as natural gas and methanol.

The Technology Watch gathered information on news of upcoming projects and demonstration programmes, forecast predictions and announcements made about steps taken towards commercialisation of fuel cell and hydrogen technologies. Information sources included:

- Web portals and news websites
- Company press releases
- Conferences and seminars
- Industry journals, magazines and newsletters
- Technology contacts
- Data received through the Roads2HyCom Researchers Questionnaire[2]

The data collected from the public domain was stored in an Excel spreadsheet. The information recorded included technology category, launch date (generally proposed), country, company or organisation name, information about the technology and, finally, the information source. At the time of writing this report, the Technology Watch database contained over 500 data entries.

From the data gathered, a series of time lines were created. These times lines, which are presented by technology category, are discussed in the following sections. Collectively the Technology Watch Time Lines form a calendar of R&D milestones.

The information is used, together with analysis of relevant technical performance indicators, to seek insight into the future prospects of the applications, and to validate (or otherwise) conventional thinking on the status of the sector.

[2] In order to collect data on H2&FC RTD activity across Europe, Roads2HyCom launched an on-line survey called the “Researchers Questionnaire”. The results from this survey are contained in the Roads2HyCom report “A Map of Hydrogen and Fuel Cell Research and Technology Develop Activity in Eruope” (R2H1015PU), which can be download from www.roads2hy.com

4. Technology Watch Time Lines

4.1 Passenger Cars

Introduction

Application of Fuel Cell and Hydrogen technologies to the passenger car is seen by many as the “holy grail” in the field. There are good rational arguments for this, including the following:

- The Passenger Car sector offers a large greenhouse-gas abatement potential if the Hydrogen is sourced from low carbon or carbon-free energy chains
- Using Hydrogen as a fuel gives rise to near-zero tailpipe emissions, taking the product itself out of the environmental equation and concentrating the control of greenhouse-gas emissions upon a few Hydrogen fuel producers
- The automobile manufacturing sector possesses mass-production expertises that can leverage lower costs, with potential benefits that could spill into other sectors
- The application is one which every citizen experiences, hence the application is politically popular

Technologies employed in the passenger car sector are as follows:

- Fuel Cell (currently the PEM type is universally used for the powertrain) with Hydrogen as a fuel; configured in a number of ways:
  - Fuel Cell (non-hybrid): Electric power from the fuel cell being used to drive the wheels via one or more electric motors. Power of the Fuel Cell is varied directly according to drive requirements.
  - Fuel Cell Hybrid (Sometimes abbreviated FC-HEV): As above, but a battery is used to store the electricity generated by the fuel cell, thus de-coupling fuel cell output and drive power, and allowing re-generative braking. This gives an efficiency advantage as with any Hybrid vehicle.
  - Fuel Cell Range Extender: Here, the vehicle is essentially an electric vehicle (EV); a small fuel cell is used as an onboard generator to extend the operating range, the vehicle can be refuelled with both electricity and Hydrogen.
- Internal Combustion Engine (H2-ICE): Here the Hydrogen is used as a combustion fuel in an Internal Combustion Engine, which uses conventional mechanical drive to the wheels. As with any ICE, the system can also be

hybridised (added electric motor/generator capacity to re-cycle braking energy) to improve efficiency

- Hydrogen storage is a critical issue, as tanks tend to be bulky and costly. Common methods used are pressurised gas (350 or 700 bar) and cryogenic liquid Hydrogen

As yet there are a very limited number of Fuel Cell or Hydrogen products on the market (see below), but there has been substantial prototype demonstration and evaluation activity worldwide since the mid 1990s. Some of these prototypes have been loaned or leased to selected users under carefully controlled conditions. This demonstration activity provides the basis of most of the analysis presented below.

Looking forward, it is important to differentiate between levels of “Commercialisation” or sale of vehicles, because unlike some sectors, the car industry has a large existing business from which it can subsidise early activities:

- Extended demonstration - A small number of vehicles may be sold for a suitable notional sum to selected Hydrogen Community projects. The notional sum may not fully cover the cost of vehicle supply, and quantities of vehicles may be limited

- Non-profitable commercialisation - Because of the importance of this technology to the automotive industry, it is entirely possible that an intermediate step may be used to build a customer base for an “image” product on a break-even or loss-making basis. It is said that Toyota used such an approach with their first generation Prius gasoline-electric Hybrid car, which is now said to be a profitably commercialised product

- Profitable commercialisation - Where products are freely sold on a basis that is, or can be, profitable along the value chain (Suppliers, Manufacturer, Retailer)

Main Players

Most major automotive manufacturers have some kind of activity in this field:

- Daimler, Ford, General Motors, Volkswagen, FIAT, Honda, Toyota, Nissan, Mitsubishi and Hyundai have all shown one or more (in some cases much more) prototypes using Fuel Cell Hybrid (FC-HEV) technology. In some cases the fuel cell stack technology has been sourced from a supplier (most notably Ballard); in other cases it is developed in-house. In all cases the Hydrogen fuel is stored as a compressed gas

- PSA (Peugeot-Citroen) have recently shown a vehicle of the Range Extender type, with stack technology from Intelligent Energy; having shown more conventional hybridised fuel cell concepts in the past

- BMW have focused uniquely on the Internal Combustion Engine and on liquid fuel storage, and have a product on sale in very low volumes; Ford have also developed prototypes with a Hydrogen ICE, including an electrically hybridised version

Table 1 shows a summary of the major passenger car players, their affiliations, their latest prototypes and declared product plans.

Table 1: Summary of Passenger Car OEM activity

OEM	Technology	Affiliations	Latest prototypes	Declared Plans
BMW	ICE, LH2	ICE technology developed in-house, fuel tank links to Magna Steyr	7-Series limited production bi-fuel (2007) & H2 (2008); boosted test-bed engine giving 48% efficiency (2006)	Smaller, boosted engines in vehicles; combined pressure/cryo storage; no dates announced
Daimler	PEM, 700 bar	Ballard; took over Automotive Operations in 2007 with Ford	B-series F-Cell (2008)	B-series available to HyCom projects from 2010; product on sale target 2012-15
Fiat	PEM, 350 bar	Nuvera, Zero Regio project	Panda Hydrogen Concept (2006)	None specific
Ford	PEM & ICE, 700 bar	Ballard; took over Automotive Operations with Daimler in 2007; part own Mazda (Rotary H2 ICE)	Edge HySeries plug-in FC-HEV (2007)	ICE as bridge to fuel cell; FC products post 2015
GM	PEM, 700 bar	Technology developed in-house	Chevy Equinox FC	100 Equinox demo from 2008 in USA; 1000 vehicle trial in California 2012-2014
Honda	PEM, 700 bar	Technology developed in-house	FCX Clarity (2007)	Leasing of Clarity in Tokyo & LA from 2008; Home refuelling; first general product ca 2018
Nissan	PEM, 350 bar and 700 bar	FC technology developed in-house. Batteries developed in collaboration with NEC	X-Trail FCV	Limited numbers of FCVs leased to specific customers
PSA	PEM Inter-changeable Cylinder	Intelligent Energy	H2Origin (2008)	None specific
Toyota	PEM, 700 bar	Technology developed in-house	FCHV-6 (2007)	Fleet use 2010-2020; mainstream products 2020-2030; platinum-free PEM
VW	HT-PEM, 700 bar	Phosphoric acid technology developed in-house – previously used Ballard stacks	Space Up Blue (2007)	Running prototype 2010; products from 2020

Recent Developments

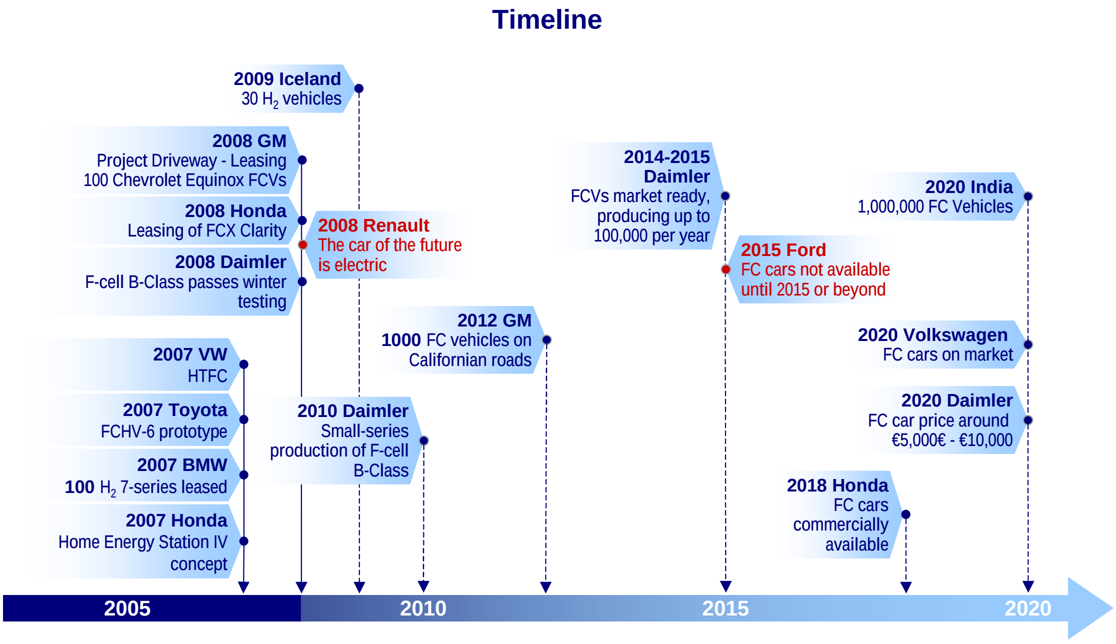

Figure 3: Timeline for fuel cells and H_2-ICE development for some of the major OEM's

Honda claim to be the first manufacturer to launch fuel cell vehicles in dealer showrooms [4.1.1]. A limited number of Honda FCX Clarity vehicles are being leased in Southern California from summer 2008. The first few vehicles were delivered to customers at the end of July 2008 [4.1.14]. Honda state that more vehicles will be rolled out in the future, as more hydrogen refuelling options become available, but this manufacturer is also one of the most publicly prominent in promoting home refuelling, via a "tri-generation" unit that uses a second fuel cell system to create domestic electricity, heat and Hydrogen fuel using a natural gas supply.

Figure 4: Honda FCX Clarity – "ready for the dealer showrooms"

However, the prospect of genuine product sales to ordinary buyers remains one for the future; it is perhaps more relevant to look at the next generation of demonstration or community-based activity as an indicator of progress. Daimler, Ford, Toyota and GM are all entering a new phase of demonstration, involving typically hundreds of cars, maximum 1000 (the previous generation of demo used typically tens of cars, maximum 100). This in itself indicates that recent engineering developments (which often remain highly confidential) have justified the investment in these much more extensive field trials.

The next generation of vehicles has also been engineered in a manner that is much more representative of standard production quality – for example, enduring exhaustive testing in hot and cold climatic conditions, and systematic rig-testing of multiple units of the fuel cell and other key components to establish and improve their durability. The objective, broadly, is that this next generation of vehicles should be able to operate under the most "normal" conditions possible – although lack of Hydrogen infrastructure means that most will remain close to their chosen point of sale or leasing.

Figure 5: Daimler (Mercedes) B-Class F-Cell undergoes winter testing

The next generation of vehicles are also demonstrating significant improvements in efficiency, which is one of the key attributes that make the fuel cell attractive. Some earlier prototypes (which tended to be engineered primarily for reliability in the field) yielded disappointing efficiency results. For example, the Daimler A-Class F-Cell cars returned a Hydrogen consumption which was equivalent (on an energy basis) to 3.6/l100km of Diesel [4.1.2], which is only slightly lower than that of the best B-segment Diesel vehicles on sale today (3.7l/100km).

However, such data can be misleading, as they relate to early prototype products that may be non-optimal or engineered with an emphasis on surviving the fleet trial. The new B-Class F-Cell (see Figure 5) [4.1.2, 4.1.3] uses just 0.87kg of Hydrogen per 100km, which has the energy equivalence of 2.9l/100km Diesel. As a headline, this is as efficient as the best "3 litre" (3l/100km) Diesel cars, which were based on vehicles two segments smaller than the B-class. However it is perhaps more relevant to consider the "well to wheels" performance which takes into account the whole energy chain: Using Hydrogen made from Natural Gas by current processes [4.1.4], this gives a well to wheel CO_2 figure of around 115g/km, which is comparable to a Diesel-Electric hybrid in the same type of bodyshell [4.1.5]. Unlike the Diesel vehicle (given the limitations on uptake of biofuel) this figure can be reduced toward zero as the fuel supply is de-carbonised (see Table 2 for the comparison benchmarks).

Table 2: Comparison of Fuel Cell car with future benchmarks

Vehicle Type	Example	Based On	Power-train	Tank to Wheel fuel consumption	Energy Chain	Well to Wheel CO_2
Fuel Cell	Mercedes F-Cell	Mercedes B-Class (C-segment MPV)	80kW PEM FC; 6.5Ah LiIon, 100kW motor	0.87 kg H2 / 100km Zero tailpipe CO_2	Steam reforming of Methane, current processes; 111g CO_2 / MJ H_2	115g/km
Fuel Cell	Mercedes F-Cell	As Above			Future Hydrogen supply SMR+CCS, 45g CO_2/MJ	46g/km
HEV	PSA / Ricardo EfficientC	Citroen Berlingo (C-segment MPV)	67kW Diesel; 18/25kW motor; 2kWh LiIon; robotised transmission	3.66l Diesel / 100km 99g/km Tailpipe CO_2	Diesel with <5% Gen 1 Bio content; effective 91% CO_2 efficiency	109g/km
PHEV	Hypothetical plug-in version of the above vehicle; added 3kWh battery capacity			0.11kWh (SoC[3]) / km in urban use	Electricity Grid EU-avg 430g CO_2 / kWh at meter	46g/km for Electric urban use

Fuel Cells compete with some very mature technologies such as the Internal Combustion Engine, which are cheap by virtue of a history of almost 100 years of mass production, and the use of cheap materials such as iron, aluminium and plastics. Current demands for clean exhaust emissions and higher fuel efficiency have increased the cost of these incumbent technologies, by effectively mandating the addition of extra components such as exhaust after-treatment and hybridisation technologies.

The Roads2HyCom "State of the Art" (SOTA) study found that recent R&D efforts have resulted in significant reductions in fuel cell system costs, toward the HFP "Snapshot 2020" target [4.1.6] of less than €100/kW. Data for PEM FC costs (Figure 6) shows data from both Ballard [4.1.7] and Johnson Matthey [4.1.8] indicating the ability to produce a stack (not complete system) for around €50/kW (in this case, these figures are indications of what production costs would be, in high volumes;

[3] A difference of State of Charge (SoC)

costs for prototype or low volume systems remain over €500/kW). This picture is encouraging; however, sustained research into both lower cost designs and manufacturing technology is required to ensure that these costs are actually realised for both stationary and transport applications.

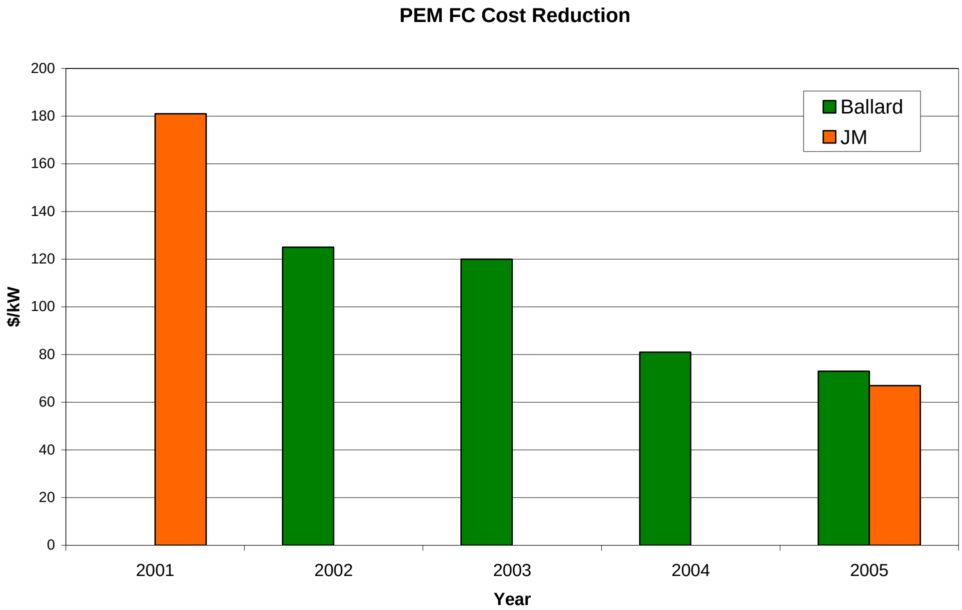

Figure 6: Reduction in PEM FC stack costs - Volume of 100k-500k p.a

Source: Ballard [4.1.7] and Johnson Matthey [4.1.8]

Durability needs to match that of benchmark products, under identical real world operating conditions. A passenger car with life of 200,000 km requires a fuel cell life of 5000 hours. Here, SOTA data can be supplemented with “real world” experiences from demonstration projects [4.1.2]. Field trials of the Mercedes A-class F-Cell car indicated a fuel cell stack life of 1000-2000 hours in a range of climatic and usage conditions, with typically a failure every 4000 km toward the end of the trials. The new B-Class F-Cell has a claimed stack life of 5000 hours [4.1.2, 4.1.3]. So, promising progress is evident in fuel cell durability, and also in the associated field of extremes of high and low temperature operation. Further research must translate this progress into durable products made in higher volumes.

So, with encouraging progress in terms of cost, operating envelope and durability, it may be appropriate to consider when the first generally available products will reach the market. Media quotes from front runners including Daimler, Honda and GM indicate a range from 2012 to 2018, though others such as VW and Toyota are more cautious, citing post 2020. However as a caveat it should be noted that similar quotes in the past have proved unreliable, with the same players having originally indicated that products might be in sale from around 2004 onward.

Drivers and Barriers

As explained at the start of the section, the key drivers for Fuel Cell and Hydrogen technologies are the pairing of greenhouse gas reduction and fossil fuel resource depletion. As an added bonus the fuel cell offers effectively zero emissions at the point of use, though this is less of an advantage than it used to be, due to progress in cleansing the emissions of conventional internal combustion engines. For example, the Californian SULEV emission standard (which is one level removed from the zero emission standard) can be met by many production Gasoline-engined vehicles, and laboratory research indicates that solutions are on the way for the Diesel [4.1.9].

Political pressure to address the carbon / fossil dependency issue is growing, with 2008 seeing significant regulatory developments in both Europe and the USA:

- In the EU, legislation passing through Parliament in 2008 will mandate an average CO_2 emission (at the tailpipe) of 130g/km for new cars [4.1.10], compared to 164g/km in 2007. This average can be met with much simpler technologies than Fuel Cells and Hydrogen (in fact, even Hybrids are only likely to be needed in small quantities [4.1.11]), but the legislation could be a starting-point for further measures beyond 2020 which create pressure to commercialise more efficient alternatives.

- In the USA, a new standard for corporate average fuel economy (CAFE) will require a fleet average of 35mpg (US) by 2020 [4.1.12]. Given the high proportion of SUVs and light trucks sold as passenger vehicles in the USA, this level of legislation may require more radical change, albeit over a longer timescale.

As a result, legislative drivers post 2020 could create a market environment where a Fuel Cell or Hydrogen vehicle could succeed commercially, if the state of the art has advanced sufficiently by then to address remaining known issues. A key issue is the bulk and cost of the Hydrogen tank.

Unlike for the fuel cell itself, there is little available information on reducing the cost of Hydrogen storage, in terms of current achievements or future projections. A recent press feature on GM's activities cited a cost of around €10,000 per tank for production of 5000 vehicles [4.1.13]. The 700 bar tank is a complex component, involving an impermeable liner, a carbonfibre shell that is robot-wound in a process that takes days, and typically 200 embedded sensors to monitor for the onset of failures. A tank giving 300 km range in a car is a bulky component whose shape cannot be adapted to fit available package spaces. Until significant developments occur, it is possible that the tank, more than the fuel cell itself, may define what types of transport application can be successful.

As a product, the fuel cell car will be competing not with conventional vehicles as we know them today, but with a new generation of technologies being developed to meet the legislative challenges from 2015 to 2020 (Table 2):

- Hybrid Electric Vehicles (HEV) combine an Internal Combustion engine (conventionally fuelled) with one or more electric motors and a battery, to re-cycle energy that is otherwise wasted under braking. On a well to wheel basis, a best-in-class HEV (which would feature a Diesel engine) will emit slightly less CO_2 per km than the best prototype Fuel Cell vehicle has demonstrated to date (based on today's Natural Gas energy chain); of course de-carbonising of the Hydrogen energy chain will reverse this situation

- Biofuels: Although the limitations of "first generation" Biofuels have received much bad publicity in the last few years, it is likely that a second generation (using crop waste, not food material) will be in use by 2020, which could close any competitive CO_2 advantage that the Fuel Cell car enjoys as a result of de-carbonised Hydrogen supply. However it is commonly believed that, once the needs of other sectors are considered, bio-content of liquid fuels is unlikely to rise above 30%.

