FUEL CELLS NICHE MARKET APPLICATIONS & DESIGN STUDIES

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EXECUTIVE SUMMARY

Background Mainstream fuel cell markets such as stationary power and transport propulsion have already received considerable attention. However, the niche areas considered in this report also offer considerable markets that are considered potentially ready for exploitation. This report examines those markets and considers the broad issues for exploitation.

This programme of work has been funded under the DTI's Advanced Fuel Cell Programme.

Objectives The overall aim of this project was to identify and evaluate niche market applications that have the potential to provide early commercially competitive market opportunities for fuel cell systems. Battery replacement, portable, mobile auxiliary power and stationary applications for non-standard generation are covered.

Approach This report identifies and describes a wide range of niche market applications which may provide market opportunities for fuel cells. It is divided into four broad sections as follows: battery replacement markets, power generation applications, transport applications and other niche markets. Where possible, market sizes have been quantified, including forecasts up to 2010. The necessary technical and commercial criteria for success are also discussed.

The report includes an assessment and ranking of the various niche markets, from which scoping system designs were developed for the leading five niche market applications. Subsequently the leading players likely to be interested in such systems have been identified and listed. In addition, an environmental impact assessment of fuel cell systems in comparison with their conventional power source alternatives has also been carried out on a world-wide scale.

Results

Of the niche markets identified, several would appear to be ideally placed for exploitation, whilst others either have technical reasons why they would be unattractive or the market is simply too small. Of the promising markets identified, the following are the top five:

- Auxiliary Power Units (APUs) for Executive Cars
- Leisure / Outdoor (including gardening, camping etc.)
- Portable Power
- Portable Electronics (laptop computer, mobile phone and video camera)
- Custom / Premium Power

Promising Areas for Development and System Designs: *APUs for executive cars* are already being developed. Indeed, BMW are planning the use of a 5 kWe SOFC unit in their 7 series models in the near future. Of the *leisure/outdoor* area, lawnmowers and camping appear promising areas. In particular, 3 – 4 kWe PEM powered lawnmowers could provide a premium market where electric mowers fed by mains electricity cannot compete. *Portable power* is a large market for products in the range 1 - 75 kVA. It is ideally suited to hydrogen fuelled PEM fuel cells, and could provide an early market with considerable emission savings. *Portable electronics*, though a comparatively small market, again could give early penetration using direct methanol fuel cells. The *premium power* market, though relatively small, is ideally suited to early niche applications using PEM fuel cells.

Materials: By far the three largest markets are portable power (35GW), car APUs (25 GW) and garden equipment (20 GW). Portable power and garden equipment would both probable require hydrogen fuelled PEM fuel cells, whilst car APUs seem likely to be supplied by small SOFCs. There are few material concerns, though the shift reactors used in low temperature fuel cells should be disposed of by specialist contractors. Replacement of lead-acid batteries could also save over 1 billion tonnes of battery production.

Fuel: There would be a large decrease in the use of most fuels due to the better fuel economy of niche fuel cells. Hydrogen supply, however, would require new infrastructure to meet new demand of 230 billion cubic metres. Also, methanol production capacity would need to increase by around 8%.

Emissions: There are potential savings in CO_2 emissions of around 800 million tonnes. The majority of this is due to a reduced use of diesel fuel, which is achieved from the portable power and marine APU markets. There are also potential NO_x emissions savings of around 18 million tonnes, SO_x and hydrocarbon emissions savings of 3 million tonnes each and CO savings of almost 2 million tonnes. The majority of these savings would be due to the marine APU market.

Implications This report should provide further guidance to those organisations interested in exploiting niche markets for fuel cells. Considerable emission savings are possible, which could help countries meet emission targets already committed to. Hydrogen produced from renewable sources would also find extensive applications in many of the niche markets considered.

Glossary of Terms

AC	Alternating current
AFC	Alkaline fuel cell
AGV	Automatic guided vehicle
APU	Auxiliary power unit
DC	Direct current
DMFC	Direct methanol fuel cell
DNO	Distribution network operator
EU	European Union
EV	Electric vehicle
GCU	Gas clean-up unit
GPU	Ground power unit
GSE	Ground support equipment
HEX	Heat exchanger
HTS	High temperature shift (reactor)
IC	Internal combustion
ICE	Internal combustion engine
LED	Light emitting diode
Li-ion	Lithium-ion
LTS	Low temperature shift (reactor)
MCFC	Molten carbonate fuel cell
Ni-Cd	Nickel-cadmium
NiMH	Nickel-metal hydride
OEM	Original equipment manufacturer
PAFC	Phosphoric acid fuel cell
PC	Personal computer
PDA	Personal digital assistant
PEM	Proton exchange membrane
POX	Partial oxidation
RCD	Residual current device
SLI	Starting, lighting and ignition
SOFC	Solid oxide fuel cell
UPS	Uninterruptible power supply

Contents

1. Introduction

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The report includes an assessment and ranking of the various niche markets, from which scoping system designs were developed for the leading five niche market applications. Subsequently the leading players likely to be interested in such systems have been identified and listed. In addition, an environmental impact assessment of fuel cell systems in comparison with their conventional power source alternatives has also been carried out.

2. Battery Replacement Markets

Batteries are used to store and transport electrical energy and are essential to today's industrial and consumer-oriented society. With annual sales of just under $40 billion, the world battery industry can be divided into two segments[1]:

(i) *Primary* devices which have to be thrown away after use. These include alkaline and zinc-based batteries sold by companies such as Duracell and Matsushita of Japan.

(ii) *Secondary* or *rechargeable* batteries which can be reused. These include the well-established lead-acid batteries used in most cars, and the much faster growing types of devices used in products such as mobile telephones and laptop computers.

The values of the world rechargeable and primary battery markets by application are shown in Tables 2.1 and 2.2 respectively. It can be seen that the value of rechargeable batteries sold world-wide is about twice as much as primary devices, mainly due to the huge demand for car batteries which are the biggest selling battery type. The markets with the largest projected growth rates are communications (both primary and rechargeable batteries), electronics and medical applications.

Table 2.1: Projected World Rechargeable Battery Market by Application (value at 1997 prices)[1]

Category	**1997 $billion**	**1998 $billion**	**2000 $billion**	**Annual growth (%)**
Auto, cycle and truck SLI	15	16	17	5
Motive (golf, factory, EVs, cycles, AGVs)	2.1	2.2	2.4	7
Communications (telephones, multiplex or line concentrate, ringers)	0.8	0.9	1.0	10
Electronics (portable computers, camcorders, notebooks etc)	0.4	0.5	0.55	12
Toys	0.25	0.26	0.3	6
Tools	2.0	2.2	2.5	8
Emergency power and light (telecom, stand-by and UPS)	1.5	1.6	1.8	7
Power condition (peak shaving, solar)	0.15	0.16	0.17	5
Signalling	0.15	0.16	0.17	5
Medical	0.3	0.35	0.45	15
Military/aerospace	0.5	0.55	0.65	4
Total	**23.2**	**24.9**	**27.0**	**5**

Fuel cells could be used to replace batteries in many applications. Some of the niche markets where fuel cells could be introduced are considered throughout the remainder of this section. Examples include portable electronic devices, navigational aids and uninterruptible power supplies.

Table 2.2: Projected World Primary Battery Market by Application (value at 1997 prices)[1]

Category	1997 $billion	1998 $billion	2000 $billion	Annual growth (%)
Communications (radios, telephones, pagers etc)	1.0	1.1	1.3	10
Games and toys	3.5	3.8	4.3	8
Lighting	3.5	3.7	4.2	7
Medical	0.55	0.58	0.65	6
Military	1.0	1.0	1.1	4
Other	0.5	0.55	0.65	8
Total	**10.0**	**10.7**	**12.2**	**7**

2.1 Portable Electronics

Rechargeable batteries are used in portable electronic equipment such as laptop computers, handheld computers and cellular phones. The global market for portable rechargeable batteries is growing at a compound annual growth rate of approximately 12% and revenues are forecast to increase from $3 billion in 1997 to $6 billion in 2003 as shown in Table 2.3. Nickel-cadmium batteries have accounted for 70% of sales, powered by the escalating demand for cordless consumer products, emergency systems and medical devices. Emergency lighting is a market that represents 35% of all portable batteries[5].

Table 2.3 Value of the Market for Portable Batteries[1]

	Base year	Revenue ($billion)	Forecast year	Revenue ($billion)
World[2]	1997	3	2003	6
Europe[2]	1999	2.57	2006	4.16
United States[4]	1999	4.97	2004	6.35

[1] World figures are for portable rechargeable batteries; European and US figures are for both primary and rechargeable portable batteries.

The three most common battery chemistries in use in portable electronic equipment are nickel-cadmium (Ni-Cd), nickel-metal hydride (NiMH) and lithium-ion (Li-ion); an indication of their respective energy densities is given in Table 2.4[3]. Lithium-polymer batteries for these applications are still rare but are now available for a small number of cellular phones and laptop computers[12,13]. Nickel-cadmium batteries are generally the cheapest option, NiMH batteries are typically 15% more expensive and lithium-ion chemistries can be up to twice the price of equivalent Ni-Cd batteries[5]. However, these costs are non-specific examples, and generally most costs are dependent on the application.

Table 2.4: Energy Densities of Rechargeable Batteries Used in Portable Electronic Equipment

Cell Chemistry	Energy Density (Wh/kg)
Nickel-cadmium	30 to 35
Nickel-metal hydride	45 to 60
Lithium-ion	120 to 150
Lithium-polymer	135 to 175

For portable electronics applications, rechargeable batteries are the main competitor to fuel cells. To compete in areas where batteries are already well established, fuel cells will have to offer distinct advantages over the battery. Requirements are:

- Improved energy densities compared with current battery technology (see Table 2.4).
- Simple and rapid recharging/refuelling procedure. With current battery technology, recharging times are typically between 1 and 8 hours. Fast charge batteries can be recharged in 15 minutes to 2 hours but are subject to trade-offs in the form of cost, capacity and complexity of recharging circuitry.
- Compact and safe fuel supply.
- Increased number of operating cycles, currently 100 to 1,500 cycles.
- Reduced weight and volume.
- Increased duration between recharges (i.e. increased capacity). The current duration of 1 to 5 hours means that more than one battery must be carried for true portability throughout the working day.

A number of developers are developing small compact fuel cells aimed specifically at portable electronic applications such as cellular telephones and laptop computers. Developers include Energy Related Devices, Los Alamos National Laboratory, H Power and the Fraunhofer Institute for Solar Energy in Germany[9,10,50,84]. They are all developing small PEM or direct methanol systems.

The markets for three specific portable electronic devices, namely cellular phones, portable computers and video cameras are considered in sections 2.1.1 to 2.1.3 below.

2.1.1 Cellular Phones

The cellular phone market has experienced rapid growth through the 1990s as can be seen in Figure 2.1[8,22]. The world-wide market is expected to exceed 597 million phones by 2003[16].

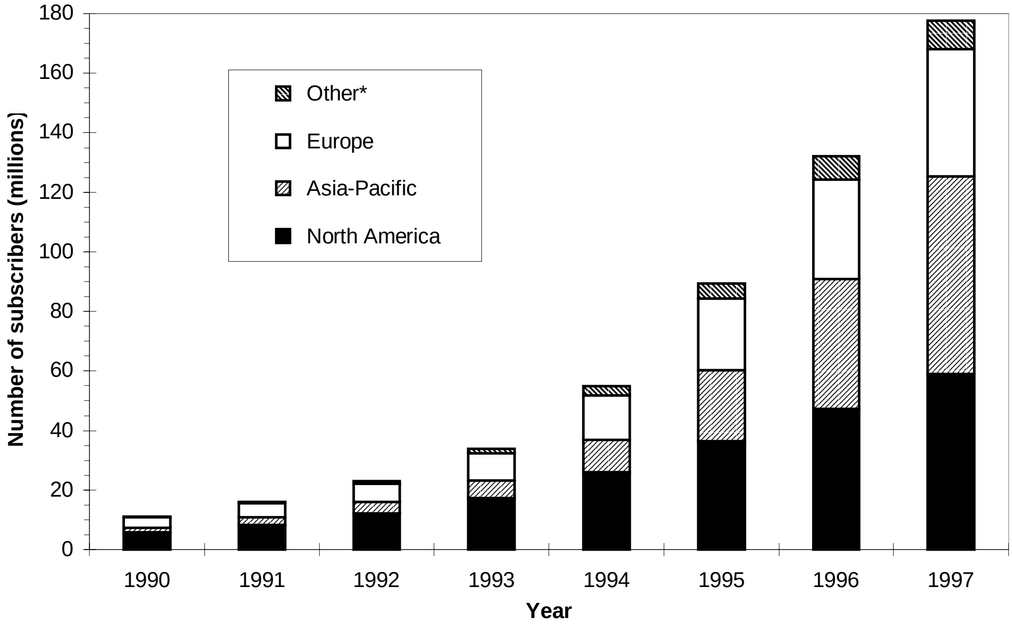

Figure 2.1 Growth in Number of Cellular Phone Subscribers from 1990-97

* Other = South and Central America, Africa and the Middle East

Forecasts for the future number of cellular phone subscribers tend to vary. Figures for Western Europe and North America are shown in Table 2.5 and it can be seen that the market is still expected to exhibit strong growth up to 2003. In 1998, the Western European cellular phone market was worth an estimated $42 billion and is projected to reach nearly $84 billion by 2003, representing an annual average growth rate of 11%[6].

Table 2.5 Current and Forecast Number of Cellular Phone Subscribers

	Base Year	Subscribers (million)	Forecast Year	Subscribers (million)
Western Europe[6]	1998	92	2003	211
North America[7]	1997	42.8	2000	66.4

Nickel-metal hydride is probably the most common battery type currently in use in cellular phones. The more expensive, higher specification phones run on lithium-ion batteries and lithium-polymer batteries are now offered as an option on some models[13]. Typical performance details of the various battery types are given in Table 2.6 [13,17].

Table 2.6 Performance of Typical Cellular Phone Batteries

	NiMH	Li-ion	Lithium-polymer
Capacity (mAh)	900-1,500	1,300	600
Weight (g)	55	48	32
Cost ($)	35-60	60-75	not available
Talk time (hours)	3-5	3-8	2-3.5
Stand-by time (hours)	60-270	60-300	40-180
Standard charging time (hours)	4	4	2.5

Several developers are targeting the cellular phone industry as a potential multi-billion dollar market for fuel cells. These include:

- Energy Related Devices and Manhattan Scientifics are developing the Micro-Fuel Cell™, a small, low cost, lightweight and low temperature direct methanol fuel cell[9]. It has recently been reported that one of their Micro-Fuel Cell™ test devices has achieved a specific energy output of 300Wh/kg, around three times greater than standard lithium-ion batteries currently used for cellular phones[14]. Researchers have set an ultimate target of exceeding ten times the energy output of conventional batteries.
- Motorola Laboratories and Los Alamos National Laboratory have recently produced a working version of a methanol-powered miniature fuel cell designed for use in cellular telephones[10]. The fuel cell measures just 25mm x 25mm x 2mm and has an energy density ten times that of conventional rechargeable batteries. It is envisaged that the methanol needed to run the fuel cell will be packaged in small cartridges similar to those used for ink.