- Plug-In Hybrids (PHEV): Derived from the Hybrid vehicle, these have extended battery capacity, which can be topped up by plugging the vehicle into the electric grid. This enables short journeys (up to 20-50 km) to be completed using electric drive only. The total energy-chain efficiency of electric drive can be relatively high (around twice as high as converting the electricity to Hydrogen in an electrolyser, then back again in the Fuel Cell), so this technology creates a strong competitor to the Fuel Cell. Table 2 shows very similar "well to wheel" performance for a PHEV in Electric mode, and a Fuel Cell car using carbon-captured Hydrogen

- Electric Vehicles (EV): Pure Electric vehicles continue to suffer from driving range limitations, though both range and re-charge time are improving. EVs are likely to be most attractive as second cars for city use

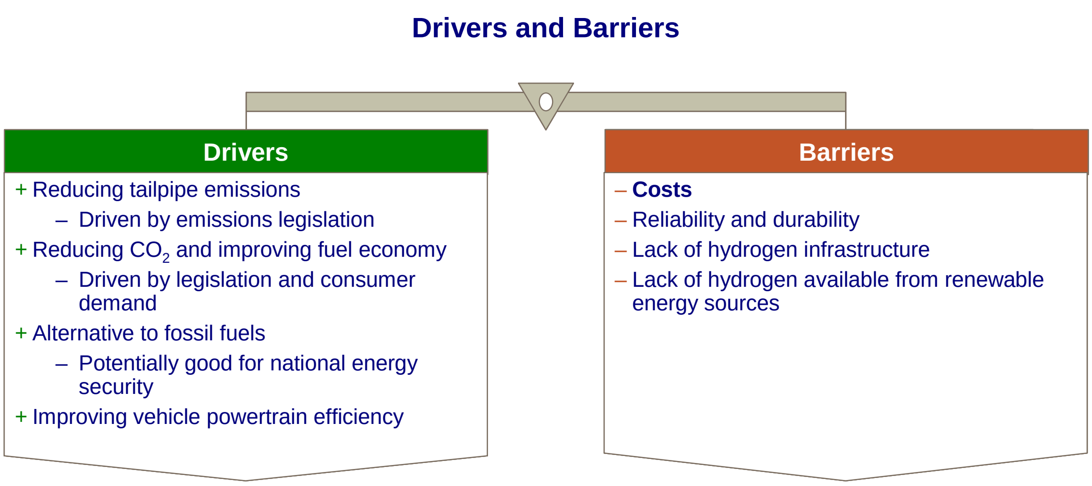

Figure 7: Drivers and barriers for introduction fuel cell and hydrogen technology into passenger cars

Concluding Remarks

The passenger car is a very important application for Fuel Cells and Hydrogen, due to its ubiquity, which creates both a need and a route to economies of scale. Encouraging progress is evident in terms of technical performance of Fuel Cells (and also Hydrogen ICEs) in the latest field-trial vehicles, and also in terms of the level of commitment displayed by a number of manufacturers. There appears to be a route map for addressing the Fuel Cell cost issue, though not, as yet, for the cost of the fuel tank.

The PHEV is both a significant competitor and a stepping-stone for the fuel cell car; it will set a high benchmark by providing cheap, emission-free electric operation in urban environments, and long driving range on the highway. But it will also provide an ideal platform for replacing the combustion engine with a fuel cell, possibly retaining the electric re-charging feature (which would mean that Hydrogen refuelling can be concentrated on trunk routes). The precise nature of the products that finally become fully and profitably commercialised will depend on the outcome of one of the defining technological battles of the twenty-first century: The battle between the storage of Electricity and storage of Hydrogen.

4.2 Buses and other Captive Fleets

Introduction

The Fuel Cell / Hydrogen bus may be regarded as a less glamorous application than the passenger car by some, but it is also seen by many as an important early market step for road transport. The bus is an attractive application because it can be used by the general public without their needing to commit to a product purchase, and because city authorities are keen to promote public transport to reduce problems of congestion and private vehicle parking.

As with the passenger car, vehicles tend to be available only on a project-specific basis, although there have been open procurements (competitive tender) for buses. Bus applications have used a mix of Fuel Cell and Internal Combustion powertrains, both generally using compressed Hydrogen stored in tanks on the vehicle's roof. The Internal Combustion vehicles usually use the conventional mechanical transmission of the donor Diesel bus (although a Series-Hybrid Electric drive is possible and would be more efficient); the Fuel Cell vehicles use electric drive (though in some cases this passes through a standard Diesel bus transmission unit).

Buses are an attractive application from an infrastructure viewpoint, because they can return to their depot for refuelling. A similar argument can be applied to taxis and urban delivery vans, which may eventually use passenger car Fuel Cell and Hydrogen technologies but are more similar to Buses in terms of early market adoption, since they are closely controlled captive fleets.

Main Players

Because of the inevitable connection to civic authorities, bus and other fleet transport applications tend to be even more strongly linked to publically funded fleet demonstration projects.

HyFLEET:CUTE is one of the bigger projects. Supported by the European Commission, the project involves the EU, Australia and China. It started in 2006 and is expected to finish in 2009 [4.2.1, 4.1.2]. The HyPATH project [4.2.2] is a sidetrack of HyFLEET:CUTE, which included 31 members from the HyFLEET:CUTE project. It started in 2007 and the aim is to drive the development of fuel cell buses forward.

In Zero Regio [4.2.3] the aim is to construct and demonstrate a hydrogen infrastructure for supplying fuel cell vehicles. Zero Regio started in 2004 and will end in 2009. The project combines 16 partners from four EU countries and uses a range of hydrogen sources, infrastructure configurations and vehicles in two different locations.

The Hydrogen Bus Alliance [4.2.4] is an international project that aims at creating a genuine market for hydrogen-powered buses. Each member of the Alliance has committed to buy at least five new hydrogen buses to begin operating between 2008 and 2012.

Table 3 summarises the main manufacturers involved in the Bus sector. The picture for other fleet vehicles is very much more application-specific – for example London

Taxi and Intelligent Energy are collaborating to develop a Fuel Cell taxi that meets London's unique taxi regulations but is also applicable globally [4.2.5].

Table 3: Key players in the Bus sector

Company	Technology	Projects	Collaborations
Daimler Chrysler	FC	HyFLEET:CUTE	Ballard Power Systems
Ford	H_2 internal combustion engine	8 buses-fleet in Orlando	-
Van Hool	FC	Demonstration in Belgium	UTC Power
Hyundai	FC	Germany 2006 FIFA World Cup games	Enova
MAN	H_2 internal combustion engine	HyFLEET:CUTE in Berlin 2006 FIFA World Cup games	-
Irisbus	FC	Demonstration in Turin (2004)	UTC Power
Toyota	FC	JHFC in Japan	-

Recent Developments

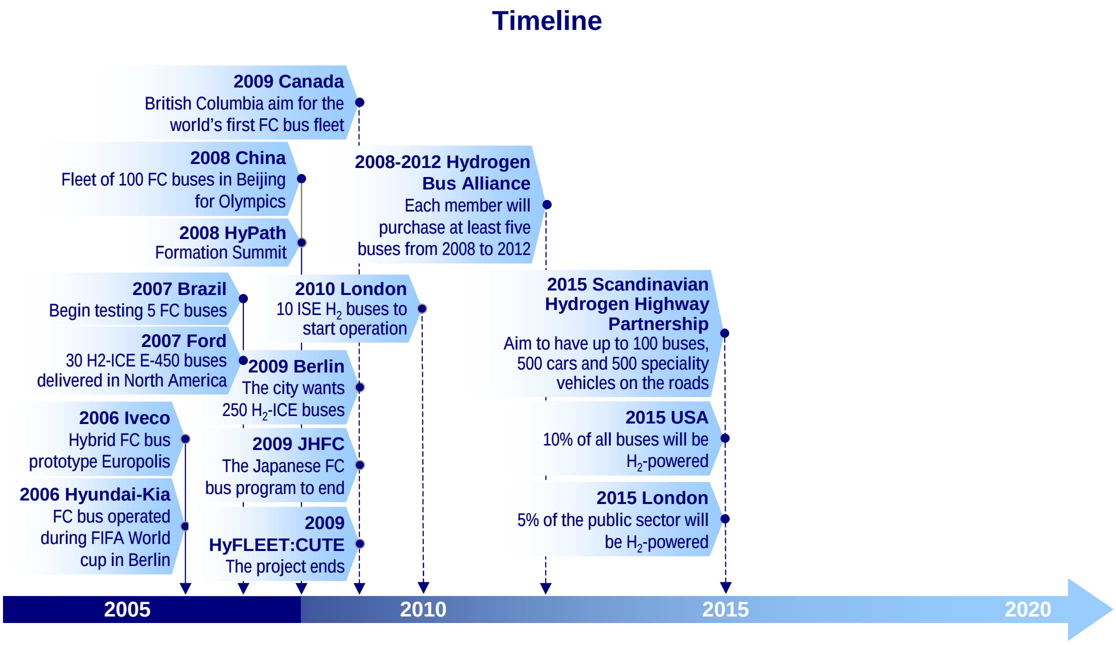

Figure 8: Key Milestones and Future Developments for Hydrogen / Fuel cell powered buses

Figure 8 contains an overview of recent fuel cell bus demonstration projects, along with proposed future plans from several cities and regions.

The vehicles in use in current global demonstrations were mostly developed in the late 1990s. This means that there is good data on the performance of these products in the field [4.1.2]. In the bus sector, stack life of over 4000 hours and availability of 99.6% were recorded, in trials that encompassed a range of climatic conditions. The availability figure (which was a best case recorded toward the end of the CUTE project) is competitive with a conventional vehicle; however this level of stack life represents only a year's use at 12 hours per day. Experience from these projects also showed that control of Hydrogen purity is critical to achieving good durability.

The trials demonstrated that (in common with any bus application) fuel consumption is strongly linked to passenger cabin heating and cooling needs. Averages of between 20 and 30kg H_2 per 100km were recorded [4.1.2], with 15-18kg/100km being used as drive power. A consumption of 15kg/100km is equivalent on an energy basis to 50l/100km of Diesel; for comparison a contemporary 12m Diesel bus records a fuel consumption of 36-40l/100km on a typical city drive cycle [4.2.6].

As with the passenger car, reading too much into the efficiency of first generation demonstration prototypes is misleading. A next generation of Hydrogen bus is in development, however as yet no data has been made available on the performance gains. However, it is likely that the relative comparison between a Fuel Cell bus and a Diesel-Electric Hybrid will be similar to the case for passenger cars.

Recent political developments in the use of buses are very significant. The formation of the European Hydrogen Regions and Municipalities Partnership (HyRaMP, [4.2.7]) brings together civic authorities with a combined need for over 12,000 buses (a market of over 1000 units per year), which is a significant volume for bus manufacture. Typically these authorities (such as London and Hamburg) are mostly replacing their fleet with Diesel-Electric Hybrids, and acquiring a smaller number of Hydrogen buses for extended evaluation. Potentially a larger Hydrogen bus procurement might be considered when the currently new Hybrid buses reach the end of their working life, around 2015-20.

Drivers and Barriers

Environmental and energy dependency issues are similar to those for the passenger car (Section 4.1 above), but there is as yet no proposal for fuel efficiency or CO_2 legislation in the bus sector (the EU and US legislation does however cover light commercial vehicles).

The Roads2HyCom project has highlighted "political will" as the strongest driver for the adoption of Fuel Cell and Hydrogen technologies by civic authorities [4.2.8], and this is certainly a highly relevant factor in this sector. Another study within Roads2HyCom [4.2.9] has found, unsurprisingly, that high-utilisation vehicles like buses and taxis show greater sensitivity to fuel price, and lower sensitivity to capital cost. Combining this factor with the possibility of continued initiatives for fiscal support indicates that the bus and fleet vehicle sector is a promising early market for road transport.

The findings on promising potential cost reduction described in the section on Passenger Cars (Section 4.1) are equally applicable to these other types of road vehicle; again, future research effort must ensure that this potential is realised in a commercialised product. Hydrogen storage again presents a challenge, but in the case of the bus, roof-top storage is often possible (though in some circumstances, height restrictions prevent it; and it is not applicable to a double-deck bus).

In the bus sector (and also taxis and delivery vans), the Diesel-Electric Hybrid will effectively be the competitive benchmark at product introduction, though for bus application the case for "plug-in" functionality does not exist with known battery technology. As shown above, efficiency improvement in the next generation of prototype, plus de-carbonisation of the Hydrogen supply, are needed to ensure that the Fuel Cell and Hydrogen product remains competitive.

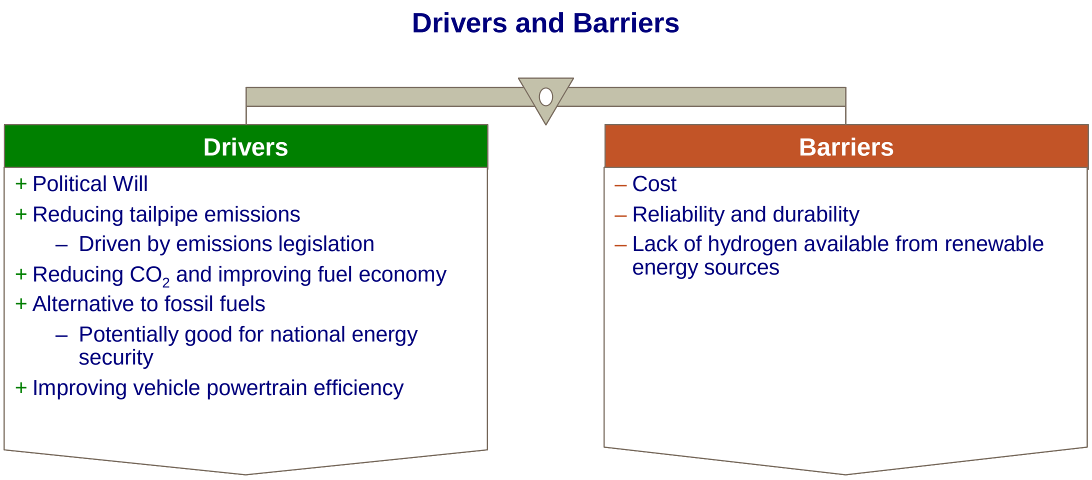

Figure 9: Drivers and barriers for introducing fuel cell and hydrogen technology into buses and other captive fleets

Concluding Remarks

The captive fleets sector is known to be a promising early market for Fuel Cells and Hydrogen, because of lower infrastructure dependency and the beneficial effect of local political will on purchase decisions. Perhaps importantly, these early fleets might provide seeds for the growth of a more extensive Hydrogen infrastructure, linking city centres to highway refuelling.

It is therefore important that the new generation of prototype vehicles, for which data is not yet generally available, show similar improvements to those seen in the latest prototype passenger cars. Given this factor and the "seed potential" described above, the success of the next generation of Fuel Cell and Hydrogen vehicle will be critical to the success of Hydrogen in Transport.

4.3 Material Handling Vehicles

Introduction

One of the first fuel cell vehicles was the Allis Chalmers Fuel Cell Tractor, produced in 1959. Since then, especially over the last decade, fuel cell and hydrogen ICE technology has been applied to forklifts, pallet trucks, tow vehicles, ice-surfacers, golf carts and small indoor trucks and wagons [4.3.1] (see Figure 10). Most of the prototypes to date have used hydrogen PEM fuel cells in conjunction with batteries or super capacitors to make “plug-n-play” fuel cell hybrid systems that can replace the existing battery power pack on battery forklifts. However, at least one industry consortium is researching the potential of DMFC technology for this sector and in May 2008 Linde launched a prototype hydrogen ICE forklift.

Examples of prototype fuel cell material handling vehicles

Figure 10: Examples of material handling vehicles powered by fuel cell systems

Main Players

The research and development of hydrogen and fuel cell powered material handling vehicles involves organisations from across the spectrum. Manufacturers of fuel cell stacks, such as Ballard, Hydrogenics and Nuvera Fuel Cells, are involved in seeing how their fuel cell technology can be adapted and applied to this vehicle segment. System integrators, such as Plug Power, Jülich Forschungzentrum and H2 Logic, are involved in building the fuel cell technology into hybrid power pack units that can be fitted to forklifts, pallet trucks and other similar vehicles. Material handling vehicle OEMs are involved, working along side the system integrators, in fitting of fuel cell systems to their forklift vehicles and promoting the technology. And users of material handling vehicles are involved in testing the fuel cell vehicles in the field. A summary of the organisations active in RTD of hydrogen and fuel cell powered material handling vehicles in supplied in Figure 11.

Figure 11: Organisations known to be involved in the development and testing of hydrogen material handling vehicles

Hydrogenics and Plug Power appear to have the most advanced “plug-n-play” fuel cell products designed for the forklift market (Plug Power bought into the fuel cell material handling sector by acquiring General Hydrogen Corporation and Cellex Power in 2007). Hydrogenics use their own fuel cell stacks, while Plug Power buy their fuel cell stacks from Ballard. Both systems incorporate ultra capacitors and compressed gas hydrogen storage. The Hydrogenics system, called HyPX, can store 1.6 kg of hydrogen at 350 bar, while the Plug Power system, called GenDrive, stores the hydrogen at 700 bar. Both Hydrogenics and Plug Power have been involved in numerous fleet trials of fuel cell powered forklifts across North America since 2005.

In Europe, Proton Motor (part of Proton Power Systems plc Group), Jülich Forschungzentrum and H2 Logic are involved in R&D programmes preparing for the commercialisation of fuel cell powered material handling vehicles. The fuel cell systems from Proton and H2 Logic run on hydrogen, while Jülich is developing DMFC power pack systems for pallet trucks as part of an industry lead consortium.

Nuvera have adopted a slightly different approach than the other system integrators, preferring to team with battery manufacturers who will use their fuel cells in hybrid power pack systems. In USA, Nuvera are working with East Penn Manufacturing, who use Nuvera’s fuel cell system to make the ReadyPower hybrid power pack. In Europe, Nuvera are working with Hoppecke Batterien.

Toyota launched an fuel cell hybrid powered forklift at CeMAT 2005. This system featured a 30 kW PEM fuel cell stack, a double layer capacitor and 350 bar gaseous hydrogen storage. This prototype forklift has been displayed in recent years at many trade shows throughout the world. However Toyota’s next generation fuel cell forklift prototype has not yet been launched and the status of their development is currently unclear.

Nuvera, Hydrogenics and H2 Logic also produce on-site hydrogen generation and refuelling systems that can be used for hydrogen powered forklifts, solving the issues surrounding providing a hydrogen infrastructure. The Nuvera system, known as PowerTap, generates hydrogen from natural gas. The Hydrogenics and H2 Logic systems generate hydrogen by electrolysis. Hydrogenics currently use an alkaline electrolyser in their on-site hydrogen generation system, but they are developing a PEM electrolyser option.

Recent Developments

Development of H2&FC powered forklifts began in the late 1990s, with Linde launching the first prototype fuel cell forklift in 1997. Since then the number of companies investing in this H2&FC application area has grown. An overview of the major recent developments and future projections is supplied in Figure 12.

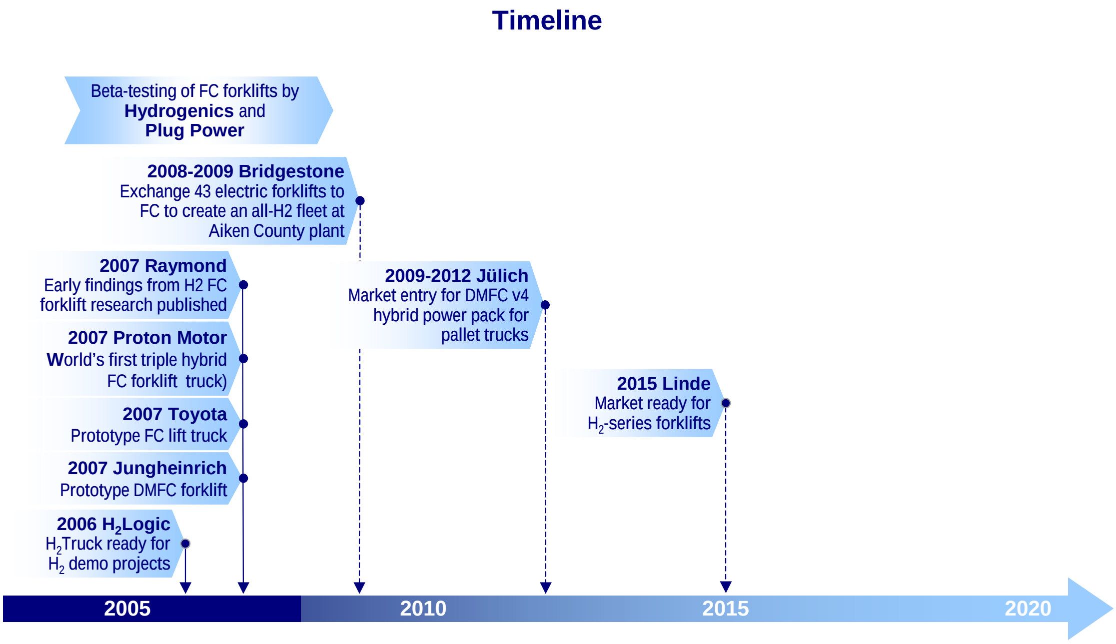

Figure 12: Key Milestones and Future Developments for Hydrogen / Fuel cell powered Material Handling Vehicles

The development focus in recent years has been on fleet trials of fuel cell forklifts at user warehouses and distribution centres. Data from these fleet trials is being used by the forklift manufacturers and system integrators to improve the design of the fuel cell products. The trials are also helping to grow demand for fuel cell forklifts, with several of the forklift users, such as Bridgestone Firestone Tire and Concurrent Technologies Corporation, placing orders to support further fleet trials.