The target cost for fuel cells for cellular phones is around 100$/W; this is the approximate current retail price for small power devices (< 1W)[9].

2.1.2 Portable Computers

The portable computer market includes handhelds, personal digital assistants (PDAs) and notebooks. There appear to be no comprehensive statistics on the size and value of this market. However, the following observations can be made:

- The world-wide market for handhelds is expected to increase from 3.9 million units in 1998 to 20 million in 2003, and be worth an estimated $7.6 billion[11].
- 14 million PDAs are expected to be sold annually by 2003[16].
- Japan accounts for 24% of the global market for portable PCs[6]. 4.7 million portable computers were sold in 1999, equating to a world market of more than 19 million units.
- The market for notebooks in Latin America, particularly Mexico, is exhibiting strong growth.

The three battery chemistries in common use in laptop computers are nickel-cadmium, nickel-metal hydride and lithium-ion. Examples of battery specifications for various Toshiba models are given in Table 2.7[17,18,19]. Run down times typically range from 1.5 to 5 hours and charging times vary between 1 and 5 hours[3]. Electrofuel has recently started distributing its lithium polymer technology in its PowerPad 160™ laptop computer which can run upwards of 16 hours[12].

Table 2.7 Characteristics of Typical Laptop Computer Batteries

	Ni-Cd	**NiMH**	**Li-ion**
Capacity	9V 1.1Ah	12V 3Ah	10.8V 3.6Ah
Weight (kg)	2.2	2.6	1.7
Cost ($)	30-50	160-180	280-300
Dimensions (l x w x h) (mm)	147 x 94 x 21	141 x 90 x 20	173 x 69 x 18

There are still major shortcomings with portable computers and a survey carried out by International Data Corporation has highlighted[6]:

- 94% of notebook users stated that battery life was not sufficient
- 82% stated that their notebooks were still too heavy

It has also been reported that users are prepared to pay a premium for lighter machines and increased capacity[3]. If fuel cells can address these issues, then this could represent a key market opportunity for the introduction of such technology.

Fuel cell developers working in this area include the Fraunhofer Institute for Solar Energy Systems where a cheap, low power PEM cell is being developed for use in laptop computers and other portable electronic devices. The fuel cell has a power of 25W and is supplied with hydrogen from a hydride storage cartridge with a capacity of 400Wh[84]. It can be used to power a laptop for up to 10 hours compared with typically 2 to 3 hours using conventional battery technology. The aim of the development programme is to reach a system energy density of 240Wh/kg[85], which is significantly higher than can be achieved with existing battery chemistries (see Table 2.4).

2.1.3 Video Cameras

The market for video cameras in 1997 is shown in Table 2.8[8,22]. No figures on future trends are currently available.

Table 2.8 Sales of Video Cameras in 1997

	Sales (000 units)
North America	3,882
Japan	19,996
Hong Kong & China	35,644
Australasia	206
European Union	2,217

Video cameras typically retail for between $450 and $1,000 and are powered by Ni-Cd, NiMH or Li-ion batteries. A typical battery has a capacity of 6V 1.8Ah and costs around $40 for nickel-metal hydride and $65 for lithium-ion. As with other portable electronic equipment, reducing system weight and increasing capacity are the key technical issues that fuel cells need to address if they are to compete with traditional rechargeable batteries.

H Power have demonstrated a professional video camera powered by a 12V DC PEM system[50]. The fuel cell utilises a compact metal hydride based hydrogen fuel cartridge that provides twice the operating time of the battery typically used in this application. In addition, instant refuelling is possible and the fuel cartridge weighs 0.6kg compared with 4.1kg for a traditional battery.

2.2 Power Tools

The value of the power tools market in 1996 and 1998 is shown in Table 2.9; in both years around 89 million tools were sold world-wide. Demand for power tools directly mirrors economic activity as can be seen from the sharp decline in sales in Asia between 1996 and 1998 following the economic crisis in the region during that period. Overall, however, the world power tools market is still a growth market and over the last 25 years has shown an average annual growth of 4%[34].

Table 2.9 Sales Value of the Power Tools Market ($million)[34]

	Year	
Region	**1996**	**1998**
World	5,870	6,400
North America	1,800	2,400
Asia	1,550	850
Europe	2,080	2,560
Latin America	240	320
Africa	50	100
Australia	100	200

No figures are available on the market for cordless power tools but it is believed to be an expanding market as battery technology improves and unit costs reduce. It is this area of the market where fuel cells could be introduced as a replacement for rechargeable batteries. The key features that a fuel cell powered tool must exhibit are:

- It must be powerful enough to replace a conventional mains-powered tool
- It needs to be compact, light and well balanced
- It should have a fast recharging/refuelling cycle

Cordless drills typically weigh between 1.4 and 2kg and, in the UK, retail for between $80 and $240. They are usually powered by 12V 2Ah nickel-cadmium batteries with a recharging time of 30 minutes to 5 hours.

2.3 Uninterruptible Power Supplies

An uninterruptible power supply (UPS) is a device that sits between a power supply (e.g. a wall socket) and an item of equipment (e.g. a computer) to prevent undesired features of the power source (outages, sags, surges, bad harmonics etc) from the supply adversely affecting the performance of the equipment. The UPS market is divided into three categories: *stand-by/off-line, line-interactive* and *on-line* topologies[35]. Applications involving uninterruptible power supplies include protection of computers and peripherals to key telecommunications equipment, as well as sophisticated test and measurement equipment.

The rapid proliferation of computers and related electronic systems is one of the major drivers of the market, since a UPS system can significantly decrease the chances of costly system downtime, information loss and damage to equipment and software. Table 2.10 shows the current and forecast values of the UPS market, and it can be seen that world-wide sales are projected to increase from $3,400 million in 1995 to $7,700 million in 2002, an average annual growth rate of over 12%[2].

Table 2.10 Current and Forecast Values of the UPS Market

	Base Year	$million	Forecast Year	$million	Average Annual Growth Rate Over Forecast Period (%)
World[2]	1995	3,400	2002	7,700	12.1
North America[7]	1997	1,547	2001	2,330	8.5
Europe[15]	1995	1,136	2000	1,450	5.0
Pacific Rim[2]	1996	775	2000	1,394	15.7

Other information about regional UPS markets is as follows:

- The UK is Europe's third largest national market and currently accounts for about 15% of UPS sales[15].
- The United States holds the largest share of the UPS market. In 1996, it was valued at more than $1.3 billion and accounted for 40% of the world market. Revenues for the UPS market in the United States are expected to increase at a compound annual growth rate of nearly 13% to 2003[2].
- The Pacific Rim is a faster growth market than other regions of the world due to rapidly developing economies in this area. There is a large market for uninterruptible power supplies due to the continual poor quality and unreliability of power in this region, as well as the fact that UPSs are necessary for infrastructure development[2].

The computer end-user market is the largest and fastest growing market for UPS systems in terms of both revenue and unit shipments; market size is forecast to continue to increase due to the abundance of computers and peripherals[2]. The telecommunications industry is the second largest end-user market of UPSs and growth within this sector is fuelled by an increased world-wide demand for constant, clean power. Together, the computer and telecommunications industries account for around 60% of the global UPS market[2].

Typical ratings of UPS devices are as follows[2]:

- 1 to 2.9kVA systems are used to protect office PCs and workstations
- 3 to 10kVA systems are used to protect various telecommunications equipment
- Above 10kVA the majority of end-user applications are industrial

UPS systems vary considerably in price depending on their specification. Off-line power protection devices designed for stand-alone desktop PCs retail at around $150 and high specification on-line UPSs (for protecting networks, servers, telecommunication equipment, industrial process control equipment etc) typically cost between $800 and $3,500[19]. Such devices are generally powered by sealed lead-acid batteries.

For fuel cells to compete with batteries in UPS systems, it is crucial that they demonstrate very high reliability, produce high quality power and have low maintenance requirements. ONSI Corporation have recognised the high quality, continuous power market as a key application for their PC25™ PAFC system[80]; for further details see section 3.2.

2.4 Navigational Aids

Navigational aids are used to mark places hazardous to shipping in coastal waters, including buoys, lights, fog signals, radar beacons and radio beacons. In England, Wales and the Channel Islands, the Corporation of Trinity House provides nearly 600 aids including[29]:

- 72 lighthouses
- 13 major floating aids
- 18 beacons
- 429 buoys
- 48 radar beacons

In addition, Trinity House annually inspects a further 9,000 aids to navigation provided by local port and harbour authorities. There are reported to be more than 100,000 navigational aids in use throughout the world[30].

Navigational aids are currently powered by diesel generators, mains electricity (with diesel stand-by), batteries with diesel generator, wind, wave or solar power sources. Power requirements range from a few Watts to several kW.

Solar photovoltaic power is used increasingly as the power source of choice for aids to navigation, particularly on buoys. However, the relatively low conversion efficiencies of solar photovoltaic systems means that not all the energy needs of the aids to navigation can be met by this power source alone. As a result, hybrid systems such as combinations of wind, diesel, solar and wave are being investigated. UK navigational aid experts anticipate that this is an area where fuel cells could compete[30].

The main requirement for navigational aids is for a power source that is reliable, rugged and which requires little maintenance. The aim is for one maintenance day per 10,000 hours of operation and a lifetime of 5 to 10 years[30].

For a fuel cell powering a navigational aid such as a buoy, availability of fuel is of utmost importance. Compressed gas and methanol are the likely candidates; it has been estimated that 40 litres of methanol would last 1 year for a 10W fuel cell.

2.5 Medical Applications

The battery market for the medical industry is currently categorised by low unit shipments although there is tremendous potential for growth (see Table 2.1). Medical devices requiring batteries include defibrillators, pulse oximeters and infusion pumps.

In 1998, the US battery market for medical applications generated $11.9 million and is forecast to grow at a compound annual rate of 20% to 2005[2]. Much of this growth is expected in portable medical applications. For example, the pre-hospital market for defibrillators is growing as installation of these devices is now required on airlines, in police cars and in a variety of public locations.

As many medical applications are critical and high risk, battery manufacturers supplying the medical industry must comply with stringent regulations concerning both safety and reliability issues. Fuel cells in medical devices would obviously have to meet the same exacting standards. They have the advantage, however, of being far more environmentally acceptable than rechargeable battery chemistries such as nickel-cadmium. There is a move by original equipment manufacturers to use power sources that support the preservation of the environment and hence this could represent a good market opportunity for the introduction of small PEM fuel cells.

2.6 Portable Variable Message Signs

Portable variable message signs are typically large trailer-mounted LED arrays used to provide information to motorists at the side of roads, particularly during roadworks. Such signs are usually powered from a bank of batteries that are normally kept charged by a solar photovoltaic array. Under certain conditions, the solar charging system is unable to maintain the batteries at a sufficient state of charge. This may be due to unfavourable weather conditions, a location that does not receive sufficient sunlight or a malfunction of the solar charging system. Low battery voltage then causes a malfunction of the sign to the point where it must be taken out of service. Other roadside devices that could benefit from fuel cells include speed cameras and traffic monitors.

A fuel cell could be incorporated into the message sign either as a battery replacement or to provide back-up power when low voltage occurs. H Power have recognised this niche market and have developed a 50W PEM fuel cell system for variable message signs[32]. Their design incorporates an electronic system to sense low voltage which turns on the fuel cell to bring the batteries up to an acceptable voltage. The sign continues to operate normally and the result is lower maintenance, improved traffic safety and longer battery life due to avoidance of deep discharge. The fuel cell is supplied with hydrogen from 200psi cylinders weighing around 20kg. H Power's prototype fuel cell system was tested in New Jersey during the 1996/97 winter season and, based on the experience gained in the field tests, the Department of Transportation have decided to retrofit all their solar powered variable message signs with fuel cell back-up systems[32].

It is difficult to estimate the size of the market for portable variable message signs but it is believed that North America is the largest market. Many of the manufacturers are from the United States and include the American Signal Company and Vultron Inc.; the latter company is reported to have 2,000 portable trailer signs in use in the United States[31].

2.7 Television and Outside Broadcast

The television industry uses portable cameras for filming and news items. Such cameras are powered by 12V 4Ah nickel-cadmium batteries which last for one hour's filming and cost in excess of $240 each[30]. To cover a day's work, four to six batteries will be needed. Hence the initial capital cost of batteries for a portable TV camera is high.

Outside broadcast units have a much higher power requirement of 10 to 25kVA. Such units can power two to eight cameras and the larger units are fully equipped with monitors, sound engineering, air conditioning etc.. Power comes from connection to the mains on site. The smaller units source their power either from the mains or through a generator. Safari cars and caddy cars have a lower power requirement. Safari cars are used to follow horse races and generally tow a 3.5kW generator. The caddy cars are small battery powered vehicles fully equipped with camera, electronics etc for filming. These use 180Ah lead-acid batteries which last about half a day before they need recharging.

Fuel cells could be used for any of these applications but the most promising markets are as generators for outside broadcast units (see section 3.4 for more information on portable generators) and as battery replacements for portable cameras. For the latter application, the most important factors are weight, size, noise and time between recharging/refuelling.

3. Power Generation

3.1 DC Power Supply

A considerable range of DC supply opportunities exist, ranging from power levels of just a few Watts, e.g. in electronic power supplies, to several MWe, e.g. for railway traction systems, either via overhead or third rail systems.

At the small-scale end of the market, up to say power levels of a few tens of Watts, the main market opportunities are believed to lie in the portable electronics sector; typical applications are likely to include laptop computers and cellular telephones. These markets are considered further in section 2.1.

At the larger scale end of the market, DC supplies are extensively employed for urban tram networks and also for railway traction systems. Railway locomotives, in particular, may draw currents of up to 4,000 amps from DC supply systems with starting currents of several times this value. Whilst superficially attractive, any fuel cell power plant, installed at regular intervals along the side of the track, would have to cope with[30]:

- Severe fluctuations of demand
- Very high instantaneous load conditions
- The possibility of reverse current flows from regenerative braking systems

Thus, whilst still a DC supply, a well designed and engineered power conditioning and protection system would be required to service such loads and to protect the cell stack integrity. The market potential for such applications is not believed to be sufficiently large for systems developers to address this sector as an initial market opener, although applications could follow in the longer term if commercial success is achieved in the larger volume and more conventional applications.