One R&D project of particular note is Raymond Corporation's fuel cell forklift test laboratory based at their plant in Greene, New York, USA. This project began in January 2007, after receiving funding from the New York State Energy Research & Development Authority (NYSERDA). Raymond are testing several fuel cell forklifts and pallet trucks in a "real world" test environment. Fuel cell products have been supplied by Ballard, Hydrogenics, Nuvera and Plug Power. Initial findings from this study were published in December 2007. Raymond observed that:

- The fuel cell forklifts had comparable performance to the battery forklifts with equivalent braking distance, operation range and lift speeds

- The fuel cell forklifts had significantly reduced refuelling times. It took a couple of minutes to refuel the hydrogen fuel cell systems compared with 20 minutes to replace a forklift battery pack

- The fuel cell forklifts required additional weight to be added to the fuel cell system so that the centre of balance of the counter-balance forklift was the same as for the battery counter-balance forklift

Raymond Corporation is part of the Toyota Material Handling Group.

Drivers and Barriers

Fuel cell technology is well suited for material handling vehicle applications. Fuel cells combine the advantages of battery systems (low emissions, quiet operation) with those of ICE (quick refuelling, longer run times) (see Figure 13). For example, it takes a few minutes to refuel a hydrogen or methanol forklift compared with 20-45 minutes to replace the forklift's battery pack. Also, the performance of the fuel cell forklift will not degrade across the shift, unlike a battery powered forklift. These advantages contribute to a genuine business case for applying fuel cell technology to battery forklifts and pallet trucks.

However there are still several technical barriers to be overcome (see Figure 13). For example, battery powered forklifts use the weight of the battery to act as a counter weight. Fuel cell systems are lighter than the battery packs, changing the centre of mass of the forklift. This can be solved by careful design of the power pack and may lead to fuel cell systems being incorporated into a forklift, rather than just being a battery replace pack.

Drivers and Barriers

Drivers

+ Higher energy density leading to enhanced functionality and longer run time
+ Instant recharge by refuelling
+ No performance degradation experienced across the shift
+ Environmentally friendly
  - Low emissions
  - Remove the need to handle and dispose of lead acid batteries
+ Quiet operation
+ Hybrid systems capture and release regenerative energy
+ Elimination of battery recharging infrastructure
+ Increased productivity
+ Less maintenance than battery systems

Barriers

– Costs
– Lifetime / durability issues
– Balance of plant (e.g. thermal & water management)
– Packaging, system and component miniaturisation
– Codes & Standards
– Infrastructure
– Solution to the change in counterweight
  – Fuel cells are much lighter than batteries
– Need to educate the workforce regarding working with this technology

Figure 13: Drivers and Barriers for Hydrogen / Fuel Cell powered Material Handling Vehicles

Concluding Remarks

Forklifts have been identified as a promising near-term market opportunity for hydrogen PEM fuel cells [4.3.2]. The benefits of fuel cell technology make it an attractive alternative to the incumbent technologies of large battery packs and ICEs.

On the surface, fuel cell systems for material handling vehicles appear to be on the tipping point of commercialisation. Several system integrators have produced fuel cell hybrid power packs for electric forklifts and pallet trucks designed to replace the existing battery packs. Technical specifications on these products are publically available through the system integrator websites [4.3.3, 4.3.4, 4.3.5], although price information needs to be requested.

However, before the mass commercialisation of fuel cells in the material handling vehicle sector can occur, the technology needs to be proven. This is happening with numerous small-scale fleet trials taking place in North American and now also in Europe. Early users appear to like the technology, releasing plans for further trials or for converting a forklift fleet to run on hydrogen (e.g. Bridgestone Firestone Tire [4.3.6]). Material handling vehicles are captive fleets, making it easier to create a suitable refuelling infrastructure, either by buying hydrogen in bottles or through an on-site hydrogen generation system.

However in spite of the near-term potential of applying fuel cell technology to the material handling market, it is likely to be another 4-5 years before fuel cell applications for this sector are truly market ready.

A potential threat to the introduction of fuel cell technology to the material handling sector is the likely adoption of fast charging technology for battery forklift trucks, which could negate some of the advantages of fuel cell technology over battery packs.

4.4 Scooters, Electric Bicycles and Wheelchairs

Introduction

The first fuel cell motorcycle was developed by Karl Kordesch in 1967. However, it is only in the past decade that 2-wheeled vehicles have reappeared as a potential early market for Fuel Cell technology. Over the past ten years, more than 40 prototype fuel cell scooters and motorcycles have been launched, along with a range of fuel cell bicycles and wheelchairs. These prototypes have tended to use PEM, DMFC or AFC technology, usually in conjunction with batteries or super capacitors to make them hybrid systems. The battery and/or super capacitor helps the vehicle to cope with peak loads, while the fuel cell runs at more constant running conditions. This type of product is considered attractive as an early market, because the relatively low power requirement of the fuel cell (below 1kW) reduces both its cost and the difficulty of storing fuel. The Fuel Cell offers significant environmental improvements relative to the incumbent technology – typically 2 or 4 stroke internal combustion engines with no emission control and poor noise performance, or electric devices with heavy batteries and limited range.

The PEM FC and AFC systems run on hydrogen. Hydrogen is stored on-board the vehicle either in metal hydride or compressed gas (350 or 700 bar) canisters. In most cases, the vehicle is refuelled by replacing the canisters. The canisters are then re-filled away from the vehicle, possibly by the hydrogen supply company. For example, on the HyChain project, l'Air Liquide is responsible for supplying the hydrogen in 700 bar and 350 bar canisters as required by the project vehicles. The DMFC systems run on methanol, usually supplied in bottles.

Main Players

Over 30 organisations are known to be involved in developing at least one prototype fuel cell scooter, bicycle or wheelchair. A sub-section of these organisations is illustrated in Figure 14. The players can been categorised into OEMs, whose primary business is to make scooters, motorcycles or bicycles; system integrators, who wish to show their capability at adapting fuel cell technology for these application; and fuel cell manufacturers, who want to demonstrate how their fuel cell technology can be used on an application. In many cases, the OEM, system integrator and fuel cell manufacturer have worked together to produce the prototype.

Figure 14: Organisations known to have developed a prototype fuel cell scooter, bicycle or wheelchair

Yamaha and Asia Pacific Fuel Cell Technologies (APFCT) appear to be the technical leaders in the fuel cell scooter sector. Since 2003 Yamaha have launched six concept or prototype fuel cell scooters. Some of these used DMFC technology, while others used PEM fuel cells. APFCT have been developing fuel cell scooters since the late 1990s and are currently working on their 5th generation of prototype ZES (Zero Emission Scooter).

The prototype fuel cell scooters and motorcycles that have been developed so far tend to be in the power range equivalent to 50cc – 250cc.

Recent Developments

Although there have been many prototype fuel cell scooters and motorcycles launched, there appears to be a lack of data available regarding testing these vehicles in a real world environment. One of the exceptions to this is Yamaha who leased their FC-me scooter prototype to the Japanese Shizuko Prefecture from September 2005 to March 2007. Yamaha have published as least one technical paper on their observations from testing the scooter during this lease period. Their results show a reduction in fuel cell performance over the lease period, which they considered to be due to the frequent stopping and starting of the vehicle. They also noticed that the fuel economy was worse during winter months due to the additional power required from the battery to bring the fuel cell up to operating temperature. Yamaha are using the results from the FC-me testing to improve future designs for fuel cell scooters [4.4.1]. In the developed world, fuel costs have not historically been a major issue in this sector; however in the developing world, and given recent rises in energy prices, reasonable efficiency can be expected to be important.

When one considers potential fuel cell applications, electric bicycles is a sector not usually included on the list, and yet this may be one of the first to market fuel cell applications. At least two companies in Europe are known to be selling electrically assisted bicycles with fuel cell power systems. UK based Valeswood ETD Ltd have adapted an electric bicycle to be powered by a fuel cell. This fuel cell bicycle has a retail price of £2,475 (€3,220) excluding taxes [4.4.2]. Veloform, in Germany, make tricycle rickshaws for transporting passengers or cargo around an inner city environment. They have a DMFC option within their product range that costs €3,750 in addition to the price of the base vehicle [4.4.3]. The DMFC system is supplied by SFC Smart Fuel Cell AG. SFC also have an agreement with the Dutch bicycle company van Raam [4.4.4]. Van Raam specialise in the manufacture of bicycles for people with disability. From February 2008 their "Fun2Go" tricycle has been equipped ex works with a SFC EFOY DMFC (refer to Glossary at the end of this report).

Some of the recent developments in fuel cell scooters, bicycles and wheelchairs are displayed in the time line in Figure 15. One other recent development to note, which has not been included in this timeline, was the launch of the SFC Smart Fuel Cell DMFC scooter and DMFC wheelchair. These were exhibited at the Hannover Messe in April 2008. The fuel cell scooter was displayed with an attached price tag of €4,999. It is unclear if SFC intend to enter the FC scooter market, or if the purpose of this prototype was to demonstrate how their DMFC products could be applied to a scooter. However it is unusual for a fuel cell product to have a visible price tag.

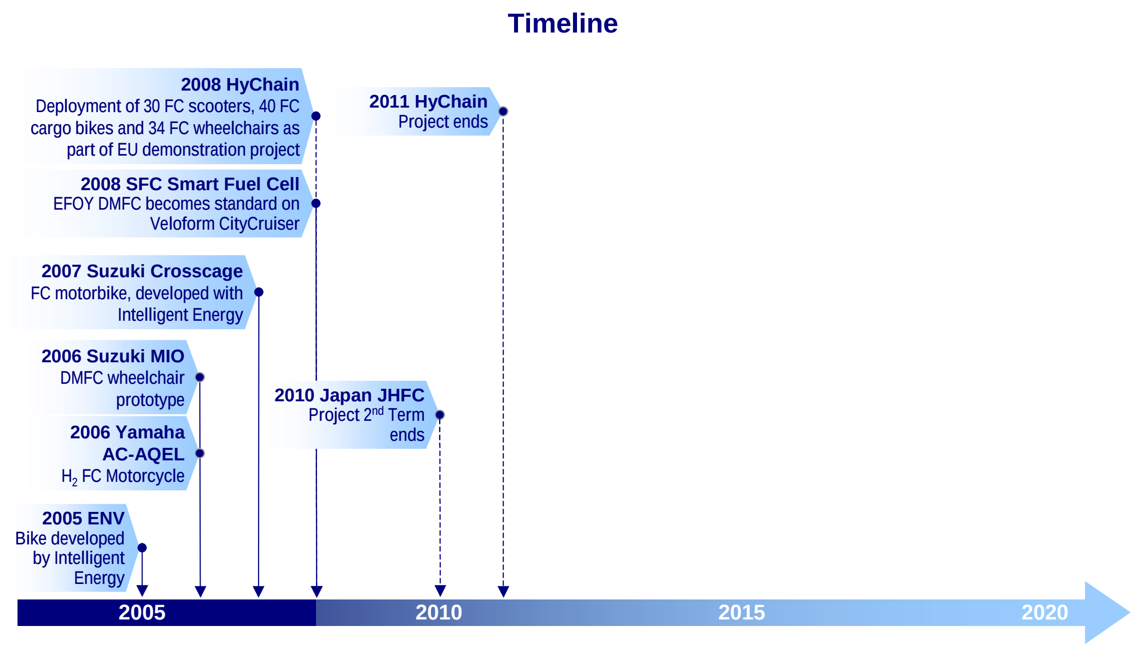

Figure 15: Key Milestones and Future Developments for fuel cell scooter, bicycle and wheelchair applications

Drivers and Barriers

Drivers for applying fuel cell technology to scooters, bicycles and wheelchair include reducing vehicle emissions, while maintaining a suitable recharging time. Figure 17 provides an overview of the other drivers and barriers to introducing fuel cell technology in this sector.

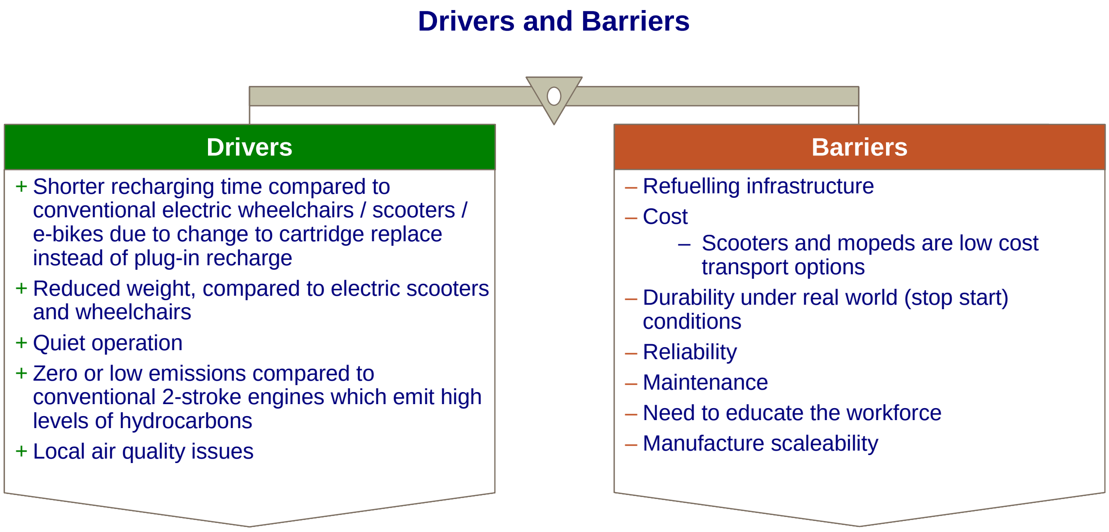

Figure 16: Drivers and Barriers for fuel cell scooters, bicycles and wheelchairs

There is a very significant potential market opportunity for fuel cell scooters and bicycles in the developing world, particularly China. Motorised two-wheel vehicles are a popular form of transportation throughout the country. However over 40 cities in China have introduced restrictions on the purchase or use of motorised two-wheeled vehicles in order to reduce crime, to reduce the number of road accidents and to improve local air quality. These restrictions have contributed to the surge in sales of electric bicycles and scooters in China since the late 1990s (21 million electric bikes were sold in China in 2007 [4.4.5]). Although the rise of battery-powered electric scooters and bicycles could challenge the short-term market opportunity for fuel cells, it does provide a long-term market opportunity, as Fuel cells could be used to enhance the e-bike products by acting as range extender.

As for all fuel cell applications, the uptake of fuel cell scooters, bicycles and wheelchairs is dependent on the development of a suitable fuel infrastructure. However there are several novel approaches which could be adopted for developing a fuel infrastructure for fuel cell scooters, bicycles and wheelchairs. For example, the HyChain project is developing cartridge dispensers with which users can obtain new, full hydrogen canisters in exchange for empty ones..

Cost is another significant issue for this sector. Scooters and bicycles are relatively inexpensive vehicles, so although the low power fuel cell is relatively cheap compared to a passenger car fuel cell drivetrain, it can still be difficult for fuel cells to compete with the existing internal-combustion technology. Therefore this sector is likely to succeed where legislation is limiting hydrocarbon emissions from conventional two-wheeled vehicles, or where incentives for cleaner alternatives create a market that attracts significant numbers of early adopters.

Concluding Remarks

To exploit the potential of this early market sector for the Fuel Cell, the following need to be realised:

- Transport policy needs to support the development of markets for zero-emission two wheelers in Europe, as without a domestic market it will be harder to export products or know-how to the larger developing world markets

- Low power stack systems (perhaps exploiting synergy with light industrial vehicles) need to be realised at a level of cost, size and durability suitable for vehicle use

- Improvements in the fuel cell / fuel tank package need to remain ahead of improvements in competing battery technology

- The supply of fuel, potentially remaining with the canister principle, needs to become sufficiently widespread that it remains competitive with inevitable developments in electric charging infrastructure

In conclusion, the sector is potentially promising, and appears to offer the potential of an untapped global market for basic, low cost but clean individual mobility. Further investment in better products, and the retailing of fuel, is needed in order to exploit this market; but there is a real risk that products developed and made cheaply in China could dominate world markets.

4.5 Vehicle Auxiliary Power Units

Introduction

Auxiliary Power Unit (APU) applications have the potential to become a lucrative niche market for the Fuel Cell. In this application, a small Fuel Cell is used in conjunction with a main “prime mover” such as a traditional combustion engine or electric motor. Hence FC APUs enhance the power flexibility of the products without necessarily replacing the existing technology. Their usual use involves providing a continuous supply of power for onboard demands that do not relate to the propulsion of the vehicle, for example refrigeration of a payload or powering occupant comfort features. Novel market approaches exist in the area of onboard power supply for commercial and recreational vehicles. The fuel cell technology allows power generation without engine operation and enhances the operation of batteries.

Investigations for this study have found that fuel cell APUs are being developed for a range of different fuels from hydrogen and methanol to LPG, JP-8 and diesel. The reason for this fuel diversification is the desire to design the fuel cell APU to run on a fuel that is readily available to the end user. For example, the majority of commercial trucks run on diesel. Therefore fuel cell APUs for trucks are being developed to run on diesel, and so utilise the on-board fuel supply. This factor is extremely important for market uptake, and can be considered a defining factor that differentiates this application from others.

The choice of fuel influences the type of fuel cell and reformer technology selected. Fuel cell APU development is following three technology streams, which are direct methanol, solid oxide and proton exchange membrane. DMFC APUs run on methanol and do not require a reformer. SOFC and PEM APUs usually incorporate a fuel reformer built into the unit so that the system can run on alternatives to hydrogen.

Main Players and Recent Developments

Delphi and Cummins Power Generation are known to be working on projects to demonstration SOFC APU technology on commercial vehicles, funded by the U.S. Solid State Energy Conversion Alliance (SECA) [4.5.1, 4.5.2, 4.5.3]. Delphi’s project partners include PACCAR Incorporated, Volvo Trucks North America (VTNA), Electricore Inc. and Battelle. Cummins’ project partners include Protonex LLC and International Truck & Engine Corp. Both consortia have produced early SOFC APU prototypes that ran on Natural Gas. Both projects are now developing prototype SOFC APUs that will run on diesel. Cummins expect to have a working prototype demonstrated in a vehicle by June 2009, while Delphi expect to complete their project by 2010. Therefore commercial products are not expected until at least 2012 or beyond.

PowerCell, a joint venture between Volvo and StatoilHydro, is developing a diesel PEM FC APU for heavy duty trucks, in collaboration with project partner H2 Logic [4.5.4, 4.5.5]. Although their research and development is taking place in Europe, PowerCell have stated that they plan to market their first fuel cell APU in North America in 2011.

There is one known example of a PEM FC APU system for a commercial vehicle application that used hydrogen as the fuel. In 2007 Hydrogenics supplied one of their HyPX fuel cell systems to MAN Nutzfahrzeuge to act as the fuel cell APU on MAN's hydrogen ICE bus for the European HyFleet:CUTE project [4.5.6]. The Hydrogenics HyPX is a hybrid PEM fuel cell power pack that was designed for use on material handling vehicles (see Section 4.3 for more information on this system).