3.2 Custom/Premium Power Applications

A whole series of users are demanding the availability of supplies to a higher, or premium/custom standard. Such applications include the supply to very sensitive electronic systems, where adverse waveform variations can be severely detrimental to the equipment, and also those where the cost of disruption is high. The latter category includes financial trading halls, banks, air traffic control, emergency co-ordination centres and hospital installations. Within the latter category, stand-by power systems are the conventional safeguard against supply disruption (see section 3.3). Uninterruptible power supplies are also used to provide premium and stand-by power; these are discussed in section 2.3.

The custom, or premium, power market has been recognised by ONSI Corporation as a key market for their PC25™ PAFC system[80]. Their customers have included hotels, large office buildings, high-tech manufacturing sites and universities. A typical example is the PC25™

system at AT&T's Bell Laboratory site in Crawford Hill, New Jersey which services the laboratory's requirement for a clean power supply with minimal supply disruptions. As installed at the Bell Laboratory, the PC25™ unit acts as the primary supply for selected parts of the facility, with the utility supply acting essentially as a back-up. Whether this arrangement meets statutory standards for such critical applications as hospitals is a matter of some conjecture, although clearly it is an arrangement that could have attractions under particular sets of circumstances.

3.3 Stand-by Power

Two essential prerequisites for stand-by power units are:

(i) Their ability to come up to power quickly in the event of a loss of the primary supply

(ii) A requirement to run on a stored fuel to cater for the contingency of total loss of site services, e.g. both gas and electricity supplies

For short-term disruptions, battery back-up systems are the norm; these are typically able to maintain a limited number of critical loads for between 30 minutes and one hour. For longer-term disruptions, diesel engines are generally the preferred solution, running on gas oil supplies stored on-site and in sufficient quantities to allow several hours of generation. Engine installations will usually service only the critical loads in a particular application, with all non-essential loads being shed.

The relevant codes of practice and statutory guidelines often require such installations to be test run on at least a weekly basis to ensure their availability in the event of supply disruption. The use of several engines to service a given load is also common practice, to provide a degree of system redundancy and to cater for instances where specific units may be off-line for overhaul or maintenance. Electrical generation efficiency is not an essential pre-requisite of such engines, due to their very low annual utilisations.

The requirement for rapid start-up (and weekly test runs) effectively precludes the use of SOFC systems. From a cell stack assembly point of view, the PEM system is ideal, but the choice of fuel may then become a limiting parameter. Until such a time as a logistics fuel processor becomes available, methanol remains the only liquid fuel readily available for long-term storage on site. Gaseous hydrogen is also a possibility, although its acceptability may present problems from a perception point of view. For these reasons, it is difficult to see where a PEM-based system can offer any real advantage over conventional diesel systems, unless noise and vibration levels are a critical consideration. Some hospital installations may fall in this category.

Sales of diesel engines for stand-by applications amounted to around 20,000 units in Europe during 1999 with growth at an average compound rate of 1.5% expected over the next five years[2].

3.4 Portable Power

Portable generators are used for powering electric lights and equipment on boats or in caravans, workshop and gardening tools and many other applications where power is needed at a site remote from a convenient mains power source. The world-wide market for diesel and gas engine driven generating sets in 1997 is given in Table 3.1. The majority of units were in the range 1 to 75kVA[81]. Whereas the market grew by 15% between 1992 and 1996, it declined by 1.5% in 1997, mainly due to the effects of the economic recession in the Far East.

Table 3.1 World-wide Market for Generator Sets in 1997[81]

Region	Unit Sales (000)	Sales Value ($million)	Generating Capacity (MWe)
Europe	79.5	1,450	8,352
Africa	14.7	232	1,392
Middle East	13.4	174	1,044
Americas	64.6	1,508	9,744
Far East	213	2,436	14,268
Total	**385**	**5,800**	**34,800**

There is an adequate range of devices to meet most domestic and light industrial requirements, and engine technology is both well established and proven. If fuel cells are to successfully penetrate this market they will have to demonstrate comparable performance and provide additional benefits to the user. These benefits include low noise, lightweight and low pollution which could be advantageous for powering auxiliaries in caravans and pleasure boats.

Table 3.2 Examples of Portable Fuel Cells Currently Available

Company	Model	Power Output (W)	Dimensions (cm x cm x cm)	Weight (kg)
ElectroChem	EC-PowerPak-200	200	41 x 23 x 23	9
Warsitz	HydroGen™	150	68 x 40.5 x 33	20
Dais-Analytic	FC-150	150	25 x 16 x 16	4

A number of developers have recognised the market opportunity of using fuel cells as portable power supplies. Various low power products are already available and these include (see also Table 3.2):

- *ElectroChem Inc.* offer the EC-PowerPak-200[82], a 200W PEM fuel cell power pack which is housed in an aluminium carrying case. The fuel cell is designed to run on hydrogen and oxygen at an inlet pressure of 12psig; this can either be supplied from external gas cylinders or from the on-board gas storage facility which provides several hours operation.

- *Warsitz Enterprises Inc.* offer a range of rugged portable PEM fuel systems operating on hydrogen gas[83]. For example, the HydroGen™ is a 150W lightweight electric generator costing $5,795 and which can run for up to 20 hours. Warsitz also produce the RoamPower™ range with units available from 30 to 90W[83]. These are primarily designed for recharging small electrical and electronic devices such as laptop computers, cellular phones, models and flashlights. Running times vary from 1 to 5 hours and refuelling times are typically between 3 and 5 minutes. Costs range from $2,495 for the 30W model up to $4,495 for the 90W version.

- *Dais-Analytic Corporation* offer the FC-150 and the FC-200. These are small PEM fuel cells which operate on hydrogen and air and provide power outputs of 150 and 200W respectively. The FC-150 is currently being used as a military manpack power source[86] and the FC-200 has been used to power a three-wheeled scooter[87].

3.5 Chemical Industry

Chemical and petrochemical industries generate large volumes of hydrogen-rich streams as by-products of electrochemical and dehydrogenation processes. Many of these streams are co-burned in plant boilers or wasted by venting or flaring. The hydrogen utilisation capability of fuel cell systems make them ideal candidates to match to readily available supplies of hydrogen off-gas from such industrial process operations.

The chlor-alkali industry produces caustic soda, chlorine and hydrochloric acid together with hydrogen as a by-product from the electrolysis of brine. It has been estimated that a fuel cell integrated into the chlor-alkali process could recover up to 20% of the electrical energy consumed by the electrolysis process, as well as generating steam that could be used for caustic soda concentration by evaporation[20].

Hydrogen by-product utilisation in fuel cells has been recognised as a niche market by several developers and MCFC, PAFC and PEM systems are all being considered[61,76,77]. There appears to be most interest in Italy where the following developments took place in 1999:

- De Nora installed a prototype 100kW PEM fuel cell on one of their chlor-alkali plants[76].
- Ten ONSI PC25™ phosphoric acid fuel cells were installed at the Assemini chlor-alkali plant in Sardinia with a total power output of 9MW DC. It is planned to generate 68GWh of electricity and 62,000 tonnes of steam per annum from 48 million Nm^3 of hydrogen by-product[77].

Based on the chlor-alkali industry alone, there is sufficient hydrogen by-product availability to install up to 600MWe fuel cell power in Europe[77]. This could double if the chemical and petrochemical sectors are considered.

3.6 Coal Gasification

The molten carbonate fuel cell (MCFC) is a high temperature unit typically operating at 650ºC. The main applications of this system are targeted at the larger MW scale, rather than the smaller markets. MCFCs can run on either a hydrogen or a hydrogen/carbon monoxide mixture which make them an ideal candidate for working with a gasification plant. It is reported that an MCFC system combined with a coal gasifier could reach efficiencies of more than 70%[79]. Hybrid systems are potentially more efficient and less environmentally harmful than current state-of-the-art integrated gasification combined cycle (IGCC) and pulverised coal power plant, providing proper thermo-chemical integration is achieved between the fuel cell and the gasifier.

Coal gasifiers combined with fuel cell systems could provide a niche application from around 2005 following the full commercialisation of MCFC plant[79]. There will be a relatively small number of large-scale opportunities, with a typical plant having an output of 500MWe.

4. Transport Applications

Fuel cells for mainstream transport applications such as buses and cars are currently nearing commercialisation. This section covers niche transportation markets where fuel cells could also make an impact. Examples include marine applications, two wheeled vehicles, auxiliary power units and airport ground support equipment.

4.1 Marine

At the beginning of 1998 the world merchant fleet comprised 85,828 ships[40]. The UK owned 486 trading vessels of 500 gross registered tons and over and a breakdown of vessel type is given in Table 4.1.

Table 4.1 UK Owned Trading Vessels of 500 Gross Tons and Over (1998)[49]

	Number	Thousand Gross Tons
Tankers	127	2,408
Bulk carriers	29	1,230
Specialised carriers	10	42
Container (fully cellular)	62	1,841
Ro-Ro	91	991
Other general cargo	148	526
Passenger	19	541
Total	**486**	**7,579**

In 1998, the average age of the total merchant fleet was 14.54 years[78]. This represents a slight decrease on recent years and reflects a small increase in new ship construction. Table 4.2 shows the number of new building contracts world-wide for ships over 300 gross registered tons (grt) between 1994 and 1998.

Table 4.2 New Building Contracts for Ships Over 300grt[78]

Year	Tankers	Bulk Carriers	Combined Carriers	Container Vessels	Passenger Ferries	Total
1994	256	339	2	227	118	942
1995	243	381	4	345	144	1,117
1996	274	271	0	257	144	946
1997	428	282	2	299	96	1,107
1998	280	166	0	333	117	896

The main applications for fuel cells in marine shipping are:

- Generators for auxiliary power requirements
- Engines for main propulsion

Conventional marine propulsion systems include diesel engines, gas turbines and nuclear reactors. Engine sizes are large, typically 5 to 30MWe depending on vessel size. Gas turbines in this range generally cost between 500 and 700$/kWe.

The auxiliary power needs of marine vessels are commonly supplied by electric generators which are powered by stand-alone diesel engines rather than coupled to the main propulsion system. Typical auxiliary hotel loads include lighting, heating and electrical power for navigation equipment. Fuel cells have the advantage of low noise and vibration and would be particularly beneficial on cruise liners where cabins are often located near to the engine room.

It is anticipated that emission limits from ship engines/generators will be tightened in the near future. Compared with diesel engines, fuel cell systems are inherently clean and offer increased fuel efficiency. A key consideration of fuel cell powered ships is the choice of fuel; ideally a system operating on diesel would be adopted since the necessary fuelling infrastructure is already in place.

A number of the world's navies are considering the use of fuel cells for propulsion. Both the German and Italian navies have ordered new U212 submarines incorporating air-independent propulsion with PEM fuel cells supplied by Siemens. These operate from on-board supplies of hydrogen and oxygen and enable the submarines to remain submerged for around five times longer than is currently possible with standard lead-acid battery technology[91,92].

Other applications of fuel cells for marine propulsion include:

- The repowering of a United States coastguard cutter with twelve 215kWe MCFC modules[93]
- The Shipbuilding Research Centre of Japan in conjunction with the country's leading shipbuilder are investigating the feasibility of installing a 1MWe methanol fuelled PEM power plant on a 1,500 dead-weight ton cargo vessel[94].

4.2 Lightweight, Low to Medium Power Personal Transport

4.2.1 Two Wheeled EVs

There are more bicycles in the world than any other type of transport equipment and they are still a growth market. It is reported that over 100 million conventional bicycles are sold world-wide each year with East Asia having the largest share[41].

Power-assisted or electric bicycles are also a growth market with global sales of 300,000 in 1999[47]. These vehicles are similar to conventional bicycles but include a small electric motor and power supply. To date, Japan has been the largest consumer of electric bicycles (around 50% of the global market), although evidence suggests that China will be the leading consumer by 2001[41].

There are a large number of small manufacturers producing power-assisted bicycles; these include Charger Bicycle in the USA and Powabyke in the UK. All of the configurations currently available use lead-acid batteries, and the motors deliver between 150W and 400W of power. Some examples of power-assisted bicycles are given in Table 4.3.

Table 4.3 Comparison of Different Power-Assisted Bicycles

Model (type)	Unit Price ($)	Power Requirements
Powabyke[42] (Assist bicycle)	799	150W motor, 36V 12Ah, sealed lead-acid battery weighing 12kg
Charger - Standard[43] (Assist bicycle)	1,300	375W system, 24V lead-acid battery weighing 10.5kg
BAT - Jazz[44] (Assist bicycle)	750	Not available
Average non-power[45] (traditional pedal only)	345	Not applicable

A battery pack of 36V for a two wheeled EV would typically comprise of three 12V or six 6V sealed lead-acid monoblocks. Sealed lead-acid batteries are used because they are maintenance-free and cheaper than more advanced batteries technologies such as nickel-metal hydride. Examples of typical battery packs are shown in Table 4.4[19].

Table 4.4 Examples of Lead-Acid Batteries Used in EVs

Battery	Weight (Total - kg)	Life (cycles)	Price (Total - $)
Sonnenschein A500 12V 10Ah (3 off)	12.3	300	260
Sonnenschein A500 6V 10Ah (6 off)	10	300	323
Yuusa NPC 12V 17Ah (3 off)	20.4	500	280

Most of the designs contain the motor within the enlarged hub of the back wheel. The motor can be configured to provide total propulsion for the cycle or to assist the rider's own pedal power. A configuration offering total propulsion means the cycle can typically reach speeds of 24km/h and have a range of at most 30km. In the UK, if the bicycle is powered at speeds greater than 24km/h, then it becomes subject to UK road tax.

The battery is usually mounted on the frame of the bicycle between the handle bar stem and seat stem. The mass of the battery pack is around 12kg. On most models the battery packs can be quickly removed to allow the bicycle weight to be reduced for non-powered operation. Any replacement power source such as a fuel cell will need to be light and compact. Many of these cycles are operated by children and therefore they must be easy to refuel.

NovArs GmbH, in conjunction with Manhattan Scientifics, have developed the Hydrocycle™, a prototype electric bicycle powered by a 670W cylindrical fuel cell[96]. The high current, low voltage PEM fuel cell stack is mounted over the front wheel and weighs 780 g. It is reported that the Hydrocycle™ has a driving range of 70 to 100km and can reach speeds of up to 30km/h.

The fastest growing transport sector is motorcycles/two wheel scooters. These are traditionally powered by internal combustion engines (ICEs); scooters are generally in the range 50 to 125cc and motorcycles are up to 1,100cc. Two wheel ICE scooters passed $17 billion global sales in 1997 with most sales in China and South East Asia followed by Europe, Japan and India[41]. In 1997 there were 14,595 new scooters (up to 50cc) and 110,081 new motorcycles (above 50cc) registered in the UK.[48].