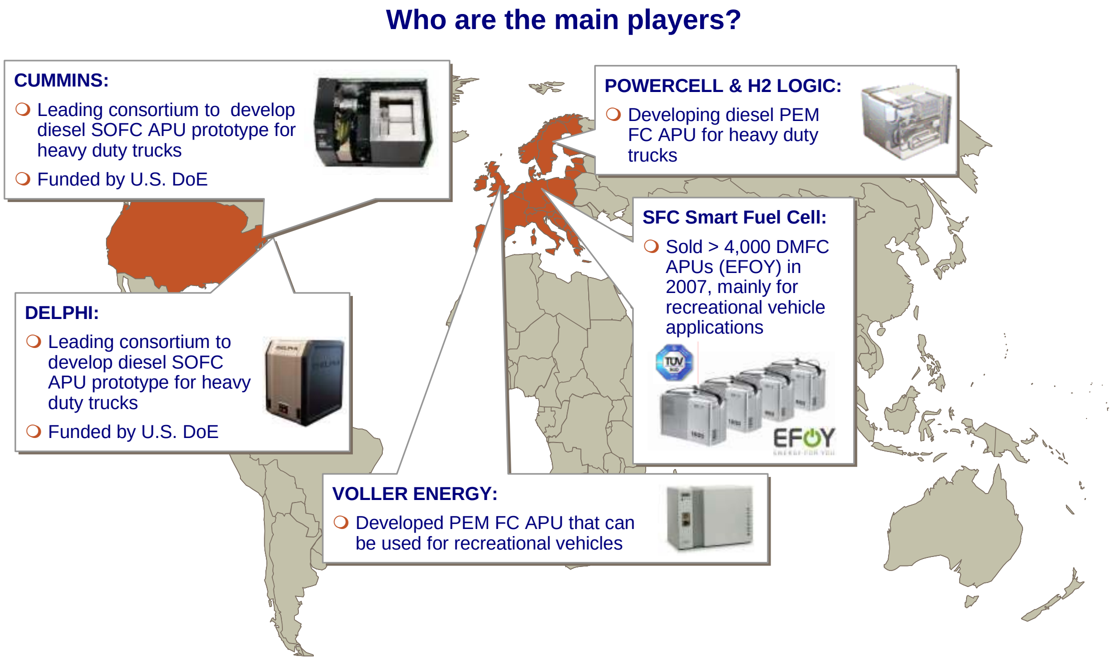

Figure 17: Main players in the fuel cell APU market

Europe is leading the development of fuel cell APU products for recreational vehicles. There are two companies known to have products available for this niche market; SFC Smart Fuel Cell AG in Germany and Voller Energy Group plc in UK.

SFC was first to market with a fuel cell battery charger installed in a Hymer S-Class recreational vehicle (RV) in 2005 [4.5.7]. Since then SFC has been building their brand within this new market in the leisure and recreational vehicle industry (in January 2008, SFC were awarded 3rd place on "Best Brand" Reader Award for motor home magazine "promobil"). SFC's business strategy has been to partner with the major European manufacturers of retail vehicles, such as Hymer, Rapido and Webasto, to get their fuel cell products included in recreational vehicles.

SFC's main product family is called EFOY (Energy for You). These are DMFC units, with a choice of four power ratings (25W, 38W, 50W and 65W) and have been certified by TÜV Süd since 2006. SFC sold over 4,000 EFOY fuel cells in 2007, mainly to manufacturers of recreational vehicles [4.5.8]. SFC also supply the methanol fuel required by their fuel cell products in 5 or 10 litre containers, distributed through a network of RV retailers throughout Western Europe. DMFC technology may not have the prestige of PEM fuel cells, but SFC's identification and exploitation of the RV niche market for DMFC means they could be one of the first fuel cell companies to be commercially successful.

Voller Energy's Emerald unit is a 1kW PEM FC system, which includes an advanced reformer that can be adapted to run on LPG, propane or butane [4.5.9]. Voller are targeting this product at the marine leisure industry, however it can also be applied to motor homes and caravans. In 2007, Voller installed an Emerald fuel cell in a motor home.

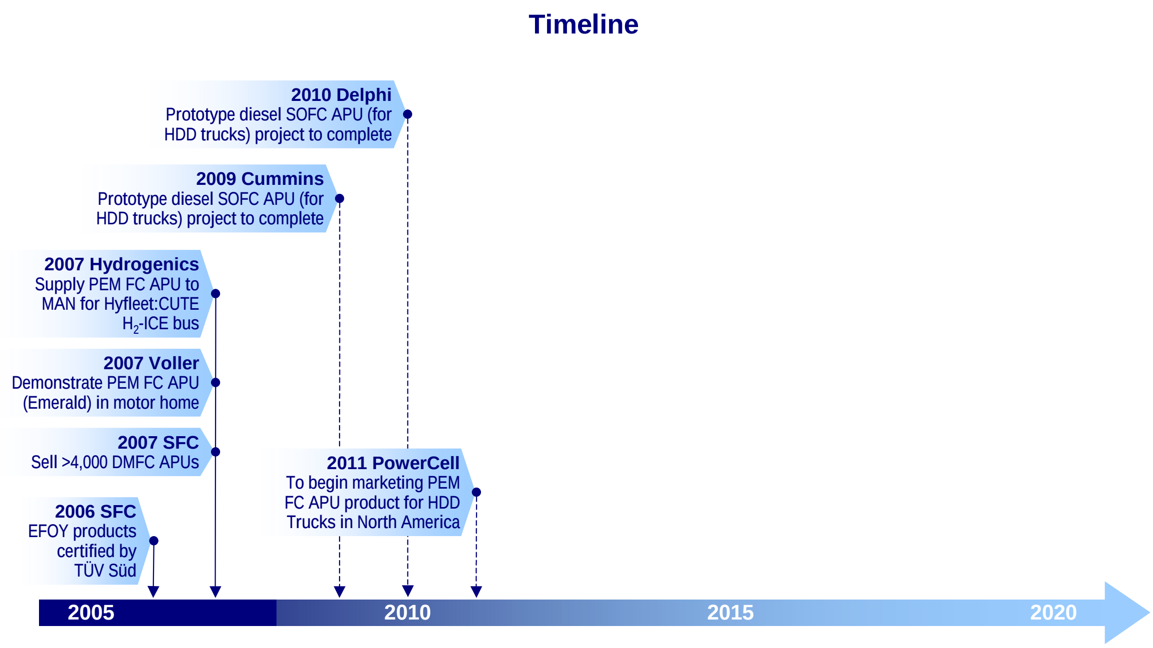

Figure 18: Key Milestones and Future Developments for fuel cell APU applications

Drivers and Barriers

The application of fuel cell technology in APUs is being driven by an increasing electrical demand in commercial and recreational vehicles. This increase in electrical demand is due to the desire of the end user for more "home conveniences" on-board, such as TVs, fridges, kettles, electric blankets, laptops and GPS systems. In USA, anti-idling regulations are being introduced in several States, such as California, which mean that truck drivers will not be allowed to run the engine at idle of long periods of time in order to provide electrical energy. This too is driving development of APUs towards fuel cells.

Fuel cell technology offers other advantages for APUs such as quiet operation (the system has few moving parts, however there is noise from compressors, etc.) and efficient use of fuel.

Current barriers to the introduction of fuel cell APUs include cost, durability, heat management, unit size and system tolerance to sulphur. The pay back period is an important consideration for owners of commercial vehicles, with OEMs specifying a pay back period of less than 2 years for a fuel cell APU [4.5.1]. SOFC operate at high temperatures and intelligent control of the heat produced is required to obtain good overall efficiencies of the system. A fuel cell APU comprises of balance of plant parts and, possibly, a fuel reformer, in addition to the fuel cell stack. Careful design of the package is required to minimise the APU size. Sulphur is known to poison fuel cells. However diesel fuel contains sulphur. Therefore the APU fuel reformer must be capable of removing the sulphur from the fuel before it reaches the fuel cell.

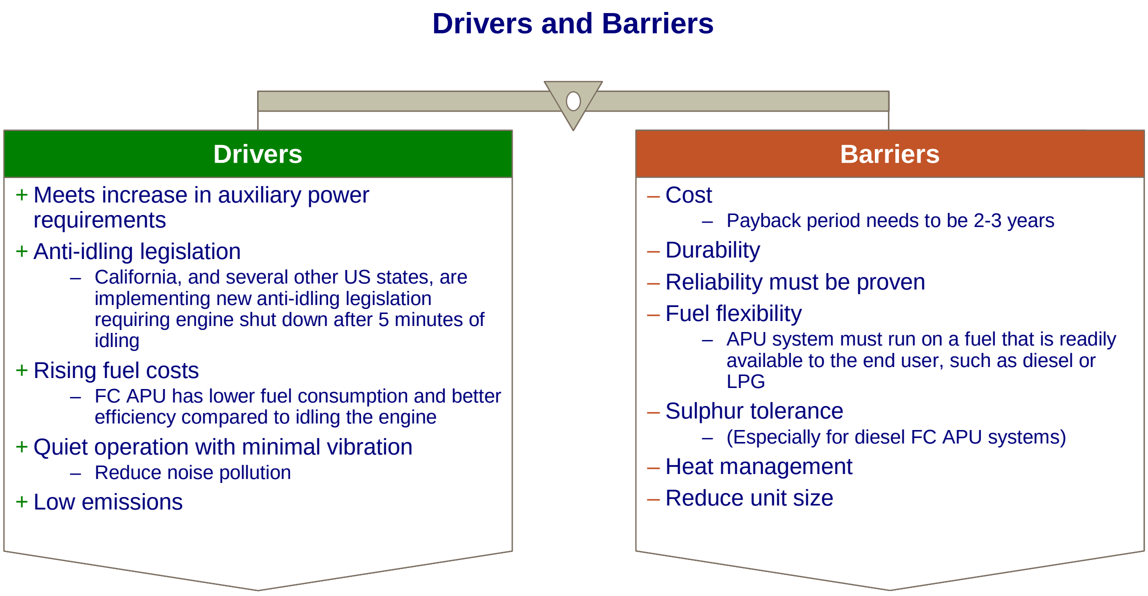

Figure 19: Drivers and Barriers for fuel cell APU applications

Concluding Remarks

The findings of this study in terms of the APU application indicate that the conventional view, that APUs are an attractive early market, remains valid. There is an existing, genuine market for the product, with thousands having been sold to genuine users without special incentives and on a basis that is probably profitable along the supply chain – and this in itself is still unusual in the fuel cell business. However, there is only one very active supplier selling products right now, and it is a product that requires its own dedicated fuel, and its power output is not sufficient for it to migrate directly from the leisure sector to commercial transport application.

So, to consolidate its success as an early market sector for the Fuel Cell, the following need to be realised:

- Ongoing developments in sulphur-tolerant reformers for Diesel-fuelled systems need to deliver technologies that can be put into mass production and that are compatible with future fuel specifications in major markets. Introduction of low sulphur fuels in Europe and now the US makes this task easier, but it must be borne in mind that freight applications will cross borders into territories with higher fuel sulphur levels. This study found no public domain numerical information on recent improvements in fuel sulphur tolerance.

- APU systems with powers in the 1-10kW range need to be realised at a level of cost, size and durability suitable for commercial use. Unlike some other sectors, the study found no APU-specific information on recent progress in these attributes.

- The leisure sector will remain a significant APU application, but improvements in battery technology could create a challenge to market growth unless the use of an APU remains more attractive than a better battery. Two factors could help this to happen; the arrival of a competitor to the sole volume seller, and the emergence of APU fuel cells that operate directly on fuels used in the leisure sector, meaning LPG, Gasoline or Diesel. While there is discussion of potential products operating on these fuels in the public domain, the study did not find a product with a launch-date fitting this need.

- Where possible, better synergies with other sectors that use similar technologies and allow realisation of economies of scale. While some of the products in or near to the market are based on generic stack solutions, the study did not find a concrete product synergy between an APU and a product in another sector with higher volume potential.

In conclusion, the sector remains promising and is one of the few Fuel Cell markets with a significant sales track record, but requires continued investment in better products in order to continue growing.

4.6 Marine Transport

Introduction

According to a report from Det Norske Veritas (DNV), the worlds shipping fleet accounts for 2% of global CO_2 emissions, 4-6% of SOx emissions and 10-15% of NOx emissions [4.6.1]. Hydrogen and fuel cell technologies are a possible solution to the problem of reducing local and regional emissions caused by marine vessels.

PEM FC, SOFC and Molton Carbonate Fuel Cell (MCFC) technologies are all being considered for marine applications. Most of the prototype systems in use today are hybrids, using the fuel cell with batteries or super capacitors. Applications are from across the marine section and include APUs for luxury yachts and merchant vessels, powertrains for passenger ferries and tourist boats and powertrains for unmanned underwater vehicles (UUV) and submarines.

Main Players

Wärtsilä are one of the main industrial players in the shipping industry who are investing in fuel cell technology. They are involved in a number of European projects, such as METHAPU [4.6.2] and FellowSHIP [4.6.3], which are seeking to demonstrate SOFC and MCFC technology applied onboard commercial vessels as APUs. Wärtsilä have a prototype 20 kW SOFC system for stationary commercial applications. This system uses SOFC technology developed by Topsøe Fuel Cell A/S. It is likely that Wärtsilä will adapt this fuel cell unit for marine applications.

Voller and Proton Motor are two fuel cell manufacturers active in applying their fuel cell technology to marine applications. In 2007 Voller fitted their Emerald PEM APU to a Beneteau Oceanis yacht, which they sailed across the Atlantic Ocean as part of the engineering trials for the fuel cell system [4.6.4]. Proton Motor are supplying the fuel cells for the Zemships project [4.6.5]

Within Europe there are a number of industry consortia developing fuel cell powered boats, mainly for the tourist industry. In Iceland, Icelandic New Energy have overseen the installation of the hybrid hydrogen fuel cell APU to the Smart H2 whale watching boat. In Hamburg, the Zemship (zero emission ship) tourist ferry has recently started operating on the Alster Lake [4.6.5]. In Amsterdam the Fuel Cell Boat project is building a fuel cell powered passenger ferry [4.6.6].

In North America, development of fuel cell technology for the marine sector appears to be focused on military applications, such as submarines and unmanned undersea vehicles (UUVs) [4.6.7]. Germany also appears to be active in developing fuel cell systems for underwater military applications. Companies involved in this area include:

- ITM Power (UK)
- Siemens Industrial Solutions and Services Group (Germany)
- Versa Power Systems, Inc. (USA)

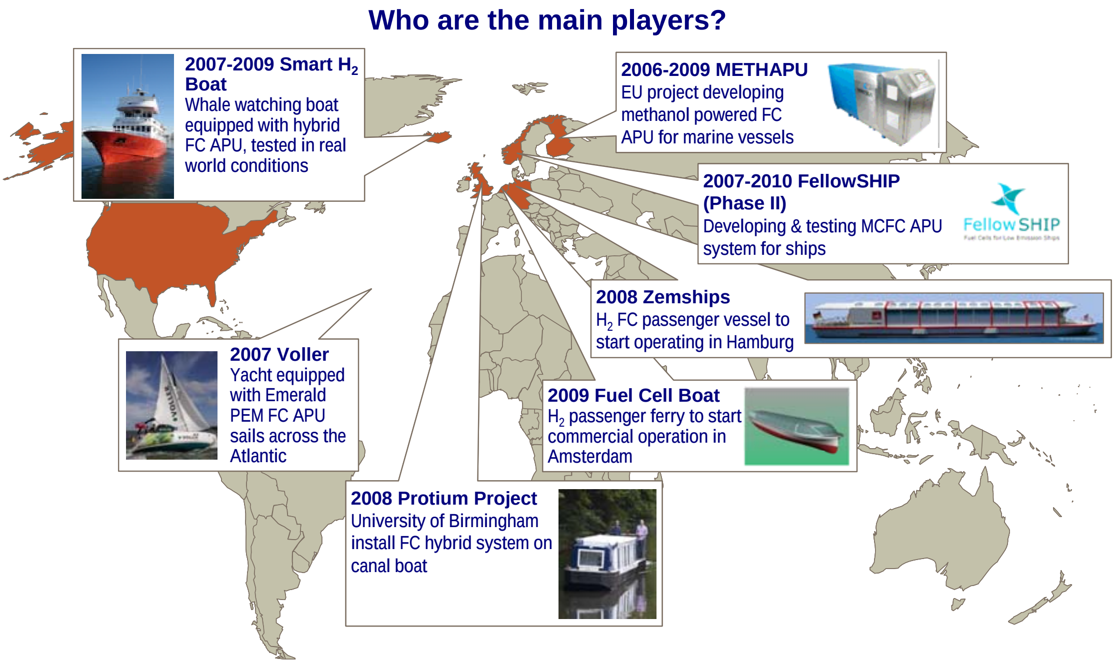

Figure 20: Geographical overview of the main players applying H2&FC technology in the Marine sector

Recent Developments

Recent developments include the demonstration of fuel cell technology:

- On-board a whale watching ship (Iceland, 2007)
- On-board a yacht (Voller, November 2007)
- To power a canal boat (University of Birmingham, 2008)
- To power a tourist passenger ferry in Hamburg (Zemships, August 2008)

All of these projects used PEM FC technology. The whale watching ship, canal boat and Zemship use hydrogen as the fuel. The PEM FC system on-board the Voller yacht included a fuel reforming, allowing the Fuel Cell system to run on propane.

An overview of other recent key milestones of fuel cell technology in the marine sector is presented in Figure 21.

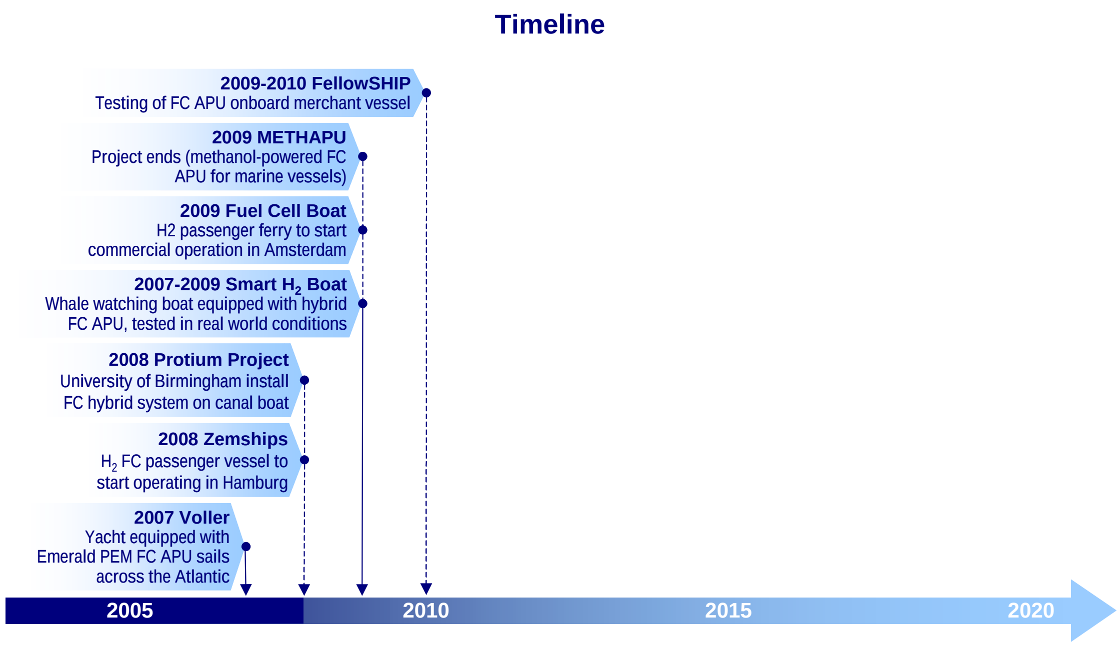

Figure 21: Key Milestones and Future Developments for applying H2&FC technology to the Marine sector

Drivers and Barriers

An overview for the drivers and barriers for applying fuel cell technology to marine applications is provided in Figure 22.

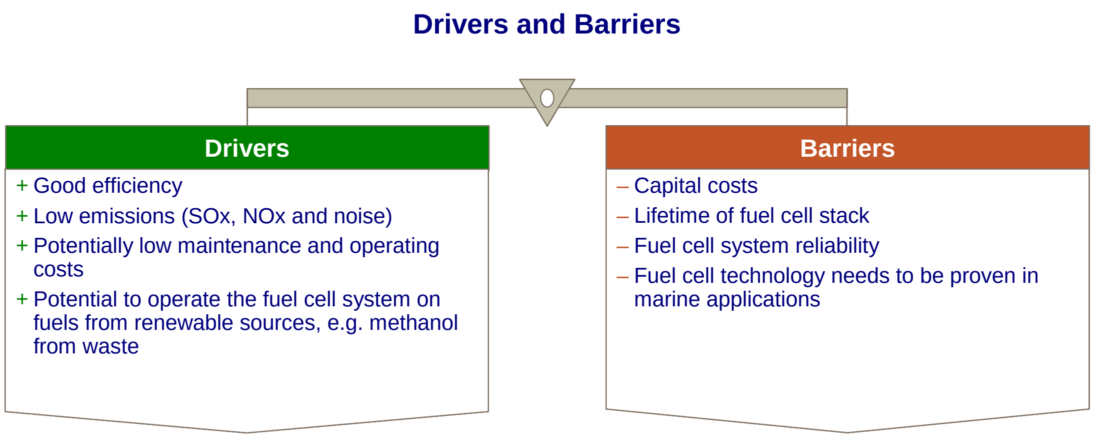

Figure 22: Drivers and Barriers for applying H2&FC technology to the Marine sector

Concluding Remarks

The marine industry is a possible market sector for fuel cell technologies. Early applications and demonstration projects are pleasure boats and passenger ferries. The fuel cell technology is used either as the main propulsion power source, or as an APU. Although these applications are mostly one-off or low volume production vessels, these demonstration projects serve a useful purpose in increasing public awareness and acceptance of fuel cell technology.