Table 4.5 World Market for Two Wheeled EVs[41]

Year	Units (000)	Average Unit price ($)	Total Sales Value ($million)
1999	350	743	260
2000	500	800	400
2005	3,000	500	1,500
2010	6,000	500	3,000

Two wheel scooters and motorcycles are projected to be a major growth market for electric vehicles (EVs), mainly driven by legislation to reduce pollution in congested urban areas. The world-wide market for all two wheeled EVs (bicycles, scooters and motorcycles) is forecast to escalate from 500,000 units in 2000 to 6 million units in 2010 as shown in Table 4.5.

4.2.2 Invalid Carriages

The requirement for the disabled is split into two distinct groups of users; the impeded and the more seriously disabled.

Fit elderly people quite often buy the single seat three or four wheeled vehicles variously known as personal assist vehicles, runabouts, scooters and buggies. Such vehicles are allowed on the road with the driver unlicensed and no road tax. Maximum speed is typically 8mph. These vehicles typically retail for between $1,000 and $3,000 and can be used for 4 to 9 years[41].

The seriously disabled may use a motorised wheelchair. Such vehicles are often substantially modified to suit the particular user and retail for up to $15,000 each. For safety reasons their top speed is usually limited to 4mph[41]. These vehicles are used intensively as they may be the user's only means of personal mobility. This results in a replacement life as short as two years.

The world-wide market for invalid carriages is of the order of 300,000 yearly and is forecast to rise strongly as shown in TABLE4.6[41]. It is projected that unit sales will reach 1.2 million in 2010, mainly for people who are slightly impeded rather than registered disabled.

Table 4.6 World Market Projections for Invalid Carriages[41]

Year	Unit Sales (000)	Average Unit Price ($)	Total Sales Value ($million)
1999	300	1,190	300
2005	800	688	550
2010	1,200	833	1,000

The personal assist vehicles have a maximum power rating of 600W with a battery weight of 17kg (see Table 4.7). Motorised wheelchairs have a similar power requirement but their equipment mass has to be much lower. Any replacement power source like a fuel cell will need to be light and compact. Also, as many of these vehicles are operated by the elderly and infirm, they must be easy to refuel.

Table 4.7 Power Requirements of Different Invalid Carriages

Model (type)	Power	Weight	
		Power pack	Overall
PowerPEM™-200H[50] (Wheelchair)	200W PEM fuel cell 500W peak power	PEM: 1.92kg Battery: 1.14kg	12kg
Pride Jazzy 1113[51] (Scooter)	600W peak power	Battery: 17kg	80kg

H Power have developed a fuel cell/battery hybrid electric power system for wheelchair propulsion. The PEM fuel cell utilises metal hydride-based energy storage containers which are readily rechargeable with hydrogen in a matter of minutes[50]. Details of the specification of the wheelchair are given in Table 4.7.

4.2.3 Golf Carts

The main vehicle in use on golf courses is the two seat people-carrying golf cart. There is also a market for large pedestrian operated golf caddies and small individual motorised caddies.

The major market drivers of growth are the number of new golf courses being built and the growing replacement market. It can be seen from Table 4.8 that the world-wide market for electric golf carts and caddies is forecast to grow from 250,000 units in 2000 to 330,000 in 2010. The world market for golf carts is around 60% electric, 40% ICE and it is projected that the proportion of electric vehicles will rise due to the increase in the number of areas outside golf courses where their use is becoming legal[41].

Table 4.8 World Market Projections for Golf EVs (Carts and Caddies)[41]

Year	Unit Sales (000)	Average Unit Value ($)	Total Sales Value ($million)
1999	250	2,000	500
2000	256	1,992	510
2005	320	1,875	600
2010	330	1,818	600

The USA is the largest market for golf carts with between 33% and 50% of world demand. Consequently, the majority of manufacturers are from the United States. Textron Inc. is the largest manufacturer and, in 1998, controlled 41% of the world market.

Golf carts are available in a range of size and power ratings. A typical cart may contain a 36V battery pack. Small carts have a battery capacity of around 100Ah or less, larger carts could have a battery capacity up to 175Ah. Batteries are either sealed or flooded lead-acid cells; sealed cells are maintenance-free whereas flooded cells require the water levels to be maintained. Examples of typical battery weights and costs are shown in Table 4.9[36,38].

Table 4.9 Examples of Lead-Acid Batteries Used in Golf Carts

Battery	Weight (Total - kg)	Life (cycles)	Price (Total - $)
Oldham RGT (sealed) 6V 98Ah (6 off)	110	1,000	600
CMP 3ET (flooded) 6V 175Ah (6 off)	180	1,000	1,000

Golf carts can also be powered by IC engines of around 5 horsepower (3.6kW). A typical engine is the Honda model 595500. This engine produces a peak power of 5.5HP (4kW) and has a list price of $214[95]. Whilst this is relatively cheap, a fuel cell powered unit would be expected to supply power with a far lower noise level, which could be attractive in this leisure business.

4.3 Auxiliary Power Units

Auxiliary power units (APUs) are provided on-board vehicles to deliver power for auxiliary loads only and not for propulsion. These loads include:

- Main engine starting
- Air-conditioning
- Heating
- Lighting
- Entertainment systems
- Public address systems
- Catering equipment

Sections 4.3.1 to 4.3.3 below discuss the requirements and market for APUs in aircraft, coaches, buses and executive cars. Auxiliary power requirements for marine applications and pleasure boats are discussed in sections 4.1 and 5.2.1 respectively.

4.3.1 Aircraft APUs

An aircraft APU serves two purposes:

(i) To produce compressed air for engine starting and air-conditioning while on the ground

(ii) To provide electricity for flight systems and hotel loads, again whilst on the ground

The aircraft mounted APU gave commercial airlines the freedom to fly to remote locations because aircraft no longer relied on ground-based power units to start main engines. However, airlines are increasingly likely to face constraints on extended (more than 30 minutes) ground running of APUs[53].

The gas turbine engine which drives the APUs on aircraft can be rated up to 1MW. A typical aircraft APU is the AlliedSignal 131-3 APU as fitted to the McDonnell Douglas MD-90 and Boeing 737 medium sized aircraft. The unit produces a maximum electrical output of 90kVA which represents one third of the output from the APU gas turbine. The remaining two thirds of the output is used to provide compressed air for engine starting and air-conditioning. The APU needs to have a major service interval of 10,000 hours[54].

If a fuel cell is to replace the complete APU then it would need to be rated at around 300kW for medium sized aircraft and much larger for the bigger aircraft (for example, the APU fitted to the Boeing 747 has a gas turbine rated at 1,450 horse power[55]). The unit will have to demonstrate high reliability and be provided in a small lightweight package. Refuelling will be undertaken by specialist operators and therefore complex systems and potentially poisonous (methanol) fuels may be acceptable.

Another common gas turbine used in APUs is the General Electric T58 (800shp) which has the physical dimensions of 1.2m long and a diameter of 0.4m[46]. This gives an idea of the space envelope for the APU power source.

An indication of the market for aircraft APUs can be obtained by considering the size of the market for new aircraft. Data on aircraft deliveries is fairly well documented in the literature and forecasts from various manufacturers are provided in Tables 4.10 and 4.11. Rolls-Royce estimate the market for large passenger aircraft (100 seats and above) to be $1,300 billion over the period 1998 to 2017[57]. Airbus Industrie and Boeing estimate the value of the whole jet market at between $1.3 and $1.4 trillion over the period 1999 to 2018[58].

Table 4.10 Major Aircraft Deliveries 1998 - 2017[57] (Rolls-Royce Figures)

	Passenger	Freight
World	16,180	680
Europe	3,849	121
North America	5,171	290
Asia Pacific	5,288	197
Rest of the World	1,872	72

Table 4.11 Comparison of Projected World-wide Commercial Aircraft Deliveries

Company	Forecast Period	Passenger	Freight	Total
Rolls-Royce[57]	1998 - 2017	16,180	680	16,860
Airbus Industrie[58]	1999 - 2018	14,750	750	15,500
Boeing[58]	1999 - 2018	19,500	650	20,150

4.3.2 Coach and Bus APUs

Strict controls are being imposed upon extended idling for coaches in residential and city centre locations. In the UK, local authorities are able to fine vehicle operators for excessive idling. However, there is a need to operate auxiliary loads on coaches and buses while stationary and, as a result, there is a growing interest in zero emission APUs.

The coach builder often fits up-rated alternators to the engines of coach and buses. Plaxton, a UK coach builder, generally fit 180A 24V alternators to their vehicles[56]. These units are able to supply an electrical load of 4.5kW. Air conditioning on conventionally fuelled ICE buses is generally operated mechanically using drive belts from the main engine. A fuel cell powered APU will have to operate all auxiliary loads electrically.

Trans/Air Corp. in the USA manufacture an electrically powered air-conditioning system aimed at vehicles with full electric propulsion[59]. Two different models are available offering 20 or 40kW cooling capacity which translates to an approximate electrical load of 5 to 10kW. The total loading on the APU is likely to be 10 to 15kW.

An indication of the size of the coach and bus market is given in Table 4.12. It can be seen that global sales are forecast to increase from over 125,000 vehicles in 1999 to more than

159,000 in 2005. In the UK, a commuter bus costs around $200,000 and a luxury coach can cost up to $400,000.

Table 4.12 Coach and Bus Unit Sales in Different Regions

	1995	**1999[62]**	**2005[62]**
World	70,000[60]*	>125,000	>159,000
UK	6,600[63]**	4,548	n/a
Western Europe	n/a	24,000	24,000
Eastern Europe	n/a	19,000	26,790
South America	n/a	16,400	26,000
Asia/Australasia	n/a	61,000	82,000
Asia Pacific[64]	8,600	n/a	n/a
North America[60]	36,300*	n/a	n/a

* 30+ seat buses
** 1997 figures for buses with over 8 seats
n/a not available

4.3.3 Executive Car APUs

BMW's latest executive car has the production option of a 5kW solid oxide fuel cell mounted within the vehicle's boot space. This APU is used to provide power for all of the electrical functions on board the vehicle including all lighting, with the option of heating and air-conditioning within the car while it is stationary. The fuel cell occupies the same volume as a conventional lead-acid SLI battery[65].

BMW and Renault have recently signed a memorandum of understanding with Delphi Automotive Systems to enable further co-operation on the development of SOFC auxiliary power units for cars and trucks[66]. Delphi will develop the gasoline and diesel fuel cell systems and BMW and Renault will integrate the system into their vehicles by 2005.

In the short to medium-term, the market for vehicle APUs will be limited to executive cars. This market is difficult to judge although the size in the UK can be estimated from new vehicle registrations. In 1996, there were 316,000 motor vehicles over 2,000cc registered for the first time, around 15% of all new motor vehicles registered in the UK that year[67]. World-wide sales of BMW cars totalled 699,400 vehicles in 1998 and around 7% (47,200) of these were of the 7 series model[68].

4.4 Mechanical Handling/Industrial Vehicles

Mechanical handling covers a wide variety of different applications. There are hundreds of manufacturers in this sector. The sector can be further divided into *heavy industrial* and *light industrial* vehicles. These are discussed in sections 4.4.1 and 4.4.2 below.

4.4.1 Heavy Industrial

Heavy industrial trucks include fork lift trucks, stackers and similar off road vehicles. On road vehicles are not included within this definition. There are three main companies within this sector producing heavy industrial EVs, each with annual sales of around $1 billion. These are Crown Equipment Corporation (USA), BT Industries (Sweden) and Linde (Germany)[41].

Fork lift trucks need to be heavy with a low centre of gravity. They generally operate over short distances in factories and warehouses and therefore they do not need an incredibly long range. This makes them ideally suited to be battery electric. It is reported that 70% of fork lift trucks in Europe are electrically powered and it is likely that a similar proportion of fork lifts in the rest of the world will soon be pure EVs[41]. Table 4.13 shows the projected size of the heavy industrial EV market up to 2010. The figures are desegregated by geographical region in Table 4.14.

Table 4.13: World Sales Forecasts for the Heavy Industrial EV Market[41]

Year	Units (000)	Average Unit Value ($)	Total Sales Value ($million)
1999	220	12,000	2,640
2000	230	12,174	2,800
2005	260	12,885	3,350
2010	350	9,571	3,350

Table 4.14: Projected Sales for the Heavy Industrial EV Market by Region in 2000

	Unit Sales (000)	Total Sales Value ($million)
World[41]	230	2,800
UK[72]	15*	243
Europe[41]	94.3	1,150
USA[41]	48.3	588
Asia[41]	87.4	1,060

* EV + ICE = 25,000

The Cushman 340 is an electric tug which has a 5.7kW electric motor powered from a 36V 244Ah battery[69]. The latest Lynch motor aimed at fork lift trucks is rated at 4.5kW[70]. Hence a fuel cell powered fork lift truck will need to be around 5kW.

A typical battery pack for a large material handling vehicle would be 72V with a capacity up to 800Ah; examples of typical lead-acid battery packs are given in Table 4.15[88,89].

Table 4.15   Typical Battery Packs for Heavy Industrial Vehicles

Battery	Weight (Total - kg)	Life (cycles)	Price (Total - $)
Exide Power Lift (Flooded) 2V 294Ah (36 off)	780	1,000	5,000
Fiamm (Flooded) 6V 585Ah (12 off)	1,260	1,000	9,600

The traction battery market was worth an estimated $2.2 billion in 1999[41]. This market is dominated by fork lift trucks as it is generally necessary to have three sets of batteries per fork lift for intensive usage: one in use, one cooling and one charging. Fuel cells as a battery replacement in the fork lift market could therefore offer the following benefits:

- Reduce the frequency of charging/refuelling
- Reduce capital costs through the elimination of additional sets of batteries

Several fuel cell developers are investigating the possibility of using fuel cells to power fork lift trucks. These include:

- Siemens have demonstrated a fork lift truck powered with a PEM fuel cell. The fuel cell has a net power output of 10kW and has completed over 1,500 hours of operation[91] at Solar-Wasserstoff-Bayern, a research and development company operated by Bayernwerk with the participation of BMW, Linde and Siemens. On the basis of these trials, BMW has announced that it plans to introduce fuel cell powered fork lifts at all its production plants[97].
- Zevco and Still GmbH, one of the world's largest manufacturers of fork lift and service vehicles, are developing a hybrid fork lift incorporating Zevco's alkaline fuel cell technology[97]. The fuel cell will have a power output in the range from 5 to 10kW.

4.4.2 Light Industrial and Commercial

Light industrial trucks come in many different sizes and configurations. They do not have large counter weights nor do they position heavy loads. This type of vehicle may be found on or off road. Examples include:

- Automatic guided vehicles (AGVs)
- Pedestrian-operated load carriers
- Mobile powered access platforms
- Airport ground support equipment (see section 4.5)
- Floor cleaning equipment
- General workmen's vehicles

The proportion of electrically powered vehicles in this sector is increasing due to environmental concerns. In addition, the fact that electric motors can be frequently stopped and started without wearing out or failing is often a benefit: no idling is needed which means a saving in power consumption, noise and pollution. Table 4.16 summarises the global market for light industrial EVs in 1999 and the projected growth to 2010 is shown in Table 4.17; much of the growth is expected to be in the airport sector where there is a trend toward entirely electric ground support equipment (see section 4.5).

Table 4.16 Global Light Industrial EV Market in 1999[41]

Category	Global Population	Unit Sales	Ex-Factory Price ($)	Gross Sales Value ($million)
Self-propelled operator riding	160,000	32,000	9,400	300
Pedestrian operated and AGVs	100,000	20,000	3,000	60
Commercial on-road vehicles	20,000	5,000	28,000	140
Total	**280,000**	**57,000**	**7,750**	**500**

Table 4.17 Projected Sales Statistics for the Light Industrial EV Market[41]

Year	Units (000)	Average Unit Price ($)	Total Sales Value ($million)
1999	57	8,772	500
2000	64	8,953	550
2005	250	6,400	1,600
2010	400	6,250	2,500

An example of a light industrial vehicle is the Textron E-Z-GO Cargo which is available with a 3.3HP IC engine or a 4kW electric motor[52]. Like many of the self-propelled operator riding vehicles, the E-Z-GO cargo is a converted golf cart (typical characteristics of batteries used in golf carts are given in Table 4.9).

4.5 Ground Support Equipment

Ground support equipment (GSE) covers a wide variety of equipment for many diverse tasks. Items include:

- Ground power units (GPU)
- Baggage tractors
- Cargo loaders (belt loaders)
- Fuel trucks (tankers or hydrant pumps)
- Galley supply trucks
- Cabin cleaning trucks
- Tow tugs
- Passenger stairs
- General access lifts
- Fire trucks

Each of the above vehicles are very different. Some are conversions of existing vehicle platforms (e.g. fire trucks, servicing trucks), and others are specially designed and constructed vehicles. Unit costs may range from the order of thousands to hundreds of thousands depending upon the application.

The stationary use of aircraft APUs is now becoming strictly controlled leading to greater demand for ground support equipment including cleaner GPUs, mobile air-conditioning units and air start units. Emissions from GSE have been receiving more attention. There is a growing demand for electrically powered vehicles to replace ICE vehicles. Many pieces of equipment are now available electrically powered or using LPG/CNG power. Most GSE vehicle specifications include maximum noise levels and these are reducing. Some examples of ground support equipment are shown in Table 4.18:

Table 4.18 Examples of Ground Support Equipment & Market Values 1999

Type	Power	Market Value ($million)[53]	Average Annual Growth (%)[53]
Baggage tractor	EV version 80V, 540A peak, 43kW[73] ICE version 120HP (90kW)	190	3.75
Passenger stair/ belt loader	53-120HP (40-90kW)[73]		
Access lift	16HP (11.8kW)[73]		
Aircraft tugs	200-400HP (150 - 300kW)[74]		
Refueller		120	3.5
Disabled passenger mover	5kW*	5	6.5
Air bridge		100	5.25
Ground power unit (GPU)	Range 40-180kVA (AC400Hz+DC28V) e.g. 90kVA-72kW continuous[75]		

* Typically converted golf carts

It can be seen that the power required varies depending upon the specific application. The range is from as little as 5kW up to 300kW. Typical power plants and prices are given in Table 4.19[90,95]. All of the applications are mobile, the air bridge being the one possible exception since it is fixed to the terminal building at one end.

Table 4.19: Typical Power Plant Currently Used in Ground Support Equipment

Engine	Power Output	Price ($)
Honda 595500	5.5HP (4kW)	214
Briggs & Stratton 351447-1048	18HP (13kW)	1,300
Deutz F3M1011F	40.7HP (30kW)	3,600
MerCruiser 5.7L	260HP (190kW)	10,205

There is a healthy demand for ground support equipment and this demand is growing due to increased passenger and cargo traffic through airports. The value of the total GSE market is shown in Table 4.20; North America accounts for 38% of the world market and Europe has the second largest share at 25%[53].

Table 4.20 Value of the Total GSE Market ($million)

	1994	1995	1999[53]	2000[71]	2005[71]
World	758[2]	818[2]	1,500		3,500
Europe	470[71]	245[71]	375	667	892
North America	824[71]		570	1,240	1,820
Asia		260[71]		400	616

5. Other Niche Markets

There are a number of other market niches where fuel cells could be introduced which do not fit into the previous sections. Examples include the use of fuel cells for educational purposes and leisure markets such as boating and garden equipment. These applications are outlined below.

5.1 Education

As fuel cell technology approaches commercialisation in the transport and stationary power sectors, there will be an increasing need to include the technology in the syllabuses of science and engineering courses at schools and universities. Hence there is considerable scope for miniature fuel cells specifically intended for education and training purposes. This can be seen in Table 5.1 which shows the number of state primary schools in various countries. Where available, information on the number of secondary schools is also given.

Table 5.1 Primary and Secondary Schools in Various Countries in 1997

Country	Primary Schools	Secondary Schools
UK[21]	23,306	4,438
European Union (inc. UK)[8]	167,697	
Eastern Europe[8]	377,375	
United States[22]	60,808	20,977
Australasia[22]	10,075	
Japan[22]	24,482	
China[22]	628,800	92,800

Although there are far fewer higher education establishments, there is still scope for demonstration fuel cells in many engineering departments for teaching and research purposes. In the UK, the number of universities and higher education institutions currently offering courses (degrees and diplomas) in engineering disciplines are as follows[23]:

- 26 chemical engineering departments
- 106 mechanical engineering departments
- 77 electrical engineering departments

The key requirements of a fuel cell for teaching and demonstration purposes include:

- Robust and safe to use by children
- Simple to set up and operate
- Rapid start up times
- Versatility to enable a number of worthwhile experiments to be carried out
- Low cost (the Electro-Chem-Technic cell (see Table 5.2 below) costs around $30 for one and $20 if bought in larger numbers[25])

It has been recognised by a number of developers that there is a need for miniature fuel cells for education and demonstration purposes. Some examples of the different systems are summarised in Table 5.2.

Table 5.2 Examples of Fuel Cells for Educational Purposes

Fuel Cell	Developer	Fuel	Performance
SOFC[1]	Keele University (Chemistry Department)[24]	Butane	220 mA at 1.5 V
Alkaline[2]	Electro-Chem-Technic[25,26]	Methanol	150 mA at 0.4 V
PEM[2]	H-TEC[27,28]	H_2 from PEM electrolyser	100 mA at 0.35 V

[1] For research and demonstration purposes
[2] Commercially available and designed for use in schools

5.2 Leisure

5.2.1 Pleasure Boats

The pleasure boat sector includes motorboats, power boats, yachts and other engined leisure craft (dinghies, jet skis, canal boats etc). Many of these are currently powered by 2 or 4 stroke gasoline engines or by diesel engines for larger boats.

In the UK, over 2 million boats are privately owned; of these 1.5 million are identified as ‘main craft’ and 500,000 as secondary or tertiary craft such as tenders. A breakdown of the ownership of main craft in the UK is shown in Table 5.3; the average age of a boat is 14 years and three quarters are purchased second hand. The value of the market for boat engines was around $200 million in 1998, just over 5% of the market value of the boating industry in the UK[33].

Table 5.3 Ownership of Boats in the UK 1998[33]

Boat Type	Number (000)
Sailing dinghy	460
Sailing yacht	380
Motor cruiser	340
Canoe/kayak	200
Sports boat	160
Total	**1,540**

There are two potential applications for fuel cells in pleasure boats:

(i) Onboard/portable generators for larger yachts and motorboats

(ii) Main propulsion systems for all boat types

These applications are outlined in sections 5.2.1.1 and 5.2.1.2 below:

5.2.1.1 Onboard Generators

Most boats and yachts have an engine either as a main source of power or as a fall back (as for sailboats). Larger boats and yachts for travelling longer distances requires facilities for the comfort of passengers, ranging from cooking facilities to air conditioning. Therefore, one of more onboard generators are needed to meet these auxiliary power needs. For larger pleasure boats, these generators can be sizeable. Sailboats and yachts tend to use batteries for auxiliary power but portable generators are commonly used to supplement the batteries, particularly when the vessels are moored.

When in dock, some marinas have power supplies available at berthing points. Otherwise, boat owners are obliged to run their generators. In such communal surroundings, noise can be a problem (as well as exhaust smells and emissions), and for this reason "gensets" are encased with sound insulation. This application would be ideal for a portable fuel cell generator (see section 3.4). Battery replacement is also a viable option since fuel cells offer the benefit of rapid refuelling which is favourable to slow recharging when leisure time for sailing is limited.

5.2.1.2 Main Propulsion

Fuel cells developed for other transport applications could be used for the main propulsion systems for pleasure boats. However, this is unlikely to occur in the short to medium-term for various reasons, including[30]:

- Pleasure boats are characterised by long lives but frequently by limited usage (days per year) and so the benefits of increased fuel efficiency make a minimal contribution to paying back the initial investment cost.
- Lack of infrastructure for alternative fuels such as hydrogen and methanol.
- Insufficient service network for fuel cells; most engine suppliers have an international network of service centres to allow the complete circumnavigation of the globe.

The exhaust gases from marine engines contribute to both airborne and waterborne pollution. This is leading to a growing interest in electric boats for inland rivers, canals and lakes. Various fuel cell developers are directly targeting this niche; for example, Ansaldo are developing a fuel cell powered boat to be operated on an Italian lake[30].

In order to profit from this market, fuel cell powered boats will have to meet the following criteria[39]:

- *Cost*. A 500W gasoline engine costs around $700 and, to be competitive, a fuel cell system must be somewhere in this region.
- *Operation*. A fuel cell generator must be as straightforward to operate as a gasoline engine, and procurement of the fuel should also be easy.

- *Safety*. Fuel cell systems must not present safety problems that are more critical than those of a gasoline engine.

5.2.2 Garden Equipment

The world-wide market for garden equipment reached a value of $7,300 million in 1997 as shown in Table 5.4[34]. The biggest individual market is the United States and this market is forecast to reach $9,600 million by 2001[2].

Table 5.4 Value of the Total Market for Garden Equipment ($million)

	1997[34]	2001
World	7,300	n/a
Europe	2,500	n/a
USA	3,850	9,600[2]

In 1997, sales of lawnmowers accounted for around 40% of the European market for garden equipment. The market was worth just under $1 billion and the breakdown by mower type is shown in Table 5.5.

Table 5.5 Breakdown of the European Lawnmower Market in 1997[34]

Type	Value ($million)
Internal combustion engine	590
Electrically powered	350
Battery operated	32
Hand operated	16
Total	**988**

Power mowers, both ride-on and pedestrian operated, could use fuel cell technology. It has long been recognised that the use of a high voltage power cord for domestic lawn mowing and garden maintenance is not an ideal solution. Battery operated home mowers are available, but account for only a very small proportion of the market (see Table 5.5) as their operating duration is limited. For the larger lawns and grass areas (sports pitches) a ride-on mower is the only feasible solution. These mowers are equipped with small low power IC engines.

Pedestrian operated ICE mowers range in price from $700 to $3,000[37].

Garden equipment other than mowers may also see the introduction of fuel cell technology. Such items include hand held equipment like hedge trimmers, garden vacs etc.. An associated vacuum market might also be the household robotic vacuum cleaner, currently limited by battery power.

6. Ranking of Niche Markets

This section ranks the suitability of using fuel cells in the various markets covered in sections 2 to 5. For each potential fuel cell application, two aspects have been addressed, namely:

(i) Market worth

(ii) Overall technical/commercial suitability

These are considered further in sections 6.2 and 6.3 below. The outcome of the individual ranking exercises have then been combined in the form of an applications matrix (see section 6.4) to determine the five most promising applications for further consideration.

6.1 Market Categories

In order to simplify the ranking exercise, the different applications considered in sections 2 to 5 have been condensed into the following categories:

- *3Cs* (computers (laptop), cellular phones and video cameras)
- *Other battery replacement markets* (UPS, navigational aids, medical applications, portable variable message signs and TV cameras for outside broadcast)
- *Leisure and outdoor* (boating, portable power for camping and caravans, garden equipment and power tools)
- *Education*
- *DC and stand-by power*
- *Portable power* (excluding that for leisure activities)
- *Custom/premium power*
- *Chemical industry*
- *Coal gasification*
- *Naval and marine*
- *Lightweight personal transport* (two wheeled vehicles, invalid carriages and golf carts)
- *APUs* for aircraft, buses/coaches and cars
- *Mechanical handling* (light and heavy industrial vehicles)
- *Ground support equipment*

6.2 Market Potential

The market potential for fuel cells has been derived by estimating the value of the power source component (e.g. battery, IC engine) of each of the market categories. When determining the market value, unless otherwise stated, it has been assumed that:

- Power generation equipment costs 1,000$/kWe
- For most items of equipment/vehicle, the power source component accounts for one third of the total equipment/vehicle cost

It should be emphasised that the purpose of this assessment is to give an indication of the current world-wide market potential for fuel cells and *not* to provide definitive market values. The outcome of the ranking exercise is shown in Table 6.1 with the value of the potential markets listed in descending order.

Table 6.1 Ranking of Fuel Cell Market Potential in Niche Applications

Market Application	Comments
Naval and marine	Largest market value. Approximate number of ships built annually is 1,000 and average engine size is 5 to 10MWe.
Portable power (excluding leisure)	Value of the world market for generating sets in 1997 was 5.8 billion (Table 3.). Around 90% of the market is for non-leisure activities.
Car APUs	Around 50 million new cars are sold annually and approximately 10% of these are executive models (> 2,000cc). A typical APU would have a rating of 5kWe and cost an estimated $1,000.
DC power/ stand-by power	The market for DC applications is considered to be small. Sales of stand-by diesel generators in Europe during 1999 amounted to 20,000 units. World-wide sales are estimated to be five times this figure and the average unit size is estimated at 5kWe.
Leisure and outdoor	*Boating*. The market for boat engines for the leisure market in the UK was worth $200 million in 1998. World-wide sales are estimated to be at least ten times greater. *Portable power for camping and caravaning*. Estimated to be 10% of the world portable power market ($5.8 billion in 1997). *Garden equipment*. The European lawnmower market was worth around $1 billion in 1997 (Table 5.5). World-wide sales estimates are three times greater. The market value of other powered garden equipment (e.g. hedge trimmers) is regarded as small. *Power tools*. World-wide sales of $6.4 billion in 1998 (Table 2.9).
Chemical industry	There is sufficient hydrogen by-product availability in the European chlor-alkali industry to install 600MWe of fuel cell power plant. World-wide potential in the chemical sector is estimated to be five to ten times this figure.
Coal gasification	Coal accounts for 40% of power generation world-wide and there is around 100GWe of capacity installed annually. Coal gasification could account for up to 10% of the global market.