In the long term, it is likely that fuel cell technology will be applied in large shipping vessels, probably as hybrid fuel cell APUs. However it is still to be proved if fuel cell technology can be suitably adapted to the marine environment of commercial shipping.

4.7 Air Transport

Introduction

Significant improvements in aircraft fuel efficiency are being achieved (1-2% per year). However annual air traffic growth (~5%) is leading to an increase in CO_2 emissions due to air transportation. This, along with aviation's strong dependency on fossil fuels, is driving research towards development on non-carbon based fuel technologies. Within the fuel cell and hydrogen technology sector, aircraft manufacturers are investigating the potential of PEM FC and SOFC systems to power light aircraft or as APUs on-board commercial aircraft.

Main Players

The main players applying fuel cell technology to aircraft are Boeing and Airbus. Boeing are working closely with organisations such as Diamond Aircraft, Saft, l'Air Liquide and Intelligent Energy in Europe and with Sandia National Laboratories and Versa Power Systems in USA. Airbus are collaborating with DLR and Michelin, using Hydrogenics fuel cell systems to build fuel cell power units suitable for an aircraft environment. Figure 23 presents an overview of the main players and their key projects.

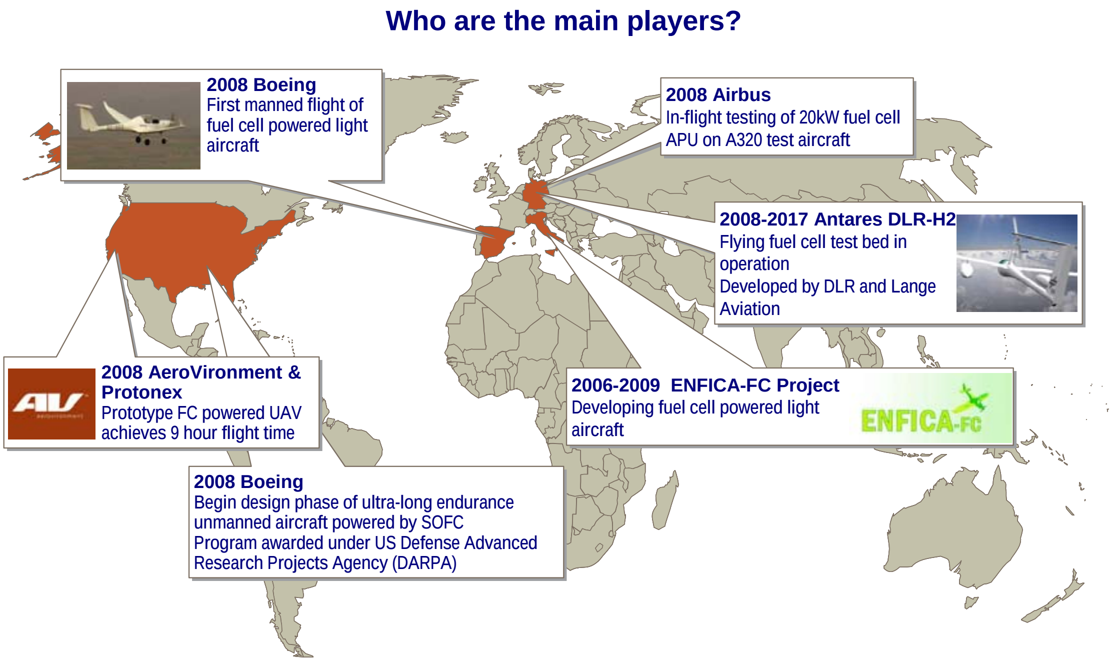

Figure 23: Geographical overview of the main players applying H2&FC technology in Aircraft

Several universities are leading design projects with the aim of building fuel cell powered light aircraft. These include the Politecnico di Torino in Italy, leading the ENFICA-FC project and the University of Stuttgart in Germany, leading the "Hydrogenius" project. The Hamburg University in Germany is leading the Green Freighter project, which is considering liquid hydrogen fuel systems for cargo aircraft.

Recent Developments

Over the past year there have been a number of significant milestones in the development of fuel cell systems for aircraft (see Figure 24). In February 2008, Boeing Research & Technology Europe (BR&TE) successfully flew a manned light aircraft powered by a hybrid fuel cell system. Three test flights took place at an airfield near Madrid in Spain. The aircraft was taken to an altitude of 1,000 m using the power supplied by the fuel cell and lithium-ion batteries, before the batteries were switched off. The aircraft flew level for 20 minutes on fuel cell power alone.

Also in February 2008, Airbus tested their fuel cell power system in-flight onboard a A320 test aircraft. The 20 kW fuel cell powered the aircraft's back-up hydraulic and electric power system.

The German Aerospace Centre (DLR), who work closely with Airbus, have developed a flying test bed for testing fuel cell systems at altitude. The research aircraft Antares DLR-H2 has been designed in collaboration with Lange Aviation and has been made available to DLR until 2017.

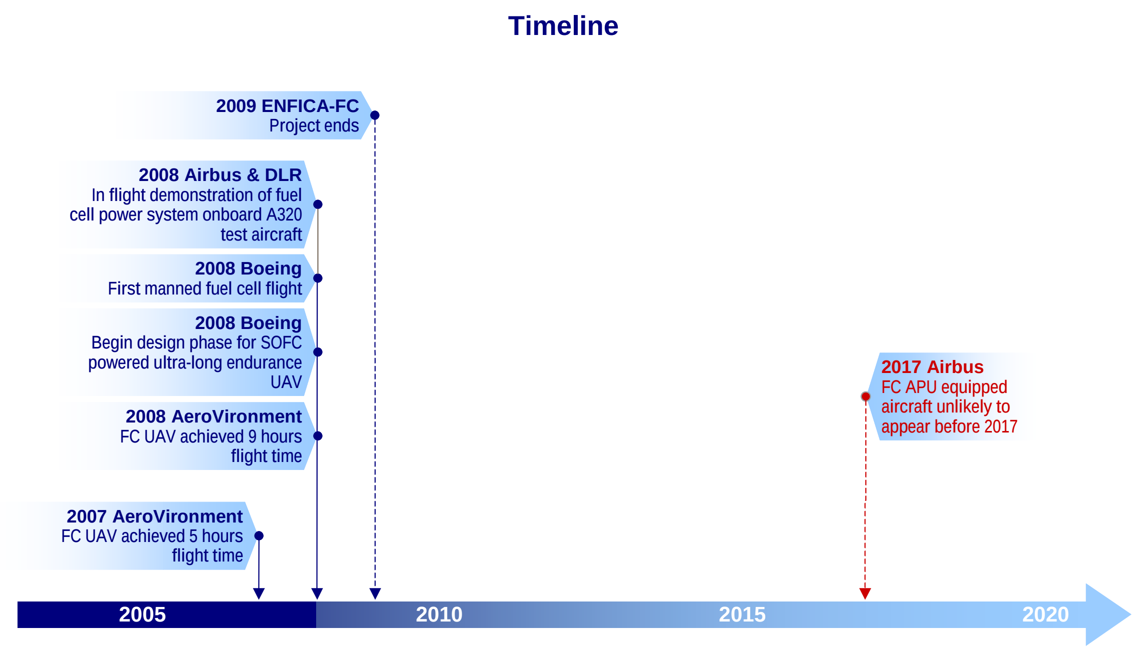

Figure 24: Key Milestones and Future Developments for applying H2&FC technology to Aircraft

Drivers and Barriers

Fuel cell technology has much to offer the airline industry. Fuel cell systems produce fewer emissions than the current kerosene-fuelled technology. Also, fuel cell systems are quieter and have the potential to be low maintenance.

However, fuel cell technology needs to be proven to work in an aircraft environment at altitude, requiring many years to testing and development before it is adopted as a mainstream technology. Also, the introduction of hydrogen-fuelled technology requires the development of hydrogen infrastructure at airports and hydrogen refuelling strategies.

An overview of the drivers and barriers to the introduction of fuel cell and hydrogen technologies onboard aircraft is presented in Figure 25.

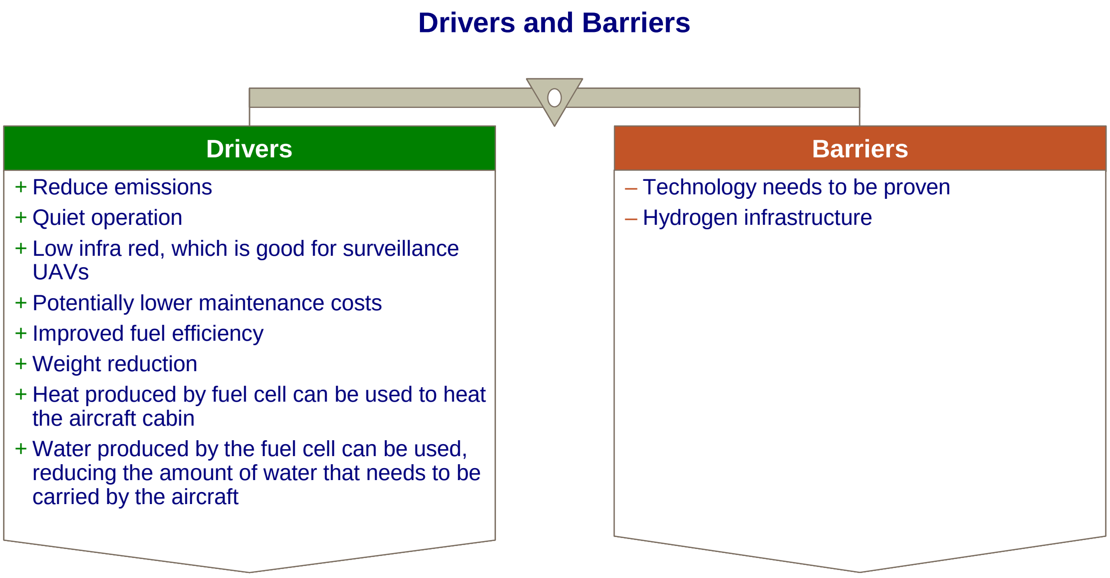

Figure 25: Drivers and Barriers for applying H2&FC technology to Aircraft

Concluding Remarks

The aircraft industry will not be an early adopter of fuel cell technology. However, given the interest in the technology displayed by two of the world's major aircraft manufacturers, it is likely that fuel cells will appear in aircraft in the future. The most likely applications are hybrid fuel cell APU systems for commercial aircraft, with products appearing around 2020; and specialised military applications for surveillance.

4.8 Domestic Stationary Applications

Introduction

The application of Fuel Cell and Hydrogen technologies to the domestic stationary market, in the form of Combined Heating and Power (CHP) systems, could achieve significant reductions in greenhouse-gas emissions. In developed countries existing domestic heating systems produce approximately 12-15% or more of the country's total GHG emissions. In the UK, for instance, this figure is closer to 20%[4] [4.8.1].

The arguments for introducing Fuel Cell technology into this sector are as follows:

- The domestic sector already uses a number of well-established fuel chain infrastructures, including natural gas pipelines, bottled gases and heating oil.
- Fuel-reformation technology for fuel cell products is advancing rapidly and has already enabled the use of other, more sustainable energy chains such as biogas or syngas, without significant investment in additional distribution infrastructures.
- CHP systems are already able to achieve overall efficiencies exceeding 70% and electrical efficiencies of over 50%. This is true even for small plants and at part loads. Conventional boilers typically achieve 35+%.
- Installing CHP as part of a national, integrated, distributed-energy-generation (and transmission) strategy could achieve the greatest potential reduction of greenhouse-gas emissions. In addition, future capital investments in electrical generating capacity could be reduced [4.8.2].
- Major boiler manufacturers already possess considerable mass-production expertise that can leverage lower costs. Integrating fuel cells within CHP systems is a significant challenge but is already being pursued by the major players, such as Baxi [4.8.3].
- Very low acoustic and chemical pollution make fuel cells ideal devices for domestic applications in residential suburban areas.
- The CHP application is one from which virtually every citizen benefits.

The choice of fuel influences the type of fuel cell and reformer technology selected. Fuel cell CHP development is following two main technology streams, which are Solid Oxide (SOFC) and Proton Exchange Membrane (PEM). SOFC is the dominant choice for CHP, though a few companies are developing PEM cell stacks. Both SOFC and PEM CHP systems incorporate a fuel reformer so that the unit can operate on alternative fuels to hydrogen.

Fuel cell CHP must compete with established technologies that are substantially cheaper but far less efficient. The primary goals must be to reduce CHP unit costs,

[4] Oil fuel equivalence usage per economic sector and CO_2/GHG emissions

continue to improve fuel reformer technologies, reduce cell deterioration due to fuel impurities and, therefore, directly extend cell-stack lifetimes.

Main Players

An overview of some of the main players in this sector is provided in Figure 26.

Figure 26: The Main Players known to be active in domestic applications of H2&FC technology

Ceramic Fuel Cells Limited are developing SOFC stacks. Fuel cell production is based at Heinsberg, Germany and there is also a pilot production plant in Victoria, Australia. CFCL has established partnerships with Gaz De France and De Dietrich in France, EWE and Bruns in Germany, E.On and Gledhill (the UK's largest boiler manufacturer) in the UK, De-Dietrich-Rehama in the Netherlands and Paloma (the number 2 manufacturer of gas boilers in Japan).

CERES Power are developing an innovative mid-temperature SOFC stack for domestic CHP. They have a partnership with gas distribution company Centrica.

Intelligent Energy (Loughborough, UK and Long Beach, California) is developing a 2-5kW SOFC CHP product, in conjunction with their prime partner Scottish and Southern Energy, for the UK market. They have already achieved efficiencies of 40% electrical, 70% overall and a cell stack lifetime of 40,000 hours. Their cell-stack cost target is $750 per kW.

Plug Power (Latham, New York) has partnered with GE and is now the exclusive supplier and manufacturer of GE's HomeGen PEM fuel cell systems. With powers up to 35kW, the HomeGen's primary market is off-grid electrical power co-generation.

Ebara Corporation (Tokyo, Japan) is developing small PEM-type residential CHP co-generation units, fuelled by natural gas or kerosene, for the Japanese domestic building market.

Versa Power Systems (Colorado, US and Alberta, Canada) is developing modular SOFC CHP units of 3-10kW for a number of target markets, including residential buildings. This is being carried out as part of the US's Solid State Energy Conversion Alliance.

Recent Developments

In February 2008 Ceramic Fuel Cells Limited received an order for 50,000 SOFC stacks for residential CHP units from the Dutch utility Nuon. Starting in mid-2009, these units will be delivered over the following 5 years.

On 2 July 2008, Plug Power extended their long-term PEM fuel cell stack supply agreement with Ballard, Canada, from 1 May 2009 to 31 December 2010.

On 2 July 2008 CERES Power passed a key technical milestone on their contract with Centrica (British Gas). After their demonstration of the company's CHP unit in September 2007, the core fuel cell module has achieved its size and weight reduction targets. In addition, CERES have completed the Alpha design phase of an integrated wall-mountable CHP unit with British Gas, a design that meets their jointly agreed go-to-market specification and satisfies the requirements for mass market uptake including installation, service and maintenance in a UK home.

An overview of some of the recent key milestones and planned future developments for the Domestic Stationary Fuel Cell sector is provided in Figure 27.

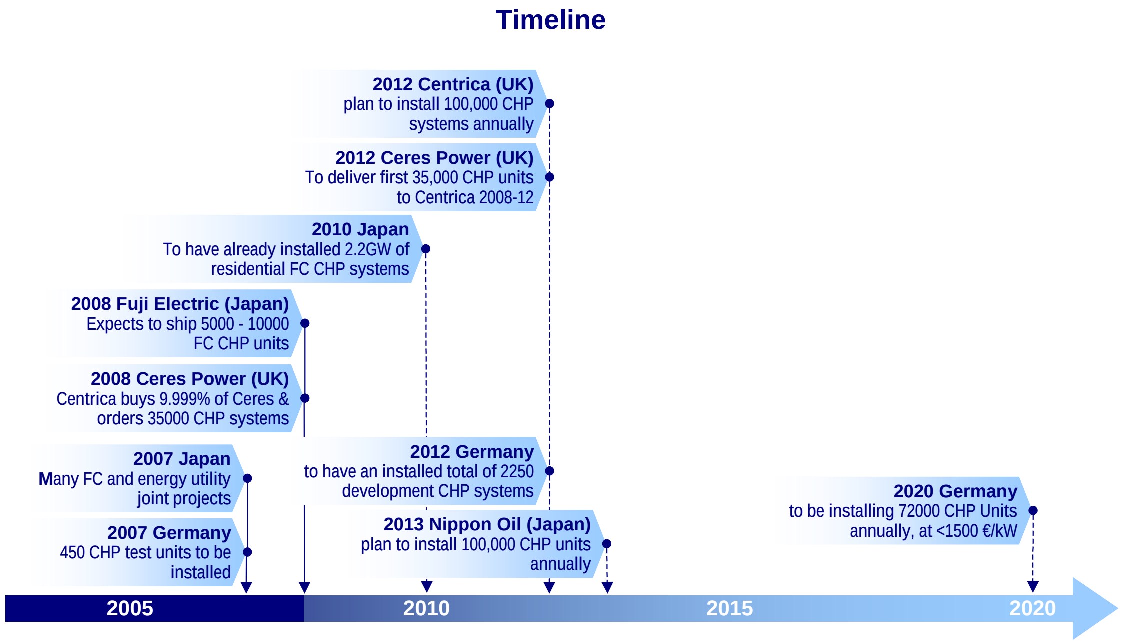

Figure 27: Key Milestones and Future Developments for Domestic Stationary Applications

Drivers and Barriers

An overview of the drivers and barriers to introducing Domestic Fuel Cell units is provided in Figure 28.

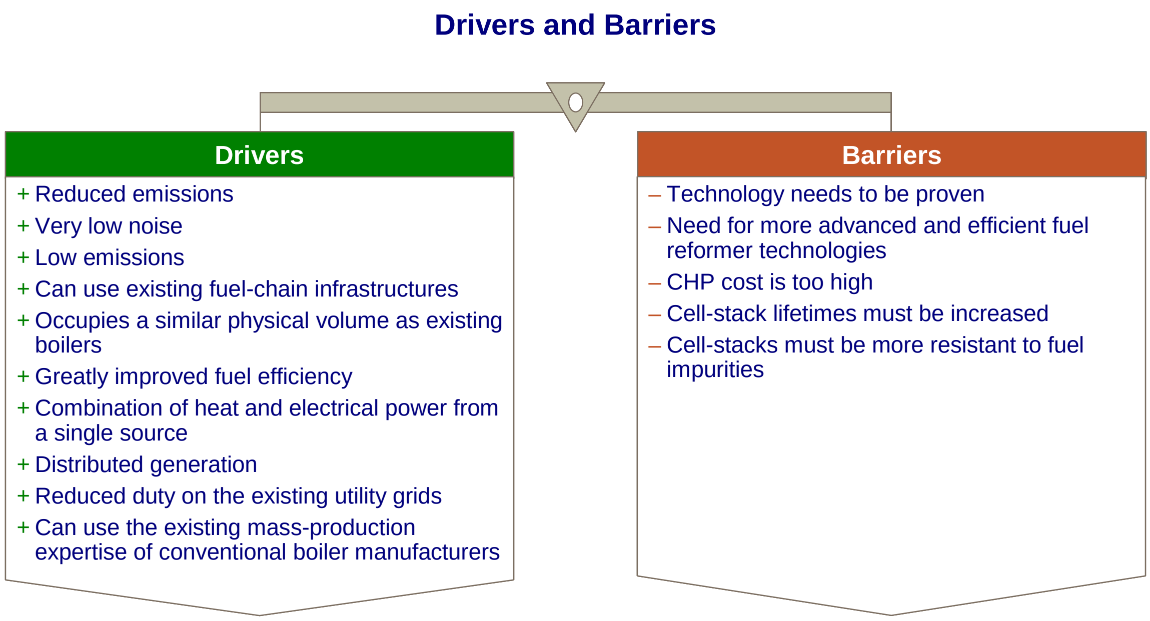

Figure 29: Drivers and barriers to applying H2&FC technology to the Domestic Stationary sector

Concluding Remarks

The findings of this study indicate that the Domestic CHP system is an attractive early market for Fuel Cell technology and is rapidly approaching true commercialisation. There is a strong, well developed existing market for the conventional product and, as fuel prices increase, many consumers will be looking to change their boilers for a number of reasons:

- Their system has reached the end of its life
- A major defect makes replacement with a new, efficient CHP unit an attractive option
- They are early adopters

There are a small number of highly active companies pursuing this market in Japan, Europe and the USA. Almost all CHP systems will use existing fuel-chain infrastructures, relying on reformer technology. Control systems are being improved to control the use of CHP and to offer the real possibility of power delivery back to the grid. So, to consolidate possible success as an early market sector for the Fuel Cell, the following need to be realised:

- Ongoing developments in reformers to improve efficiency and maximise cell stack lifetimes.
- Modular systems that can be adapted to cater for larger single dwellings and larger residential centres such as blocks of flats, hospitals, nursing centres, etc, will maximise penetration of this market.
- Where possible, better synergies with other sectors that use similar technologies and allow realisation of economies of scale. While some of the products in or near to the market are based on generic stack solutions, the study did not find a concrete product synergy between a CHP system and a product in another sector with higher volume potential.

In conclusion, the sector has potential, but requires continued investment in better products in order to develop fully.

4.9 Industrial and Commercial Stationary Applications

Introduction

The application of Fuel Cell and Hydrogen technologies to the industrial and commercial markets takes the form of co-generation or tri-generation systems. Systems available today have total powers in the range 100kW to 2-3MW (higher power, modular, systems are possible but have not been installed) and produce electricity, heating and, sometimes, cooling. Most quoted efficiencies are 70-80% overall and 45-50% electrical, suggesting that co-generation using Fuel Cells will yield significant reductions in GHG emissions. In developed countries the existing industrial and commercial power/heat sources are responsible for approximately 20-25% of the total GHG emissions, making these sectors prime targets for Fuel Cell system introduction [4.9.1].

The arguments for introducing Fuel Cell technology into these sectors are as follows:

- Many countries are investigating distributed generation strategies, influenced by renewable sources such as wind, solar, tidal and others. Fuel Cell co-generation systems suit this strategy well [4.9.2].
- The industrial and commercial sectors already use well-established fuel chain infrastructures for on-site generation and heating, plus the energy utility grids.
- Some industries already produce large quantities of potential fuel, suitable for reforming, as a direct by-product of their manufacturing/production processes. An excellent example is the chlor-alkali industry that, globally, produces 200 tonnes of hydrogen per hour. If used in Fuel Cell co-generation plants this hydrogen could produce more than 3GW of electrical power and heating.
- Co/tri-generation system efficiencies are much higher than those based on more conventional, established technologies. Fuel Cell systems will offer these sectors large potential fuel cost savings. Industries and commercial businesses will be increasingly keen to exploit GHG emissions reduction opportunities as legislation impacts their bottom line.
- Legislation in some countries is already forcing the adoption of increasing quantities of energy from renewable or greener sources. Combined with increasing conventional fossil fuel prices in the long term, a significant market already exists for Fuel Cell systems [4.9.3].

The choice or availability of fuel influences the type of Fuel Cell and reformer technology selected. Fuel Cell distributed or co-generation development is following a number of potential technology streams but with varying levels of development achieved so far. The systems that are already being produced commercially are:

- Molten Carbonate (MCFC) for applications of 200kW-2.5MW.
- Phosphoric Acid (PAFC) for applications of 100-500kW.
- Proton Exchange (PEM) for high power applications of 250kW-1MW.

- Solid Oxide (SOFC): Considerable development is still required before true commercialisation is a reality for SOFC, in spite of the significant number of companies active in this particular technology stream. Systems that have been announced so far will be suitable for many applications and operate at powers between 100-250+ kW.

All these Fuel Cell systems incorporate fuel reformers where necessary so that the unit can operate on alternatives to hydrogen. Fuel Cell co-generation systems, furthermore, must compete with long-established technologies and utility grids that are, at present, cheaper but are far less efficient. The primary goals must be as follows:

- Reduce co-generation system costs to more competitive levels.

- Reduce cell-stack operating temperatures to enable improved cell chemistry and the use of cheaper materials for the cell stacks.

- Improve fuel reformer technologies to reduce fuel impurities and hence reduce cell degradation.

- Extend cell-stack lifetime.

Main Players

An overview of companies known to be developing fuel cell systems for commercial and industrial applications is presented in Figure 28.

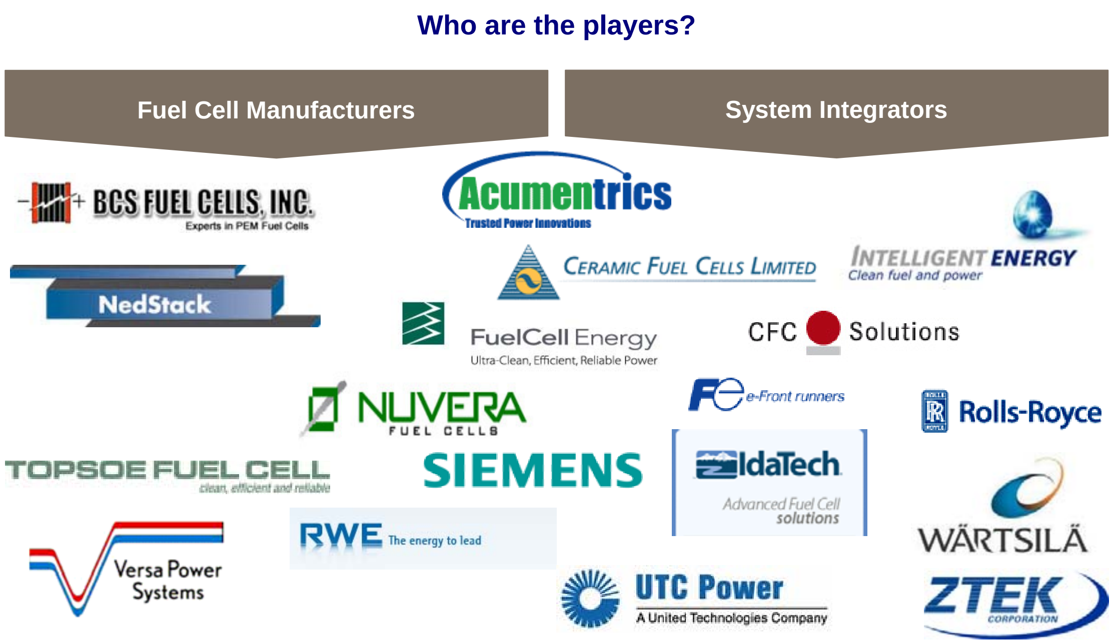

Figure 28: The main players known to be active in industrial and commercial applications of H2&FC systems

These companies can be divided into manufacturers of fuel cell stacks, system integrators who develop the actual products and those that do both. Some of the key players in this sector are highlighted in the text below.

CFC Solutions (Germany) manufacture high temperature fuel cell CHP systems. To date, CFC have installed more that 20 of their HotModule® fuel cell systems throughout Europe. These systems typically generate 245 kW of electricity and 180 kW of heat. CFC use Fuel Cell Energy's Direct FuelCell® technology [4.9.4].

Fuel Cell Energy (Danbury, Connecticut USA) is continuing to develop modular Molten Carbonate Fuel Cell (MCFC) systems with powers ranging from 300kW up to 2.4MW. They claim to be able to build systems of up to 50MW using their existing, smaller FC modules. Fuel Cell Energy owns and operates a manufacturing plant in Torrington, Connecticut, with a capacity of 50 MW of fuel cells per year at present, with plans underway to increase the production capacity [4.9.5].

Fuel Cell Energy has been working closely with its partner Enbridge to develop more efficient plants. Using the energy produced from micro-turbines, that reduce the very high natural gas transmission network operating pressure to acceptable levels, FCE is able to increase the overall efficiency of their Fuel Cell system.

NedStack (Arnhem, the Netherlands) have developed low power PEM fuel cell stacks that they sell to integration companies. NedStack is also developing a much larger PEM system, for industrial / commercial power applications, with a power output as high as 1MW [4.9.6].

Nuvera (Italy) is continuing the third phase of development of the Forza™ high power PEM Fuel Cell system specifically for chemical process industries. The hydrogen by-product of many chemical industries is an ideal fuel for this system. Nuvera expect Forza to produce up to 250kW at a net efficiency of 55-60%. Forza is being developed to allow many modules to be combined in systems with maximum powers of 2-3MW [4.9.7].

Rolls Royce Fuel Cell Systems (UK) are developing industrial/commercial SOFC co-generation systems for commercialisation in 2010. Their first field trials should start in late 2008 or early 2009.

Siemens (Germany and US) are developing SOFC systems mainly for industrial and commercial applications in the power range 100 kW to 300 kW. Their prototype products are designed either for CHP plants for combined with a gas turbine to make a hybrid power generating system. The have also developed several 25kW SOFC CHP systems for domestic trials in Japan and USA. Siemens hope to begin commercialisation of their SOFC products in 2011.

UTC Power (South Windsor, Connecticut, USA) is a single source developer, integrator and supplier of on-site, stationary co-generation and tri-generation PAFC systems with powers ranging from 195-400kW electrical plus additional heating and cooling outputs [4.9.8].

Wärtsilä (Finland) have developed a 20 kW SOFC CHP system for commercial applications. Their unit, called WFC20, is based on planar SOFC technology developed by Tospøe Fuel Cells A/S (Lyngby, Denmark). In July 2008, Wärtsilä's

SOFC CHP system was demonstrated at the Vaasa Housing Fair where it was used to supply electricity and heat, while being fuelled by landfill gas.

Recent Developments

Since early 2007 Fuel Cell Energy's largest customer, POSCO Power of Korea, has ordered nearly 40MW of systems, for delivery in 2008-2010.

UTC Power, a United Technologies Corp. company, announced in July 2008 that four models of its PureComfort® combined cooling, heating and power systems had met the emissions limits of the California Air Resources Board. This will allow UTC systems to be sited in any suitable location in California. CARB has now ordered 4 systems from UTC as part of the California Distributed Generation certification program.

On 11 June 2008, UTC Power announced that the New York Power Authority (NYPA) had selected the company to supply 12 fuel cells totalling 4.8 MW of power for the Freedom Tower and three other new towers under construction at the World Trade Centre site in lower Manhattan. Delivery of UTC's PureCell systems will begin in January of 2009. This installation has already attracted considerable interest from the building and site system services communities [4.9.9].

An overview of some of the recent key milestones is presented in Figure 29.

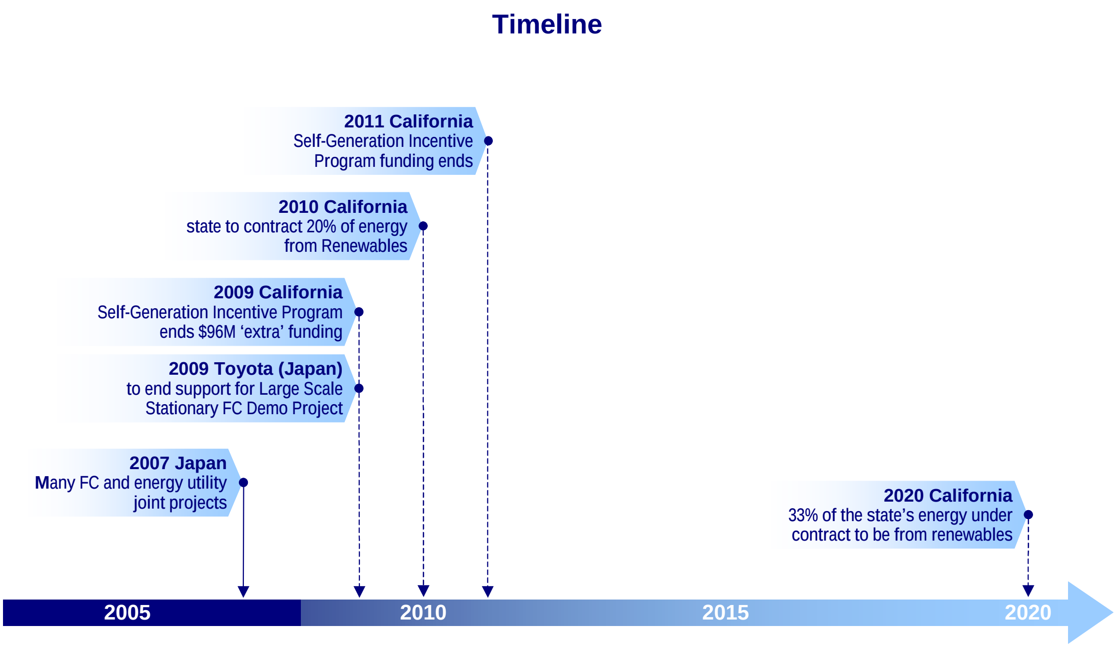

Figure 29: Key Milestones and Future Developments for applying H2&FC technology to the Industrial and Commercial Market Sectors

Drivers and Barriers

Fuel cell technology holds considerable promise for the industrial and commercial market sectors. The potential flexibility and efficiency of stationary systems, plus the many applications for which they would be ideal sources of power, are certain to be recognised. Fuel Cell systems are used predominantly in niche industries at present, but this is likely to change rapidly as the technology gains acceptance and recognition. This does depend on many elements of course, including costs, lifetimes and air quality/emissions/GHG offsetting legislation.

An overview of the drivers and barriers for industrial and commercial fuel cells is in Figure 30.

Drivers and Barriers

Drivers

+ Reduced emissions
+ Very low noise
+ Low emissions
+ Can use existing fuel-chain infrastructures
+ High overall fuel efficiency
+ Co-generation of heat, cooling and electrical power from a single source
+ Distributed generation supports many national energy strategies
+ Substantial government subsidies available in some nations (e.g. USA, Korea)
+ Modular system flexibility
+ Ease and speed of installation

Barriers

– Some technology still need to be proven
– Need for more advanced and efficient fuel reformer technologies
– Costs are too high
– Cell-stack lifetimes must be increased
– Cell-stacks must be more resistant to fuel impurities
– Established conventional technologies

Figure 30: Drivers and barriers to applying H_2 and FC systems to the industrial and commercial sectors

Concluding Remarks

The findings of this study indicate that large co- and tri-generation systems available to the market now can offer significant advantages over existing technologies. True commercialisation is limited, however, by the unproven nature of Fuel Cell-based systems and by suspected cell stack lifetimes. There is a strong, well-developed existing market for conventional products and limited Government subsidies available, in only a very few countries, to encourage Fuel Cell technologies. The high overall efficiencies of Fuel Cell systems do not yet adequately outweigh the inertia within these markets, though that situation is changing.

Only a small number of companies are successfully exploiting these markets and, until now, only to a very limited extent. Fuel Cell systems require considerable further development and have made only the smallest dent in the dominance of existing energy generation technologies. Recent shifts in Government energy strategies towards renewables, GHG emission reduction and distributed generation will improve the prospects for the future, but slowly.

More companies are carrying out research and development than are producing commercial systems. Competition should increase and help to drive the cost of the Fuel Cell systems down in time. This analysis suggests that is not likely before 2012-2015.

The current industrial and commercial uses for Fuel Cell systems are niche applications only that use existing fuel infrastructures and hence rely on the available fuel reformer technology. Manufacturers must build on their successes so far and find new opportunities by:

- Continuing development of reformers to improve efficiency and maximise cell stack lifetimes through fuel impurity reductions.
- Use modular systems that can be adapted to specific requirements but benefit from economies of scale from common components, cell stacks and balance of plant machinery.
- Improving overall system efficiencies to further distinguish between Fuel Cells and conventional generation technology.

In conclusion, the Industrial and Commercial market sectors have huge potential for growth - approximately 10 billion GWh per year is generated globally for these markets alone. Continued investment in R&D towards better products, plus increased take-up rate of Fuel Cell systems in the near future due to improved public acceptance of the technology, will ensure growth. There is no doubt that these market sectors will be critically important to the whole Fuel Cell industry.

4.10 Back-up and UPS Stationary Applications

Introduction

A back-up power system is used to supply electricity when the primary source fails. Usually there is a time interval between the failure of the main electricity source and the ramp-up of the back-up power system. An Uninterruptible Power Supply (UPS) is crucial for any operations where any interruption must be avoided at all times (for example important computer systems and complex production processes). Fuel cells can be used for both back-up power and UPS applications. However, UPS fuel cell systems have the additional requirement of ensuring the power supply is not interrupted.

A Fuel Cell back-up power system provides reliable electric power with low emissions. Compared to lead-acid battery devices, fuel cell systems provide excellent scalability for the time of operation demanded of the back-up device. The cost for power storage is low and therefore FC technology offers cost effective solutions to overcome long periods of mains failure.

For all these applications there are the following hydrogen supply options:

- Hydrogen storage tanks or cylinders (delivery by hydrogen distributors such as Air Liquide, Air Products and Linde Gas, etc.)
- Reforming of LNG, Alcohol, Ammonia, Gasoline or Diesel
- Electrolysis (Wind/Solar to hydrogen, etc)

Fuel Cell and Hydrogen technologies offer a number of significant advantages over conventional batteries and diesel generators used at present in the back-up power and UPS market sectors. These include:

- Very low emissions, with higher efficiencies.
- Robustness, with greater reliability over a wide range of operating conditions
- Fast dynamic response
- Lower maintenance costs, longer maintenance-free lifetime
- High power density, hence compact, smaller and typically lighter weight
- No limitations in start and stop cycles
- Scalable systems, optimised for specific applications

Typical applications for Fuel Cell systems include telecommunications-based uninterrupted voice, data and video services, financial institutions, medical centres, hospitals, government buildings, utilities and public safety networks. Existing technologies are mature but limited in terms of energy density and endurance. There are many instances when the specific advantages of FC systems outweigh their present price premiums.

The main arguments for introducing the technology into this sector are as follows:

- The demands of back-up power and UPS applications ideally fit the capabilities of FC systems.
- Fuel-reformation technology is advancing rapidly and will enable the use of FC systems in more locations and using a wider range of fuels.
- The footprint, quietness and very low emissions of FC systems allow the use of locations never before considered possible. This extends the flexibility of architects and market customers when specifying or procuring back-up power or UPS.
- Fuel Cell systems are more fuel-efficient and require less maintenance, lowering lifetime cost-of-ownership.
- Very low acoustic and chemical pollution make fuel cells ideal devices for domestic applications and residential suburban areas.
- The size of the storage determines the back-up time the system is able to provide and in case of gaseous hydrogen can be virtually unlimited

Fuel Cell back-up power and UPS development is following two main technology streams, which are Solid Oxide (SOFC) and Proton Exchange Membrane (PEM). SOFC is the dominant choice at present though some companies are developing excellent PEM systems. Most BUP/UPS applications demand a dedicated fuel supply or storage unit but some systems also incorporate a fuel reformer so that, where appropriate, the unit can operate on alternatives to hydrogen.

Fuel cell BUP/UPS must compete with established technologies that are cheaper but far less efficient, more expensive to maintain and with shorter lifetimes. The primary goals must be to reduce BUP/UPS unit costs, improve cell stack lifetimes further by reducing cell deterioration due to fuel impurities and, ultimately, overcome market inertia to the introduction of Fuel Cell technology.

Main Players

An overview of the companies active in development of Fuel Cell systems for back-up power and UPS applications is provided in Figure 31. These companies can be divided into Fuel Cell Stack manufacturers, system integrators and those doing both activities. Some of the key players in this sector are highlighted in the text below.

Fuel Cell Stack Manufacturers/Developers

Ballard is producing FC systems offering compact and cost-effective back up power units with powers in the range of 300W to 5kW [4.10.2].

NedStack have developed efficient low power PEM fuel cell stacks that they sell to system integration companies [4.10.1].

ReliOn, based in Spokane, Washington, USA, produces PEM back up power and UPS systems for the telecommunications industry, predominantly in the USA at present. They have two main products: the T1000 with a power of 100-1200W and the T2000 that offers powers from 100W to 6kW. ReliOn is working closely with Emerson, the world's largest power supply manufacturer [4.10.3].

System Integrators

Acumentrics (Westwood, Boston, USA) are combining PEM fuel cell technology with their 1 kW, 1.5 kW, 2 kW and 3 kW rugged, industrial and commercial UPS products to extend their runtimes and reliability [4.10.5].

Electro Power Systems (Alpignano, Italy) have developed a rack mountable 7 kW fuel cell system called the Electro7™, designed as a class 1 UPS unit. The latest variant, which was launched in January 2008, has dimensions 430 mm width by 530 mm depth by 800 mm height, so it can fit in a standard 19" rack.

IdaTech, based in Oregon, USA, produce their Electra-Gen PEM fuel cell systems for telecommunications applications. The basic FC module produces power of 1-5kW but can be combined to produce a maximum of 15kW [4.10.4].

Plug Power (Latham, New York) produces a PEM back up power system, called GenCore, for the telecommunications and utility sub-station markets. They are also penetrating the UPS market. Typical powers, in modular form, range from 1kW to more than 12kW [4.10.6].