Table 6.1 Ranking of Fuel Cell Market Potential in Niche Applications (Cont.'d)

Market Application	Comments
3Cs (computers, cellular phones and video cameras)	The battery market for portable electronic equipment is projected to be worth $2.8 billion in 2000 (Tables 2.1 and 2.2). This market is growing at around 10% per annum.
Coach and bus APUs	World coach and bus sales amounted to over 125,000 vehicles in 1999 (Table 4.). A typical APU would have a power rating of 10 to 15kWe.
Mechanical handling	The value of the global traction battery market was estimated to be worth $2.2 billion in 1999. This market is dominated by fork lift trucks.
Uninterruptible power supplies	The value of the battery market for UPS equipment is forecast to be worth $1.8 billion in 2000 (Table 2.1).
Medical applications	The battery market for medical equipment is forecast to be worth $1.1 billion in 2000 (Tables 2.1 and 2.2). The market for rechargeable batteries is growing at around 15% per annum.
Custom/premium power	Estimated to be around 1% of the annually installed capacity of 100GWe.
Aircraft APUs	Aircraft deliveries are estimated at 900 new aircraft per annum (Tables 4.10 and 4.11). A typical APU has a rating of 1MWe.
Lightweight personal transport	The total value of the two-wheeled EV, invalid carriage and golf cart market is currently around $1.2 billion (Tables 4.5, 4.6 and 4.8).
Ground support equipment	The total world-wide market for ground support equipment was worth around $1.5 billion in 1999. Such equipment is highly customised and the power source will typically be 20% of the equipment cost.
TV cameras (outside broadcast)	The battery market for this application is not considered very large and is estimated to be worth $10 to $15 million per year.
Education	In the short to medium-term, fuel cells are only likely to be introduced into schools in the westernised world. It is estimated that there are 400,000 to 500,000 schools. It has been assumed that there are three kits per school, with each kit costing $20 and being replaced every 5 years.
Navigational aids	There are 20,000 to 40,000 small navigational aids world-wide with a 10W average power requirement. With a replacement cycle of 5 years and a cost of 10,000$/kWe, this represents a very small market worth less than $1 million per annum.
Portable variable message signs	This market is considered to be highly specialist with most applications in the United States. The annual value of the market is very small and has not been considered further.

6.3 Technical/Commercial Suitability

There are two elements to the overall suitability of fuel cell systems for any given application: the *technical* viability and the *commercial* viability. A scale of 1 to 10 has been used to quantify each aspect where:

1 = totally unsuitable

10 = highly attractive

The overall technical/commercial suitability has been obtained by taking a weighted average of the scores of the technical viability and commercial viability. The weighting factor that has been used varies from application to application and has been determined dependent upon whether the technical or commercial risks are considered to be more important.

Table 6.2: Ranking of Technical/Commercial Suitability of Fuel Cells for Different Applications

	Technical	Commercial	Overall
Education	10	9	10
Car APUs	8	8	8
Custom/premium power	9	7	8
TV cameras (outside broadcast)	8	8	8
Leisure and outdoor	8	7	7.5
3Cs	9	6	7
Ground support equipment	7	8	7
Mechanical handling	8	6	7
Navigational aids	8	6	7
Portable power (excl. leisure)	8	6	6.5
Medical applications	6	8	6
Coach and bus APUs	6	5	5
Chemical industry	8	4	5
Lightweight personal transport	7	4	5
Uninterruptible power supplies	6	4	5
Naval and marine	3	3	3
DC power/stand-by power	5	2	3
Coal gasification	3	2	2
Aircraft APUs	2	2	2

The technical viability and commercial viability of fuel cells for each market application, together with the overall weighted technical/commercial suitability, are shown in descending order in Table 6.2. In addition, the following comments and observations can be made about each of the market categories:

- *3Cs*. Fuel cells are technically very suitable for powering portable electronic equipment and this is reflected by the number of developers actively working in this area. For fuel cells to be acceptable to the majority of consumers, it is important that the unit price is comparable with existing battery technologies, though fuel cells should command a slight premium. The commercial aspects are considered to be of greater importance than the technical suitability of fuel cells.

- *Other battery replacement markets*:

  (i) *Uninterruptible power supplies*. This is seen as a reasonably attractive market. UPS equipment is used in many critical applications and fuel cells must therefore demonstrate high levels of reliability and low maintenance requirements before they become commercially acceptable.

  (ii) *Navigational aids*. Fuel cells are technically suitable and attractive provided that they can meet the necessary reliability levels and very low maintenance requirements. Commercially, it is a very small and specialist market but one which can stand a very high unit cost.

  (iii) *Medical applications*. This is a reasonably attractive market for fuel cells if they can comply with exacting safety and reliability criteria. Provided that these technical requirements can be met, it is a commercially attractive market and one which is expanding rapidly.

  (iv) *TV cameras for outside broadcast*. This is an attractive market, both technically and commercially. Price will not be a significant issue compared with the overall cost of a camera and fuel cells should offer longer running times, thereby eliminating the need for multiple sets of batteries to cover a day's filming.

- *Leisure and outdoor*. This is a technically and commercially attractive market for fuel cell systems. Commercially, they are competing against well-established technologies such as diesel engines for boating, caravaning and camping. However, fuel cells offer the benefits of reduced noise and pollution, and the latter, in particular, is becoming increasingly important.

- *Education*. Technically this is a highly attractive market for fuel cells since small units are simple to make and efficiency is not a key issue. Provided that the units can be made at a sufficiently low cost, it is also a commercially attractive market, although in the short to medium-term it will probably be restricted to schools in North America and Western Europe.

- *DC and stand-by power*. In the short to medium-term, fuel cells are not considered to be technically or commercially suitable for large DC power applications. Fuel cell systems are technically suitable as stand-by supplies but do not offer many advantages as generation efficiencies are unimportant due to low annual usage. Commercially, they are unlikely to be able to compete with conventional diesel engines unless noise and vibration are critical considerations.

- *Portable power*. Fuel cells are technically suitable but it may be difficult for them to be cost-competitive with conventional portable gensets such as diesel engines. The major commercial advantages are reduced noise, vibration and emission levels which may be important in some applications.

- *Custom/premium power*. Fuel cell systems are technically very suitable for this application, producing high quality power from solid-state electronics. It is a high added value market but alternative methods may be a cheaper option than fuel cells in the short-term.

- *Chemical industry*. The use of by-product hydrogen from the chemical industry is a simple concept and one which is technically feasible. Commercial considerations are of greater importance, however, and in most cases it is likely that the associated engineering costs would make the process prohibitive.
- *Coal gasification.* There are tremendous technical and commercial risks associated with integrated coal gasification fuel cell processes. As yet there is only limited experience of running molten carbonate fuel cells and, for economic reasons, any combined coal gasification plant would have to very large (> 500MWe). Hence, the absolute cost is high and there is considerable potential for technical problems in the scale up from demonstration to full size.
- *Naval and marine*. In the short-term, fuel cells are not considered to be very suitable for these markets. It may prove difficult to fit fuel cell systems into the compact space occupied by equivalent diesel engines and gas turbine plant, and likewise, it may be difficult to compete on cost grounds. In addition, there are problems to be overcome concerning the choice of fuel and the associated infrastructure. There are two notable exceptions where fuel cells offer distinct operational advantages, namely on cruise liners and as air-independent propulsion systems for submarines.
- *Lightweight personal transport*. Fuel cells are technically suitable for this market and offer environmental benefits as a power source for scooters and motorcycles compared with conventional IC engines. As a battery replacement for golf carts and invalid carriages, there are fewer operational advantages; recharging typically takes place overnight and faster recharging/refuelling is of no particular advantage.
- *APUs*:

  (v) *Aircraft*. For this application, fuel cells would need to run on kerosene, be compact, lightweight and certified for flight. Also, there is a high demand for compressed air on board aircraft. Hence fuel cells are unlikely to be able to compete technically or commercially with proven gas turbine technology.

  (vi) *Coaches and buses*. This is a reasonably attractive market for fuel cells. There is increasing interest in zero emission APUs, due to restrictions on extended idling in urban areas, assisting the introduction of fuel cells in the medium-term.

  (vii) *Cars*. Fuel cells to power APUs for executive cars are considered to be technically and commercially attractive. They provide a good marketing opportunity for car manufacturers who are continually looking for novel and distinctive features to add to their executive models.
- *Mechanical handling*. This is a technically suitable market for fuel cells. They are competing with battery-driven fork lifts but offer the benefits of increased running times and rapid recharging/refuelling cycles, thereby eliminating the cost of multiple sets of batteries.
- *Ground support equipment*. Fuel cells are technically attractive for this market, particularly for primary propulsion. Equipment is generally highly customised resulting in a high value added market and there is an additional premium for low or zero emission vehicles. It is also a market that is expanding rapidly and hence this is seen as a commercially attractive area for fuel cells.

6.4 Overall Ranking

The market value and overall technical/commercial suitability of fuel cells in the various niche markets have been combined in the form of an applications matrix as shown in Figure 6.1. Applications appearing in the top right hand corner of the graph are those which are likely to be the most suitable and which also have the largest market size.

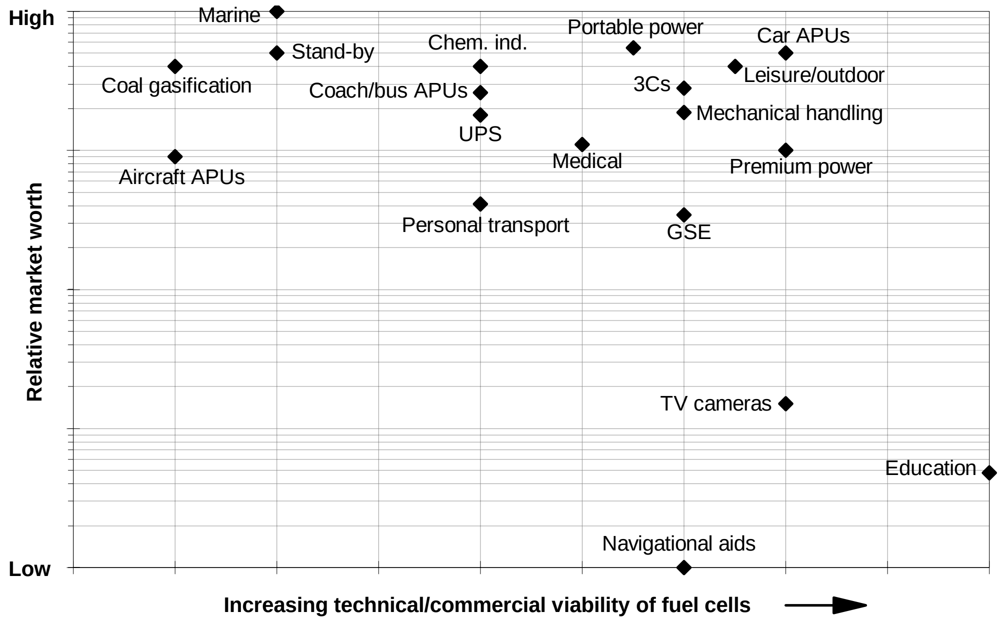

Figure 6.1: Indication of Viability v Market Potential of Fuel Cells in Different Niche Applications

From Figure 6.1 the five most promising applications for further consideration have been selected as follows:

(i) APUs for executive cars

(ii) Leisure/outdoor

(iii) Portable power

(iv) 3Cs (computers, cellular phones and video cameras)

(v) Custom/premium power

Scoping systems designs for these five applications are considered in the following sections.

7. Scoping System Designs

Having evaluated the information from section 6, the following product areas have been identified as the prime areas for further investigation:

1/ Car APUs
2/ Leisure / Outdoor
3/ Portable Power
4/ Portable Electronics - Video Cameras, Portable Computers, Cellular Phones
5/ Premium Power

For each of these product domains, three different areas are considered:

- Outline design
  - Each of these systems are considered as the combination of a fuel processor, a cell stack assembly, a power conditioning system and other balance of plant, as deemed applicable.
- Performance and functionality
  - In this area, the criteria of competing plant that are deemed important are examined.
- Cost
  - The costs of competing power sources / power plant are considered as appropriate.

All of the designs considered will require an electronic control unit to operate and control the sub-systems. Due to its commonality, it will not be referenced for each system.

7.1 Car APU

For the purposes of this report, the car APU design considered is a 5 kW_e Solid Oxide Fuel Cell (SOFC), as considered by BMW / Delphi. The fuel will be standard unleaded gasoline.

7.1.1 Outline Design

The following is a flow diagram of the fuel cell system envisaged:

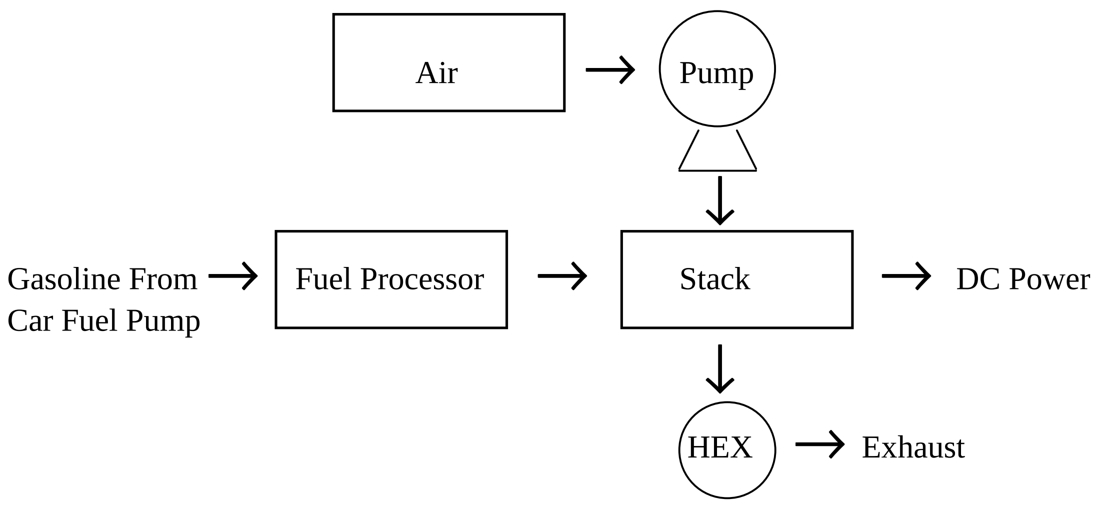

Figure 7.1: Likely Layout of Car APU Components

The gasoline is fed into the fuel processor from the existing car fuel pump. The fuel processor converts the gasoline into a hydrogen rich gas stream via a process called partial oxidation. Such a fuel processor is described in more detail in section 7.6.1. The hydrogen rich gas stream is then fed into one side of the fuel cell stack, with oxygen in the air fed into the other side of the solid electrolyte. For more details of a typical SOFC stack design, see section 7.7.1.