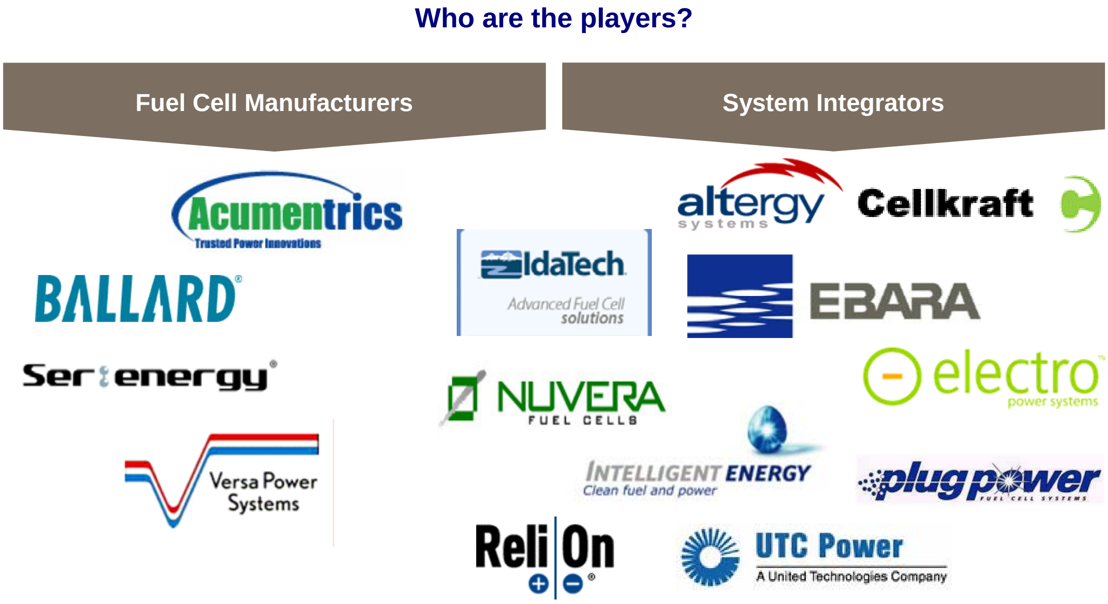

Figure 31: The main players known to be active in Back-up and UPS Applications of fuel cell technology

Recent Developments

On 4 June 2008, the US Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) awarded Acumentrics a 3.5 year $15.6 million grant to continue advancement of the company's tubular solid oxide fuel cell (SOFC) technology and to double the size of the units to 10 kilowatts [4.10.7]. Phase I of this development work was funded through the DOE Fossil Energy Solid-State Energy Conversion Alliance (SECA) program. Acumentrics will continue Phase II as part of the EERE Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) Program's effort to develop fuel cell technologies for small stationary applications.

In October 2008 IdaTech won a deal to supply nearly 10,000 fuel cell systems to Acme [4.10.8]. Acme are a telecommunications infrastructure provider based in India. IdaTech will initially supply 310 5kW fuel cell systems by the end of 2009, with a further 9,690 systems being delivered from early 2010. There is the potential to deliver an additional 20,000 units by 2013. IdaTech have described this deal as a "transformational".

Drivers and Barriers

Fuel cell technology holds considerable promise for the back up power and UPS market sectors. The principal barrier of high cost of purchase has been eroded significantly in the last few years. Now the advantages of Fuel Cell systems, in terms of overall efficiency, low emissions and physical footprint and lower maintenance costs, will encourage users to purchase them. Market penetration has been limited so far but this analysis suggests that gradual progress is being made. Back up power and UPS are small global markets overall but may become early successes for Fuel Cell systems.

An overview of the drivers and barriers to the introduction of fuel cell and hydrogen technologies to the back up power and UPS markets is presented in Figure 32.

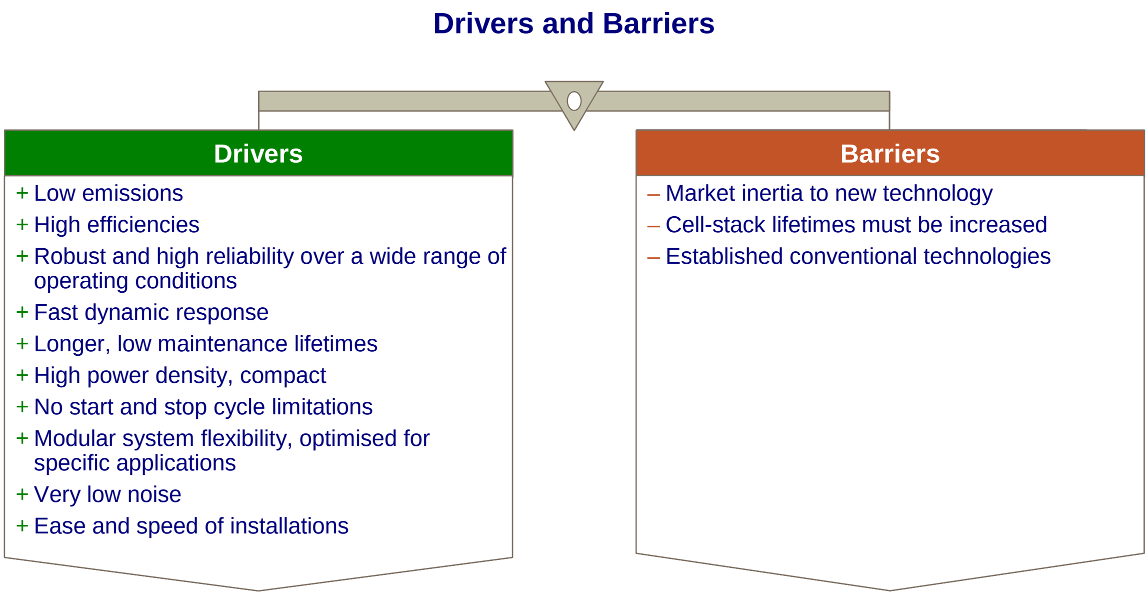

Figure 32: Drivers and barriers to applying fuel cell technology to the back-up and UPS sectors

Concluding Remarks

The findings of this study of the Back-up Power and UPS applications indicate that the Fuel Cell systems available in the market now can compete on an equivalent basis with the incumbent technology. In some locations, where exhaust emissions are of particular importance, fuel cell systems offer very significant benefits and are already making an impact. True commercialisation is limited, however, by the market inertia and unproven nature of fuel cell-based systems. Until now high purchase costs have countered the through life cost benefits. Now that air quality and exhaust legislation is making an impact, plus more competitive products, these market sectors will change.

Only a small number of companies are successfully exploiting these markets and, until now, only to a very limited extent. Fuel Cell systems still require further development. More companies are carrying out research and development than are producing commercial systems. Manufactures must:

- Use modular systems that can be adapted to specific requirements but benefit from economies of scale from common components, cell stacks and balance of plant machinery.

- Improving overall system efficiencies and through-life costs to further distinguish between Fuel Cells and conventional technology.

In conclusion, both the Back-Up Power and UPS market sectors have great potential for growth and early penetration is under way.

4.11 Portable Applications

Introduction

There are many applications for small or micro fuel cell systems. The first area to become commercially successful is educational kits and toys, with at least two companies selling Fuel Cell kits globally. The next early market area is likely to be portable battery chargers and small power packs. Two or three new fuel cell products have entered this market place during 2008. Time will tell if these products will gain enough public acceptance to become commercially successful.

Military applications are another key area for Portable Fuel Cells. Several countries, such as USA, UK and Germany, are investing in the development of Fuel Cell products to support their Infantry. It is estimated that the future infantryman power requirements could be 10 times higher that what is currently used today [4.11.1]. This is driving defence forces to seek alternatives to conventional battery packs in order to meet these future power requirements within an acceptable weight and package volume.

Consumer electronics could be a key area for micro fuel cells, with fuel cells being used to power laptop computers, mobile phones, MP3 players and other such products. Many large OEMS and small fuel cell companies are working in the area. Although many concept designs and prototypes of fuel cell powered laptops and mobile phones have been displayed at industrial fairs over the past five years, to date, there are no commercial products available.

What is the technology?

Fuels	On-board Storage	Fuel Cell Technology
Methanol	Liquid container	DMFC Reformed Methanol Fuel Cells (RMFC)
Hydrogen	Gas Canisters Metal Hydride Sodium Borohydride Ammonia Borane	PEM FC
Ethanol	Liquid container	Direct Ethanol Fuel Cells (DEFC)
Borohydride	Liquid container	Direct Liquid Fuel Cells (DLFC)

Figure 33: Overview of the types of Fuel Cell technology being developed for Portable applications

An overview of the types of Fuel Cell technology used to power portable applications is provided in Figure 33.

Portable Fuel Cell systems tend to use either DMFC or PEM technology. However there are a few companies working on novel fuel cell solutions such as Direct Liquid Fuel Cells powered by a borohydride salt. Many of the fuel cell companies in the Portable sector are also developing on-board fuel storage solutions and refuelling systems. For PEM FC systems run on pure hydrogen, the hydrogen tends to be stored as a gas or in a metal hydride canister. A few players in this sector are researching alternative solutions for transporting and storing the hydrogen, such as using ammonia borane tablets.

Main Players

There are many companies across the globe developing fuel cell solutions for portable products. Most of these are relatively new, small start-up fuel cell companies founded within the last decade. An overview of some of the main players in this sector is provided in Figure 34.

Figure 34: Main Players developing Portable Fuel Cell products

Recent Developments

One of the major developments in the Portable Fuel Cell sector in recent years has been the launch of fuel cell products that members of the public can actually buy. To date this has mainly been educational kits and toys. Prices range from ~€20 for a small fuel cell to over €2000 for an exhibition demonstration kit. Horizon is one of the most prolific producers of such kits, with the largest range of fuel cell educational toys that can be purchased through their website. In recent years they have been strengthening their market position by forming partnerships with several toy companies, such as Corgi in the UK and Wah Shing Toys in China.

In 2008 Medis Technologies Ltd (USA) launched a portable, disposable battery charger for mobile phones which used Direct Liquid Fuel Cell technology. The unit, called the "24-7 Power Pack", uses liquid borohydride as the fuel and is capable of recharging a mobile phone at least 5 times. The recommended retail price is $29.99 for the start kit and $19.99 for a replacement power pack. The 24-7 Power Pack is UL listed[5].

Horizon Fuel Cell Technologies have also developed a small portable generator called the HydroPak (dimensions 220mm x 210mm x 100mm), capable of 10 hours operation at 25W output. The system uses a sodium borohydride hydrogen storage system. The hydrogen is release when water is added. Horizon plan to make the HydroPak commercially available by the end of 2008, with a recommended retail price of $400 for the unit and $20 for the disposable fuel cartridges.

SFC Smart Fuel Cells have a family of portable DMFC power packs known as "EFOY". These products been primarily sold to manufacturers of recreational vehicles such as motor homes and caravans, to be used as portable battery chargers. However the product can be used for other applications requiring remote power such as military operations. In September 2008, SFC launched a new version called EFOY Pro Series, a hybrid DMFC power pack system suitable for professional off-grid applications.

There are several fuel cell companies at an advance stage of product development, with prototype units being sold for operation trials. One of the most advanced military products is SFC's 25W "JENNY" DMFC power system, which has reached Technology Readiness Level (TRL) 8[6]. In the USA, UltraCell's XX25™ 25W portable fuel cell system has achieved Technology Readiness Level (TRL) 7[7].

ITM Power (UK) has developed a 20W PEM FC system that can flex. Although this product is still at the laboratory stage of development, its ability to continue working while being bent and twisted makes it ideally suited for rugged environments.

There have been many design concepts and prototypes launched at trade fairs over the past 12 months. Three of the most significant are:

- Sony's prototype micro hybrid fuel cell system, with dimensions 50 mm by 30 mm. The unit includes a DMFC and Li-polymer battery and is capable of 3 W output, making it suitable for mobile phones and portable media players.

- Angstrom's prototype Motorola SLVR phone, containing a fully integrated fuel cell system based on their PEM FC technology with metal hydride hydrogen storage. The prototype has double the talk time of the conventional Li-ion battery and has completed a six-month trial

- CMR Fuel Cells DMFC demonstrator system, which was used to power a laptop computer during the FC Expo 2008 [4.11.2].

[5] Underwriters Laboratories (UL) provide product certification marks (www.ul.com)
[6] TRL 8: Actual Technology System completed and qualified through test and demonstration
[7] TRL 7: Technology system prototype demonstration in an operational environment

One of the most significant milestones for portable fuel cells was the 2007 ruling by the International Civil Aviation Organisation (ICAO) allowing fuel cells and a limited number of methanol cartridges in aircraft cabins. This ruling is due to come into effect on 1 January 2009, removing one of the social barriers to the uptake of fuel cell technology with the consumer electronics sector.

An overview of some of the key milestones in recent years is provided in Figure 35.

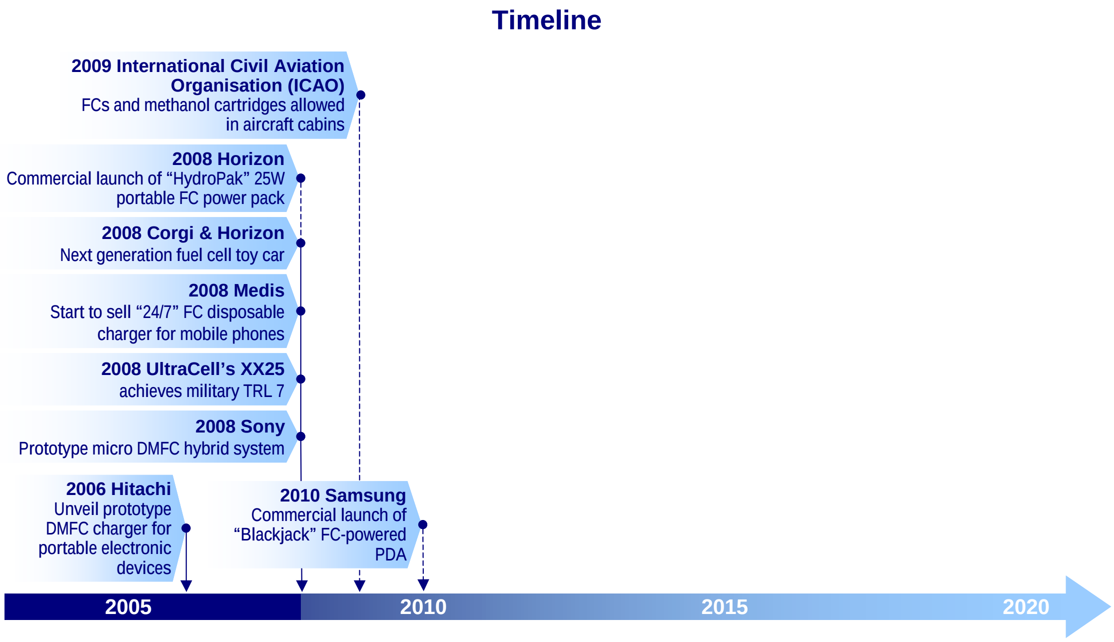

Figure 35: Key Milestones and Future Developments in the Portable Fuel Cell sector

Drivers and Barriers

The drivers for encouraging the adoption of portable fuel cells depend on the application area. If Fuel Cell technology is to become successful in the future, there is the need to educate students of today about this technology. Hence the rise of fuel cell educational kits. For the military, there is the requirement for a power solution that has a longer run time, higher energy density and lighter weight than the battery packs used today. A similar driver is in place in the consumer electronics industry, with products requiring more power in a smaller volume.

However, despite these drivers for the adoption of fuel cell technology, there are still many technical and socio-economic barriers to the uptake of fuel cells in portable products (see Figure 36). Codes and standards for the products need to developed and adopted internationally. The capability, reliability and durability of micro fuel cell systems need to be proven in the field. A suitable international distribution network for supply of refuelling cartridges needs to be developed. Fuel cell powered portable products will operate differently from the conventional rechargeable battery used today. Companies launching portable Fuel Cell products need to communicate clearly to users how to use the fuel cell technology.

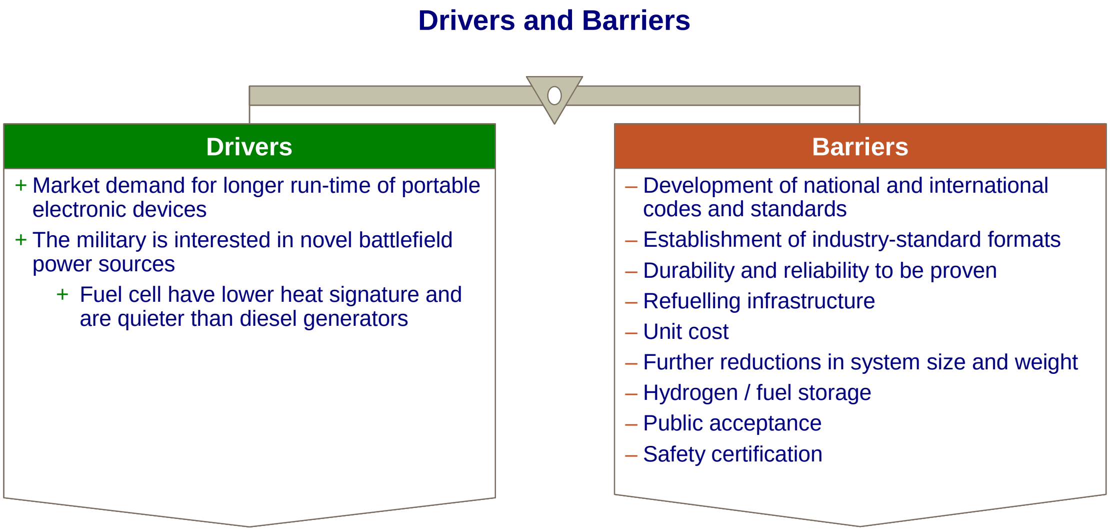

Figure 36: Drivers and Barriers for applying H2&FC technology to Portable products

Concluding Remarks

The Portable products sector is a promising early market opportunity for fuel cell technology. Already, there are a small number of companies successfully producing and selling fuel cell educational kits and toys. These kits are relatively simple to produce and do not have the same reliability and warranty requirements as other consumer electronics. They also serve as a means of educating the public about Fuel Cell technology and increasing public awareness of the potential benefits of the technology.

The USA is funding many programmes that are developing fuel cell products for military applications. Some of these programmes are specifically looking at how the future military personal power requirements can be met. Several European countries, such as Germany and UK, are investing in similar research projects. Prototype Fuel Cell systems, designed to act as an equivalent to portable battery packs for the infantry, are reaching advanced stages of technical readiness. Within the next few years it is likely that these products will be ready for full-scale deployment.

Over time technology used by the military often migrates across to the public sector, as has been seen in recent years with the rise of GPS and satellite navigation systems. This means that military applications are an important market for early portable fuel cell products.

Fuel cell portable battery chargers could be a stepping stone for introducing fuel cell technology into the consumer electronics market. These products serve the useful role of changing people's perceptions about how they recharge their mobile phones, MP3 players, laptops and other portable gadgets. Instead of plugging into the electric grid, consumers recharge by buying fuel cartridges for their charger. Several fuel cell portable battery chargers have been launched in 2008, but it is too soon to know if these early products will be commercially successful.

Research and development of fuel cell systems for powering portable electronic devices is on going. This work is being conducted by small start-ups, who manufacture portable fuel cells, and by large electronics companies. It is difficult to predict when fuel cell powered electronic devices will become commercially available. Although, there have been many demonstration prototypes and claims of when these products would come to market, to date, no fuel cell powered portable electronic devices are available to purchase. There are a number of hurdles to be overcome, such as:

- Ensuring the fuel cell system can package within the existing battery space, with a higher energy density that the existing battery technology
- Proving the reliability and durability of the fuel cell power system
- Developing a suitable refuelling system and fuel distribution network
- Gaining public acceptance of the new technology and the new method for “recharging”

However once the technology is ready and solutions for these hurdles have been found, portable fuel cells have the potential to rapidly claim market share within the consumer electronics sector.

5. Discussion and Conclusions

This part of the Roads2HyCom project has used a comprehensive review of commercial and prototype Fuel Cell and Hydrogen application products, to identify trends in the emerging technology and to validate the project's findings on the State of the Art. This approach has been successful, in that fully integrated products provide a more robust view of what the technology is capable of in a commercialisable form. In many cases there may be laboratory developments with greater apparent capability, but that capability can only be considered robustly proven once it is contained in an integrated product.

This study has revealed an extraordinary number of products at prototype or limited production stage, considering that the Fuel Cell sector as a whole is commercially immature. In total, there are more than 40 manufacturers active (meaning having prototypes or low volume products) across the vehicle sectors; the major aircraft manufacturers are engaged in programmes, and a variety of applications have been demonstrated in marine power. In stationary and auxiliary power there are more than 20 active manufacturers, with a number of energy utilities starting to make significant investments in bringing products into use.

And yet, outside the educational toy sector, the study has found just one organisation trading profitably with a Fuel Cell product. This is an important issue – to be considered truly "commercialised", a product has to be made and sold on a basis that is profitable all the way up the value chain, from parts supply through integration to retail. The definitive challenge for the Fuel Cell in the coming decade, is to start showing a different picture with more products being traded profitably.

The results of this study indicate how and where this might happen:

- **The passenger car** is a very important application for Fuel Cells and Hydrogen, due to its ubiquity, which creates both a need and a route to economies of scale. Encouraging progress is evident in terms of technical performance of Fuel Cells (and also Hydrogen ICEs) in the latest field-trial vehicles, and also in terms of the level of commitment displayed by a number of manufacturers. There appears to be a route map for addressing the Fuel Cell cost issue, though not, as yet, for the cost of the fuel tank. Battery-electric technologies are both a key competitor here and a complementary technology, as seen in recent prototypes with dual fuel (Hydrogen / Electricity) capability. The precise nature of the products that finally become fully and profitably commercialised will depend on the outcome of one of the defining technological battles of the twenty-first century - the battle between the storage of Electricity and the storage of Hydrogen. In the meantime, we will see the advent of niche or image vehicles that may not be profitable but are still commercially relevant.

- **The captive fleets sector (buses, taxis, delivery vehicles)** is known to be a promising early market for Fuel Cells and Hydrogen, because of lower infrastructure dependency and the beneficial effect of local political will on purchase decisions. Perhaps importantly, these early fleets might provide seeds for the growth of a more extensive Hydrogen infrastructure, linking city centres to highway refuelling. Technical hurdles are similar to the passenger car, although the larger daily operating range of captive fleet vehicles places Hydrogen at a clear advantage over Electricity as a fuel in many cases. The success of the next generation of Fuel Cell and Hydrogen captive-fleet demonstration vehicle will be critical to the success of Hydrogen in Transport.

- **Material handling vehicles** have been identified as a promising near-term market opportunity for Fuel Cells and Hydrogen, especially in addressing the limitations of the incumbent battery-electric technology used in indoor goods handling. On the surface, fuel cell systems for material handling vehicles appear to be on the tipping point of commercialisation. Several system integrators have produced fuel cell hybrid power packs for electric forklifts and pallet trucks designed to replace the existing battery packs. Technical specifications on these products are publically available through the system integrator websites, although price information needs to be requested. Numerous small-scale fleet trials are now taking place in North America and Europe, and early users appear to like the technology. However, given the challenges of translating these low volume products to a more mainstream context, it could take another 4-5 years before fuel cell applications for this sector are truly market ready; and advances in battery technology (including fast charging) will continue to present competition. Nonetheless, this is a promising sector.

- **Two Wheeled Vehicles** could become an interesting early market, especially if transport policy supports the development of markets for zero-emission two wheelers. The usual issues of cost, size, durability and refuelling need to be addressed but this is a less aggressive environment for many of these issues. Battery-electric two wheelers will present a challenge, though as with their four-wheeled counterparts the Hydrogen tank remains a more capable energy store. The sector appears to offer the potential of an untapped global market for basic, low cost but clean individual mobility. Further investment in better products, and the retailing of fuel, is needed in order to exploit this market; but there is a real risk that products developed and made cheaply in China could dominate world markets.

- **Auxiliary Power** for transport applications is an existing, genuine market for the Fuel Cell product, with thousands having been sold to genuine users in the leisure sector without special incentives and on a basis that is probably profitable along the supply chain – and this in itself is still unusual in the fuel cell business. However, there is only one very active supplier selling products right now, and it is a product that requires its own dedicated fuel, and its power output is not sufficient for it to migrate directly from the leisure sector to commercial transport application. To consolidate its success as an early market sector for the Fuel Cell, technological progress in sulphur-tolerant reformers, system cost, size and durability, needs to continue so that APU systems with powers in the 1-10kW range can be realised – perhaps sharing stack components with smaller transport or CHP systems for economies of scale.

- **The marine sector** offers a variety of potential early market applications, ranging from auxiliary power in the leisure and light commercial sector (essentially marinising technologies from the APU sector), to specialised motive power for environmentally sensitive situations. Although these applications are mostly one-off or low volume production, these technologies might serve a useful purpose in increasing public awareness and acceptance of fuel cell technology. Use of Fuel Cells in larger commercial shipping applications is still to be proved; this very demanding market (in terms of in-service ruggedness) will not be an early market.

- **The civilian aircraft sector** will not be an early adopter of fuel cell technology. However, given the interest in the technology displayed by two of the world's major aircraft manufacturers, it is likely that fuel cells will appear in aircraft in the future. The most likely applications are hybrid fuel cell APU systems for commercial aircraft, with products appearing around 2020. In the meantime, specialised **military applications** for surveillance will be a small but very high value market.

- **The domestic CHP sector** is an attractive early market for the Fuel Cell, and publicly stated information gives a clear indication that this sector is rapidly approaching true commercialisation – first products are scheduled to be marketed from circa 2012. There is a strong, well-developed existing market for conventional boiler replacement and, as fuel prices increase, many consumers will be looking to adopt money-saving technology. A key test will be whether these first products deliver on "business case" and durability; in this sector free-piston Sterling engines are a challenger technology but they have their own issues of cost, durability and vibration. In the long term, this sector could be threatened by super-insulated homes and solar water heating, but given the lifetime of housing stock this does not limit the market for several decades.

- The **Industrial and Commercial market sectors** offer a huge potential for growth for Fuel Cell technology as the distributed generation expands across the globe. Fuel Cell products for industrial and commercial co- and tri-generation applications are already available. However the strong, well-developed market for the conventional product combined with the higher purchase price for the Fuel Cell systems is limiting the market penetration for Fuel Cell technology. Further R&D on reducing Fuel Cell system costs by using modular components and on improving fuel reformer technology will improve the prospects for Fuel Cell technology in this sector. Suitable Government policies and subsidies may also encourage the shift from conventional to new technology.

- The **Back-Up Power and UPS market sectors** have great potential for growth and early penetration is under way, as seen in the deal between IdaTech and Acme. There are several Fuel Cell systems already available in the market place, which can compete on an equivalent basis with the incumbent technology. However, for Fuel Cell systems to establish a firm market share in this sector, the technology must be proven to be reliable, durable and at a price that can be justified on a life-time basis.

- **Portable Fuel Cells** is an interesting early market for Fuel Cell and Hydrogen technology. Education kits are already commercially successful and there are indications that the technology is breaking into the Toy market. Fuel Cell technology offers significant advantages compared to current battery technology in terms of reduced weight and higher energy density. This is helping to drive the development of the technology especially for military applications. Several military fuel cell products have already been tested in the field. Technology developed for the military is likely to spin out to the commercial sector over time. Within consumer electronics, no Fuel Cell powered electronic devices are currently available, but a couple of portable Fuel Cell battery chargers have been launched over the past year. These Fuel Cell battery chargers indicate a tentative first step into a potential market for Fuel Cell technology.

6. References

[1.1] PATTERSON, J., *A map of Hydrogen and Fuel Cell Research and Technology Development activity in Europe*, Roads2HyCom Report (Document Reference R2H1015PU.2), 9 April 2008, available to download from www.roads2hy.com/wp1.html; searchable online database of technology developers

[1.2] *The Roads2HyCom Hydrogen and Fuel Cell Wiki*, an online State of the Art encyclopaedia, accessed via www.roads2hy.com or directly at www.ika.rwth-aachen.de/r2h/index.php/Main_Page

[1.3] *Well to Tank Technology Pathways and Carbon Balance*, Roads2HyCom Report (Document Reference R2H4003PU), publication expected October 2008, to be available to download from www.roads2hy.com/wp4.html

[1.4] *Tank to User Technology Pathways and Carbon Balance*, Roads2HyCom Report (Document Reference R2H4004PU), publication expected October 2008, to be available to download from www.roads2hy.com/wp4.html

[1.5] *Analysis of Opportunities and Synergies in Fuel Cell and Hydrogen Technologies*, Roads2HyCom Report (Document Reference R2H4005PU), publication expected November 2008, to be available to download from www.roads2hy.com/wp4.html

[1.6] *Recommendations for the Fuel Cell and Hydrogen Research Agenda*, Roads2HyCom Report (Document Reference R2H6035PU), publication expected January 2009, to be available to download from www.roads2hy.com/wp6.html

Passenger Cars

[4.1.1] *Honda Sees Mass Production of Fuel-Cell Cars Possible by 2018*, 29 December 2006, Article at www.greencarcongress.com/2006/12/honda_sees_mass.html

[4.1.2] KLEIN, C., *Review of Technical, Socio-economic and Safety findings from Fuel Cell Vehicle Demonstration Activities*, Roads2HyCom Report (Document Reference R2H6031PU.2), available as a download from www.roads2hy.com/wp6.html

[4.1.3] Generation B – Article from Daimler Hi-Tech Report Issue 1/2008; available from Daimler AG

[4.1.4] *Well to Tank Technology Pathways and Carbon Balance*, Roads2HyCom Report (Document Reference R2H4003PU), publication expected October 2008, to be available to download from www.roads2hy.com/wp4.html

[4.1.5] *Ricardo, QinetiQ and PSA Peugeot Citroen's Efficient-C research project delivers ultra-low carbon emission powertrain*, Ricardo plc Press Release, 2 June 2006, link: http://www.ricardo.com/media/pressreleases/pressrelease.aspx?page=40

[4.1.6] Final version of the Implementation Plan – Status 2006, endorsed by the HFP Advisory Council on January 19, 2007, available as a download from https://www.hfpeurope.org/hfp/keydocs

[4.1.7] *The Roads2HyCom Hydrogen and Fuel Cell Wiki*, an online State of the Art encyclopaedia, accessed via www.roads2hy.com or directly at www.ika.rwth-aachen.de/r2h/index.php/Main_Page

[4.1.8] FROST, J., *Hydrogen and Fuel Cells for Automotive Application,* Johnson Matthey, IMechE Conference on Low Carbon Vehicles, London, November 2006

[4.1.9] *Ricardo Developing World-Leading, Low CO2 SULEV Diesel Engine Technology,* Ricardo plc Press Release, 17 August 2006, link: http://www.ricardo.com/media/pressreleases/pressrelease.aspx?page=51

[4.1.10] European Commission, *COM (2007) 856 Final*, Proposal for Regulation Setting Emission Performance Standards, link: http://ec.europa.eu/environment/co2/pdf/co2_cars_proposal.pdf

[4.1.11] BAKER, H. and JOHNSON, A., *Understanding Manufacturers Responses to Policy Measures to Incentivise Fuel Efficiency*, Ricardo UK (Document Reference RD07.82501.15 and RD07.82501.16), October 2007, published by the UK Department for Transport in July 2008

[4.1.12] US Congressional record - Senate, June 20, 2007, Senate Amendment 1792

[4.1.13] *GM says more joint R&D is needed to reduce CO_2,* Automotive Engineer, June 2008, page 5

[4.1.14] Honda's Fuel Cell website http://world.honda.com/FuelCell/

Buses and other Captive Fleets

[4.2.1] Hyfleet-CUTE project: www.global-hydrogen-bus-platform.com; www.hyfleetcute.com

[4.2.2] HyPath project: www.global-hydrogen-bus-platform.com/hypath1/ppt.html

[4.2.3] Zero Regio project: www.zeroregio.com

[4.2.4] Hydrogen Bus Alliance: www.hydrogenbusalliance.org

[4.2.5] Collaboration to develop a Fuel Cell Taxi (London Taxi / Intelligent Energy): http://www.greencarcongress.com/2008/05/collaboration-t.html

[4.2.6] Data supplied by the UK Low Carbon Vehicle Partnership working group on Buses, 2008

[4.2.7] HyRaMP, the European Hydrogen Regions and Municipalities Partnership, www.Hy-ramp.org

[4.2.8] SHAW, S. and MAZZUCCHELLI, P., Profiling of Hydrogen Communities in Europe: A framework for self-evaluation and advice on success factors, Roads2HyCom Report (Document Reference R2H3010PU.2), December 2007, available as a download from www.roads2hy.com/wp3.html

[4.2.9] *Analysis of Opportunities and Synergies in Fuel Cell and Hydrogen Technologies*, Roads2HyCom Report (Document Reference R2H4005PU), publication expected November 2008, to be available to download from www.roads2hy.com/wp4.html

Material Handling Vehicles

[4.3.1] H2Mobility website, link: http://www.netinform.net/H2/H2Mobility/Default.aspx

[4.3.2] MADADEVAN, K., JUDD, K., STONE, H., ZEWATSKY, J., THOMAS, A., MAHY, H. and PAUL, D., April 2007, *Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets*, Battelle Memorial Institute, prepared for U.S. Department of Energy

[4.3.3] Hydrogenics company website, link: http://www.hydrogenics.com

[4.3.4] Plug Power company website, link: http://www.plugpower.com

[4.3.5] Nuvera company website, link: http://www.nuvera.com

[4.3.6] *Plug Power Announces Sale to Bridgestone Firestone Tire*, Plug Power press release, 31 March 2008, link: http://www.plugpower.com/news/press.cfm?sr=13&yr=2008

Scooters, Electric Bicycles and Wheelchairs

[4.4.1] MURAMATSU, Y., FURUKAWA, K and ADACHI, S., Yamaha Motor Co., Ltd., *Evaluation of direct methanol fuel cell systems for two-wheeled vehicles*, 2007, SAE 2007-32-0112, JSAE 20076612

[4.4.2] Valeswood Environment Technology webpage on their Pearl Hydrogen Bicycle, www.valeswood.com/hydrogen-bicycle.php, as displayed in July 2008

[4.4.3] Veloform website, www.veloform.com, price information as stated in July 2008

[4.4.4] SFC Smart Fuel Cell website, *van Raam and Veloform start serial production*, press release issued 13 February 2008, http://www.efoy.de/index.php?option=com_content&task=view&id=922&Itemid=177

[4.4.5] *China Remains On Top Despite Pressures*, article from Bicycle Retailer, 8 July 2008, link: http://www.bicycleretailer.com/news/newsDetail/1559.html

Vehicle Auxiliary Power Units

[4.5.1] BLAKE, G. D., *Solid Oxide Fuel Cell Development for Auxiliary Power in Heavy Duty Vehicle Applications*, Delphi, June 2008, U.S. DoE Hydrogen Program Review Days 2008

[4.5.2] NORRICK, D., *Diesel Fueled SOFC System for Class 7/Class 8 On-Highway Truck Auxiliary Power DE-FC36-04GO14318*, Cummins Power Generation, 13 June 2008, U.S. DoE Hydrogen Program Review Days 2008

[4.5.3] Website for the U.S. Solid State Energy Conversion Alliance (SECA): http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/

[4.5.4] PowerCell website www.powercell.se

[4.5.5] *Nordic support for fuel cell truck APU development project between H2 Logic A/S, Volvo and StatoilHydro*, H2 Logic press release issued 29 October 2007, available from the H2 Logic website: http://www.h2logic.com/com/news/H2Logic_PR29102007_INT.pdf

[4.5.6] *Hydrogenics Receives Contract From MAN Nutzfahrzeuge AG to Provide Fuel Cell Power Unit for Berlin Hydrogen Bus*, Hydrogenics press release issued 15 May 2007, available to download from Hydrogenics website (http://www.hydrogenics.com/ir_newsdetail.asp?RELEASEID=244066)

[4.5.7] SFC Smart Fuel Cell AG website www.efoy.de

[4.5.8] SFC Smart Fuel Cell AG Annual Report 2007, available to download from the SFC website www.efoy.de

[4.5.9] Voller Energy Group plc website www.voller-energy.com

Marine Transport

[4.6.1] TRONSTAD, T. and BYRKNES, J., *Fuel Cells in Ships: Safety & Reliability*, a DNV report, link: www.dnv.co.kr/binaries/fuel%20cells%20in%20ships%20-%20safety%20and%20reliability_tcm34-20784.pdf

[4.6.2] METHAPU Project (Validation of Renewable Methanol based Auxiliary Power Systems for Commercial Vessels) website, link: www.methapu.eu

[4.6.3] FellowSHIP Project (Fuel Cells for Low Emissions Ships) website, link: www.fuelcellship.com

[4.6.4] Voller Energy company website, link: www.voller-energy.com

[4.6.5] Zemships Project (Zero Emission Ships) website, link: www.zemships.eu

[4.6.6] Fuel Cell Boat Project website, link: www.fuelcellboat.nl

[4.6.7] BUTLER, J., *Fuel Cell Today, 2008 Niche Transport Volume 2*, link: www.fuelcelltoday.com

Air Transport

No references

Domestic Stationary Applications

[4.8.1] UK Department for Transport, Statistics (data, tables and publications), Energy and the Environment, published 31 October 2007, link: http://www.dft.gov.uk/pgr/statistics/datatablespublications/energyenvironment/

[4.8.2] The growth potential for Microgeneration in England, Wales and Scotland, report by Element Energy for UK Department for Business, Enterprise and Regulatory Reform (BERR), June 2008, link: http://www.berr.gov.uk/energy/sources/sustainable/microgeneration/research/page38208.html

[4.8.3] Baxi Innotech website, link: www.baxi-innotech.de

Industrial and Commercial Stationary Applications

[4.9.1] UK Department for Transport, Statistics (data, tables and publications), Energy and the Environment, published 31 October 2007, link: http://www.dft.gov.uk/pgr/statistics/datatablespublications/energyenvironment/

[4.9.2] The growth potential for Microgeneration in England, Wales and Scotland, report by Element Energy for UK Department for Business, Enterprise and Regulatory Reform (BERR), June 2008, link: http://www.berr.gov.uk/energy/sources/sustainable/microgeneration/research/page38208.html

[4.9.3] *Advancing Renewable Energy*, brochure from the California Public Utilities Commission, link: http://www.cpuc.ca.gov/cleanenergy/design/docs/Renewableslowres.pdf

[4.9.4] CFC Solutions company website, link: http://www.mtu-friedrichshafen.com/cfc/en/cfcs/cfcs.htm

[4.9.5] Fuel Cell Energy company website, link: www.fuelcellenergy.com

[4.9.6] NedStack company website, link: www.nedstack.com

[4.9.7] Nuvera Fuel Cells company website, product page on Forza Industrial Power Fuel Cell system, link: http://www.nuvera.com/products/forza.php

[4.9.8] UTC Power company website, link: www.utcpower.com

[4.9.9] New York Power Authority Selects UTC Power to Supply Fuel Cells for World Trade Centre Site, UTC Power Press Release, 11 June 2008, link: http://www.utcpower.com/fs/com/bin/fs_com_Page/0,11491,0278,00.html

Back-Up and UPS Stationary Applications

[4.10.1] NedStack company website, link: www.nedstack.com

[4.10.2] Ballard company website, Backup Power Market page, link: http://www.ballard.com/Backup_Power_Fuel_Cells/Application_Overview.htm

[4.10.3] ReliOn company website, Products & Solutions page, link: http://www.relion-inc.com/products-telecom.asp

[4.10.4] IdaTech company website, link: www.idatech.com

[4.10.5] Acumentrics product brochure on ElectraGenTM Family of Backup Power Systems, link: http://www.idatech.com/uploadDocs/ElectraGenFamilySheet_Reduced.pdf

[4.10.6] Plug Power company website, Backup Power product page, link: http://www.plugpower.com/products/premium.cfm

[4.10.7] *Acumentrics received $15.6 million DoE Fuel Cell development contract*, Acumentrics Press Release, 4 June 2008, link: http://www.acumentrics.com/7e683b31-136b-4e00-8ed7-14974bcdb463/press-releases-release-details.htm

[4.10.8] Major Contract Win – Up to 30,000 Fuel Cell System Supply Agreement Signed with ACME Group, IdaTech Press Release, 10 October 2008, link: http://www.idatech.com/IRdocs/IDA_ACME_Supply_Agreement_9_October_2008%20-%20Final.pdf

Portable Applications

[4.11.1] HULEATT-JAMES, N. & McCARNEY, J., *Outlook: Delivering fuel cell technology to the military*, June 2008, article for the UK Low Carbon and Fuel Cell Technology Knowledge Transfer Network, link: http://fcf.globalwatchonline.com/epicentric_portal/binary/com.epicentric.contentmanagement.servlet.ContentDeliveryServlet/FCF/Fuel%2520Cells%

2520Content/Outlook%2520Articles/KTN%2520Outlook%2520Military%2520Fuel%2520Cells.pdf

[4.11.2] HUGH, M, *FC Expo 2008 Event Report* from Fuel Cell Today, 27-29 February 2008, link: http://www.fuelcelltoday.com/events/reports/FCT-Event_Report_FCExpo2008

7. Glossary of Terms

AFC	Alkaline Fuel Cell
APU	Auxiliary Power Unit
DEFC	Direct Ethanol Fuel Cell
DLFC	Direct Liquid Fuel Cell
DMFC	Direct Methanol Fuel Cell
EV	Electric Vehicle
FC	Fuel Cell
FC-HEV	Fuel Cell Hybrid Electric Vehicle
H2-ICE	Hydrogen Internal Combustion Engine
H2&FC	Hydrogen and Fuel Cells
HEV	Hybrid Electric Vehicle
ICAO	International Civil Aviation Organisation
ICE	Internal Combustion Engine
MCFC	Molton Carbonate Fuel Cell
PEM	Proton Exchange Membrane / Polymer Electrolyte Membrane
PHEV	Plug-in Hybrid Electric Vehicle
RMFC	Reformed Methanol Fuel Cells
SECA	Solid State Energy Conversion Alliance, a partnership between U.S. industry, universities and other research organisations funded by the U.S. Department of Energy
SOFC	Solid Oxide Fuel Cell
SOTA	State of the Art
SULEV	Super Ultra Low Emission Vehicle
UAV	Unmanned Aerial Vehicle
UUV	Unmanned Undersea Vehicle