Auxiliary plant required for this system includes an air pump to force air through the stack. This air may pass through a heat exchanger taking heat from the fuel cell exhaust, and may also be integrated with some form of pre-heater in order to start the reaction from cold. Additional heat from the exhaust should then be fed to the cabin heating as required.

Some form of electrical protection is likely to be necessary to protect the car electrical system from the stack, and vice versa. The DC power from the stack is however likely to be produced at a voltage usable directly by the car's electrical system, avoiding the need for a voltage booster. Therefore, complicated power conditioning equipment is unlikely to be necessary. Instead, the fuel cell is likely to feed DC directly into the car's electrical circuitry, with over voltage / over current protection likely. Such a system is unlikely to negate the need for a car battery. A smaller battery is likely to be necessary to start the APU and also to start the IC engine.

A larger 25 kW unit produced by ZTEK Corporation, had the following design specification[98]:

Fuel Cell DC Output:	27.5 kW
Inverter Loss (5%):	1.5 kW
Auxiliary Load:	1 kW
Plant AC Output:	25 kW
Net Plant Efficiency:	45.8%

It should be noted that a car APU would have a DC output, and as such would have no inverter losses. However, smaller systems tend to be less efficient, so an overall maximum electrical efficiency of around 45% would seem reasonable for a car APU.

7.1.2 Performance and Functionality

This unit is likely to operate independently of the engine, and would typically allow functions such as air-conditioning to operate whilst the engine is switched off. In the long-term it is likely that the unit could replace the alternator and fan belt, and allow the use of a much smaller lead-acid battery for engine starting and emergencies.

The following is relevant data from a typical alternator specification[99]:

System Voltage	: 12V
Regulating Voltage	: 14.35 + 0.5V
Max. Output (hot)	: 50 amps nominal (other units may range up to 100 Amps)
Approx. Weight	: 3.55 kg incl. Pulley
Operating Temp.	: -30ºC to +100ºC

As can be seen from the above specification, alternators are heavy and have a poor power density. They also only operate when the engine is on and are relatively fuel inefficient, as they are inherently less fuel-efficient than the car engine. As can be seen above, currents in the region of 50 to 100 Amps are required, meaning heavy gauge cabling is required to carry the power. Current car electrical circuits operate at 12 V DC. However, moves are underway to raise this voltage to help meet the greater power demands on cars. The planned voltage is 36 V DC with battery charging taking place at 42 V.

The ability of fuel cells to operate whilst the engine is off will allow all electric circuits to operate, and would also allow air conditioning to operate if power was supplied from the more efficient fuel cell. However, any unit would need to be able to withstand the harsh temperature and vibration operating regime of cars.

The following outline specification is viewed as realistic for a car APU:

Electrical efficiency:	45% max.
Electrical output:	5 kW (max.)
Voltage output:	12 or 36V DC
Volume:	5 litres (approx.)
Weight:	5 kg (approx.)
Expected lifetime:	10,000 hours max.

7.1.3 Cost

Alternators are not a highly expensive item, and are likely to be supplied to manufacturers for less than £50. However, a direct cost comparison between alternators and fuel cells is not justified, as fuel cells provide additional functionality as described above. In addition, the raised specification of the car would doubtless allow a premium to be charged for that model. Consequently, it is the author’s judgement that a 5 kW fuel cell unit would need to cost the car manufacturer less than £200 per unit when supplied in volume.

7.2 Leisure / Outdoors

This area includes pleasure boats and garden equipment, but for the purposes of this report, the domestic lawnmower will be considered due to its significant potential.

7.2.1 Outline Design

There would appear to be four leading design options for such a unit:

AFC + Hydrogen
PEM + Hydrogen
PEM + Methanol
DMFC

The AFC, though not containing expensive catalysts such as platinum, does require CO_2 scrubbing of air to avoid poisoning the stack. Until this problem is overcome, it is more likely that the PEM will be more cost competitive. Similarly using methanol as a fuel for PEM fuel cells increases the amount of plant required, and hence the cost. DMFCs, whilst advancing rapidly at the Watt scale, are unlikely to be competitive at the kW scale in the very near future. Consequently it is envisaged that a PEM unit running on pressurised, bottled hydrogen will be the most cost competitive design. It is not envisaged that bottled hydrogen should be unduly unsafe due to the extensive use of compressed fuel gases elsewhere in domestic (and commercial) situations. Consequently, the following flow diagram for the fuel cell is envisaged:

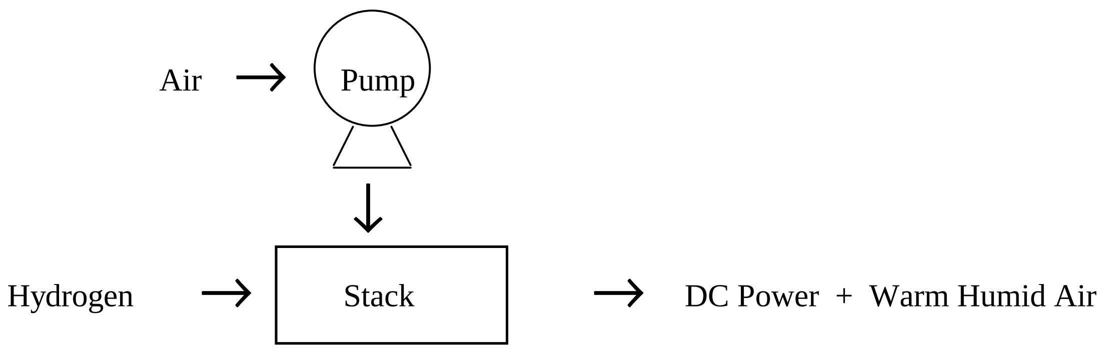

Figure 7.2: Likely Layout of Lawnmower Fuel Cell

This design is likely to be relatively simple, with little additional plant likely or affordable for the unit. This may lead to a sacrifice of some efficiency or lifetime from the unit, but neither issue should cause undue concern. However, any design for lawnmower use will use a lower efficiency and lower cost design, minimising parts and expense of materials. For more details of a PEM stack design, see section 7.7.2.

7.2.2 Performance and Functionality

This simple design would require low cost PEM stacks to be developed that would not be required to have a long lifetime. For example, if a unit were used every weekend for 30 minutes for 6 months of the year, this would only amount to 13 running hours per year. Clearly a design lifetime of 1000 hours would more than satisfy most domestic users.

The other main issue is power level. Current electric mowers are generally fed by long electric leads trailing from the house. This limits power consumption to a little over 2 kW. Consequently fuel cell units could be expected to produce between 1 kW_e and 3 kW_e with the motor being directly driven by DC power.

Using fuel cells would also allow electric lawnmowers to enter the larger lawnmower market at around the 3 to 5 kW_e level. In addition, fuel cell stacks that produce higher DC voltages would be likely to reduce the motor cost due to the lower current rating required.

Improved features over other models would include no recoil start, cooler exhaust, quieter running, being environmentally benign and having no trailing leads.

Summary of expected system performance attributes:

Design lifetime:	1000 hours min.
Power output:	3 – 4 kW initially (lower powers later)
Operating voltage:	12 / 24 V DC (higher voltage lowers motor size)
Electrical efficiency:	30 – 35%
Power density:	up to 1 kW/Litre and 1 kW/kg

7.2.3 Cost

Initial units would be likely to enter the 3 to 4 kW_e market, at which conventional units sell at a premium and in smaller numbers. In the current market, the only competition would be from internal combustion engines. Typical engines retail at around £95 excluding VAT for a 2.75 kW_e engine and £105 for a 3.75 kW_e engine[100]. Fuel cell drives would be expected to retail at a premium due to their increased functionality over the alternatives.

7.3 Portable Power

Portable power units are required at remote sites as an alternative to a convenient mains source. The majority of units are gas or diesel fuelled with power outputs in the range 1 kVA to 75 kVA. For the purposes of this report, we will consider a 50 kVA nominal output unit running on diesel. It is most likely that such a unit would be a PEM unit due to its flexible nature and potential for low cost manufacture. Diesel was selected due to fuel infrastructure problems for other fuels and its high penetration in existing markets.

7.3.1 Outline Design

The following shows the likely layout required:

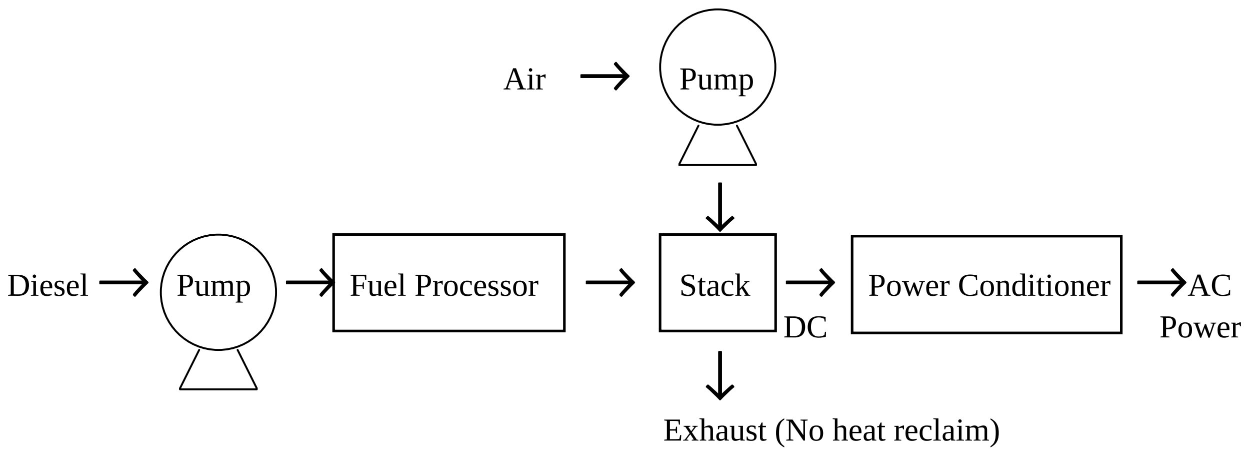

Figure 7.3: Likely Layout of Portable Power Fuel Cell

The diesel is fed into a chemical splitting device called a fuel processor, which converts the diesel into a hydrogen rich gas stream. For more details of the operation of such a fuel processor, see section 7.6.1. The hydrogen rich gas stream is then fed into one side of the fuel cell stack, with oxygen in the air fed into the other side of the solid polymer electrolyte. For more details of the functional design of a PEM stack, see section 7.7.2. The stack produces DC power, which is then fed into the power conditioning unit to produce usable AC power. For more details of the power conditioning unit, see section 7.8.

7.3.2 Performance and Functionality

Such a unit would be expected to supply voltages at 110 / 230 / 400 V AC and be capable of supplying peak current of around 70 Amps. Assuming a duty cycle of 8 hours per day, 5 days per week (a normal working week), the unit would be required to be able to run for around 2100 hours per year. A 5 to 10 year lifetime would seem reasonable. A summary of expected performance criteria is given below:

Electrical efficiency:	35-40%
Electrical output:	50 kVA
Voltage output:	110 / 230 / 400 V AC
Volume:	2000 litres (approx.)
Weight:	1000 kg (approx.)
Expected lifetime:	5 – 10 years

7.3.3 Cost

A comparable conventional diesel generator costs around £5,500 ex-factory[101]. This includes the standard generator with acoustic accessories to reduce noise level. A fuel cell unit could be expected to sell at a premium due to its low environmental / noise impact and greater efficiency.

7.4 Portable Electronics (video camera, portable computer, cellular phone)

This area covers the portable DC power market for the smaller items listed above. In this section the cellular phone, or, “mobile”, has been selected as a prime market.

7.4.1 Outline Design

Mobile phones powered by fuel cells must have the same portability that battery powered units have. This means that compressed hydrogen canisters are not feasible generally, as airlines would be unwilling to allow such units on board. Consequently methanol is the fuel of choice, and direct methanol fuel cells seem a sensible choice for the low power levels required, especially in light of the progress made by Motorola.

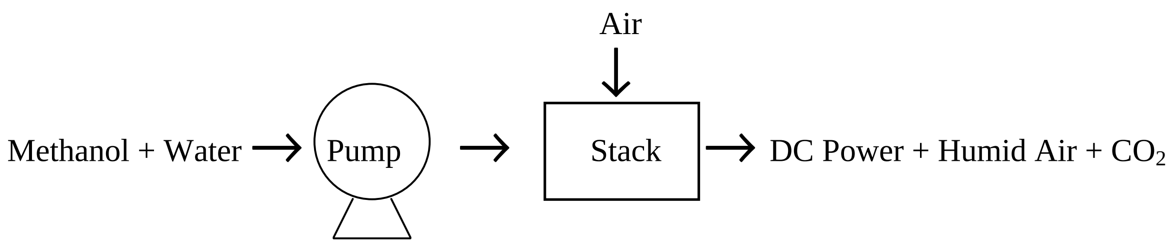

Figure 7.4: Likely Layout of Cellular Phone Fuel Cell

The fuel cell operates at room temperature. A platinum and ruthenium catalyst is used to react a dilute mixture of methanol and water to form carbon dioxide, protons and electrons. The protons are conducted through an organic membrane to another platinum catalyst, where they combine with oxygen from the ambient air to form water. For more details of a Direct Methanol Fuel Cell stack, see section 7.7.3. It is planned that the methanol would be packaged in small cartridges[102].

7.4.2 Performance and Functionality

This simple design would require low cost DMFCs to be developed that would produce very low power levels. The design would need no air pumps, heat exchangers or other complex devices. It would also eliminate the need for battery chargers and AC adapters. Circuitry has also been developed that converts the fuel cell’s low voltage output (0.5V) to the higher voltage needed to drive portable electronics[103]. Such a fuel cell has already been developed by Motorola, with claims of an energy density of 10 times that of conventional rechargeable batteries. A unit lifetime of 20 years is claimed compared with conventional battery lifetimes of around 2 years.

The following specification is also claimed:

Dimensions: 25 x 25 x 2 mm (fuel cell)
Fuel: Liquid methanol (dilute)
Running Time: 1 week (standby) from size of ink cartridge. Some claim 1 month +
Power (standby): 0.3 W[104]
Power (talking): 4 W[104]

Currently, talk times vary from 90 minutes to 4 hours, with standby times ranging from 2 days to 4 days. Phones weigh between 100g and 200g. Lithium-ion batteries are now becoming the norm, accounting for 70% of the current market, with nickel metal hydrides accounting for the majority of the balance[105]. Nickel cadmium batteries have already been largely displaced.

7.4.3 Cost

Developers claim similar costs to nickel-cadmium batteries whilst carrying around 50 times more energy[104]. It should also be remembered that chargers would also be replaced. These retail from around £10 for travel chargers[106] to around £35 for intelligent chargers[107].

7.5 Premium Power

This area covers the premium power market, where the loss to US industry from power quality events has been estimated at US$50 billion to US$150 billion annually[108].

For the purposes of this report, the unit selected is a 200 kW_e PEM fuel cell power plant supplied with natural gas.

7.5.1 Outline Design

The following is a simplified layout of the components for a fuel cell premium power plant:

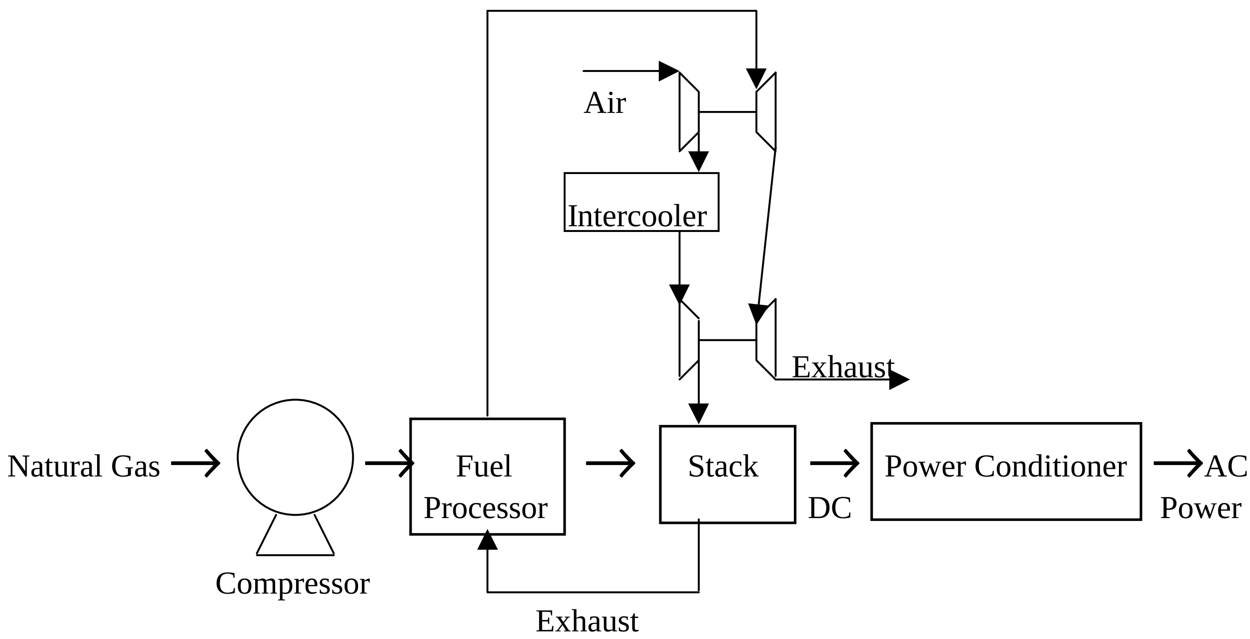

Figure 7.5: Likely Layout of Premium Power PEM Fuel Cell

Details of a typical fuel processor can be seen in section 7.6.2. The stack and its associated thermal management system can be seen in section 7.7.2 and the power conditioning system in section 7.8. In addition, there are other componentry. Systems are likely to use a fuel gas compressor, a turbocharger on the air / exhaust lines, an intercooler for the turbocharged air and auxiliary burners to heat the fuel processor. There are also likely to be various feed-water pumps, cooling fans and filters.

7.5.2 Performance and Functionality

There are numerous supply configurations available in order to supply premium power. For some the worth is to drastically reduce problems such as voltage spikes, voltage sags or just power outages. High quality power availability is typically quoted with figures such as 99.999% or 99.999999% availability. The problem, though, is not generally with the generating equipment itself, but with the other equipment connected to the network consuming electricity. Fuel cells do, however, give the added advantages of very high quality waveform, due to solid state electronics, good ability to load follow and a high availability. High availability is predicted in comparison to internal combustion engines, which require frequent maintenance intervals. Indeed, leading manufacturers such as ONSI predict 95% availability for well-maintained plant[109].

Other issues for functionality would be meaningless to itemise, as all options are available at a price. However, the proposed system is envisaged to be a simple one in which the fuel cell supplies the load directly, with the network used as back-up. It would appear that in areas of poor power quality, such systems could reduce power outages dramatically.

Electrical efficiency:	40% LHV
Overall efficiency:	80%
Electrical output:	200 kW
Voltage output:	230 / 400 V AC
Volume:	20 metres^3
Weight:	10 tonnes
Expected lifetime:	10 years
Service interval:	1 year minor service
	5 years major overhaul
Availability:	95% (for single fuel cell unit)

7.5.3 Cost

The cost of such a system is difficult to price, though one system of similar functionality already exists in the ONSI PC-25, a 200 kW_e Phosphoric Acid Fuel Cell (PAFC). It is widely known that this unit retails for between US$3000 / kW_e and US$4000 / kW_e. Whilst sales have now passed 200 units, this has been achieved over a period of around 10 years, and not all units were purchased for this intention. Consequently it can be deduced that this is a premium price that would limit the market uptake, and that retailing below $US3000 / kW_e would open up a larger volume market. Also, conventional internal combustion plant retails at up to $1000/$kW_e$, but as fuel cells offer increased functionality, a price between these levels would seem likely to stimulate the market.

7.6 Sub-Models of Fuel Processors

7.6.1 Gasoline / Diesel Fuel Processor

Unlike natural gas, which can be fed almost directly into a fuel cell stack, neither gasoline nor diesel can be. They must first be fed into a fuel processor that contains three main stages:

1/ Partial oxidation
2/ Carbon monoxide removal
3/ Desulphurisation

Partial oxidation converts the fuel into a hydrogen rich gas stream via a chemical splitting process. The desired reaction can be achieved with or without a catalyst. Non-catalytic processes for gasoline reforming require temperatures in excess of 1000°C. These high temperatures necessitate the use of specific materials of construction and significant preheating and thermal integration of process streams. The presence of a suitable catalyst substantially reduces the operating temperature, allowing the use of more common reactor materials, such as steel. Lower temperature reforming also leads to less carbon monoxide in the raw reformate, meaning the water-gas shift reactor can be considerably smaller[110].

The gases involved in the reaction within the reformer react as follows:

Hydrocarbon + Air + Steam = Carbon Dioxide + Hydrogen + Nitrogen

There are, however, several different mechanisms by which partial oxidation can take place. One mechanism reacts the hydrocarbon with oxygen from the air only, giving hydrogen and carbon monoxide[111]. Another reacts the hydrocarbon with steam to give carbon monoxide plus hydrogen[112]. Thus it can be seen there are several different, though similar, reactions which are regarded as partial oxidation. The generally accepted layout of a fuel processor is as shown below[113]:

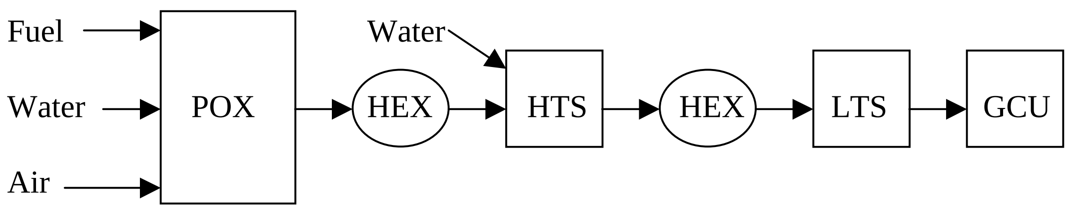

Figure 7.6: Likely Layout of Gasoline / Diesel Fuel Processor

This layout is designed specifically for use with low temperature fuel cells, and may operate at pressures up to 4 bar[113]. Here, water (via steam generator), fuel and air (pre-heated) are fed into the partial oxidation (POX) unit. This operates at around 800°C and produces a hydrogen rich gas stream that also contains a significant quantity of carbon monoxide. Heat exchangers (HEX) are required to lower the temperature for subsequent stages. The High Temperature Shift (HTS) reactor operates at around 400°C and the Low Temperature Shift

(LTS) reactor operates at around 200°C. The shift reactors are required to remove high levels of carbon monoxide. The gases are then fed to a Gas Clean-up Unit (GCU) which also operates at around 200°C, and removes the majority of remaining impurities such as sulphur compounds before the gas is fed to the cell stack.

There are several different ways to catalyse the POX reaction. One way is to utilise a substrate and a promoter. The substrate participates in the oxidation of the carbon, while the promoter dehydrogenates the hydrocarbon[110].

The shift reactors convert the majority of the carbon monoxide and steam to yet more hydrogen and carbon dioxide. The high temperature reactor might be expected to contain an iron / chromium compound, whilst the low temperature reactor might contain a copper / zinc based catalyst.

Desulphurisation can be achieved by the use of several different catalysts. Current leading technologies include active carbon or zinc oxide beds.

An example of a fuel processor was developed by Epyx Corporation, which was designed to supply a 10 kW_e stack with reformed fuel from gasoline or ethanol. The processor encompassed the reformer, CO clean-up device, the steam generator and the air pre-heater, and had the following technical specification[114]:

Operating pressure:	3 atmospheres	
Reformer thermal I/p:	45 kW	
Processor diameter:	12”	(305mm)
Processor height:	18”	(457mm)
Processor weight:	125lb	(57kg)
Hydrogen production:	55 – 115 SLMP	
Transient response:	0.9 kW/sec	
CO level:	<10 ppm at firing rates up to 35 kW_{th}	

Another system has been developed by the Argonne National Laboratory[115]. This system reforms gasoline at around 750°C with the following technical specification:

H_2 concentration:	38% dry basis
CO concentration:	10%
H_2 production rate:	40 L / min.[110]
Catalyst volume:	1.7 L
Catalyst weight:	2.2kg
Electrical capacity:	3 kW_e
Start-up performance:	30% hydrogen in <150 seconds

7.6.2 Natural Gas Fuel Processor

Natural gas is an easier fuel to reform than gasoline or diesel considered previously. The following diagram shows the typical route used in natural gas reforming:

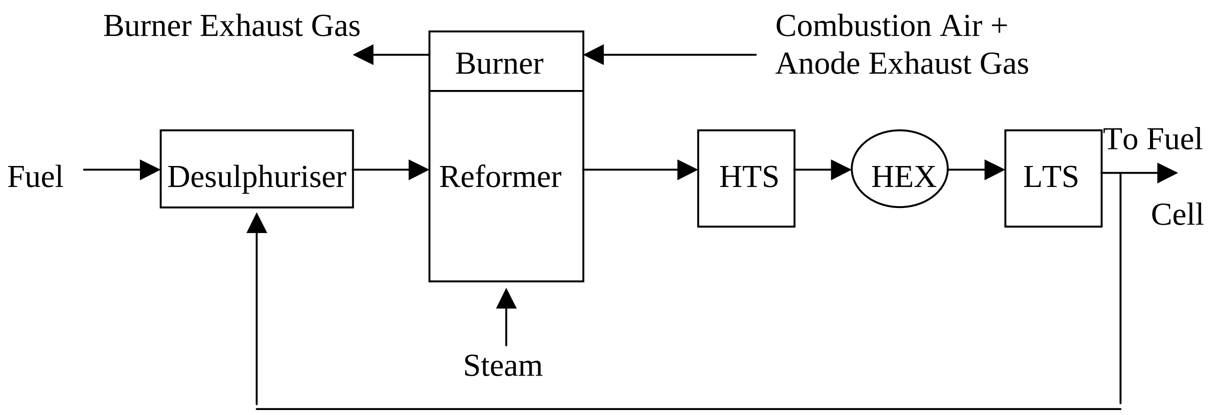

Figure 7.7: Likely Layout of Natural Gas Fuel Processor

Here the raw fuel is fed into the desulphuriser first. Typically the natural gas would be compressed and heated before entering a desulphuriser. The desulphuriser would probably contain a zinc oxide adsorbent, which becomes transformed to zinc sulphide when fully saturated. If the natural gas contains non-reactive sulphur compounds such as thiophene, or larger amounts of reactive organic sulphur compounds, a hydrodesulphurisation catalyst is needed prior to the zinc oxide bed. An alternative method of removing the sulphur uses an activated carbon bed.

The desulphurised gas is then mixed with superheated steam and fed into the fuel processor, or steam reformer, typically containing nickel based catalysts. Here, the methane is reformed in an endothermic reaction to form a hydrogen and carbon monoxide mixture. Shift reactors, then convert the majority of the carbon monoxide and steam to yet more hydrogen and carbon dioxide. The high temperature reactor might be expected to contain an iron / chromium compound, whilst the low temperature reactor might contain a copper / zinc based catalyst. A recent report quoted the use of the following catalysts[116]:

Table 7.1: Typical Catalysts Used in Reformers and Shift Reactors

Process	Typical Catalyst
Steam Reforming	$Ni/CaO/Al_2O_3$
High Temperature Shift Reactor	Fe_3O_4/Cr_2O_3
Low Temperature Shift Reactor	$Cu/ZnO/Al_2O_3$

7.7 Sub-Models of Cell Stack Assemblies

This section looks at sub-models for three different stack types. These are SOFC, PEM and DMFC stack assemblies.

7.7.1 SOFC Cell Stack Assembly

The stack assembly considered here is one that is being supplied initially by gasoline, and as such utilises a separate fuel reformer beforehand to produce a hydrogen rich gas stream. Therefore this type of stack does not utilise internal reforming.

The hydrogen rich gas stream is fed into the anode side of the fuel cell stack, with oxygen in the air fed into the other side of the solid electrolyte. The electrolyte is a ceramic material that is based on zirconium oxide, which is typically stabilised using yttria. In this model, oxide ions travel though the electrolyte, combining with the hydrogen to produce steam. The reverse flow of electrons through the electrolyte can then be collected, giving the DC power supply from the stack.

The module itself would consist of the SOFC array, the reactant distribution piping, the required thermal insulation and the power connections. SOFC electrolytes are usually tubular or planar in design. The following table gives examples of materials that have been used in tubular technologies:

Table 7.2: Materials Used in Tubular SOFCs

	Siemens-Westinghouse[117]	**Mitsubishi Heavy Inds.[118]**
Fuel Electrode	Ni-$ZrO_2(Y_2O_3)$	NiO / YSZ
Electrolyte	$ZrO_2(Y_2O_3)$	YSZ
Air Electrode	Doped $LaMnO_3$	$LaCoO_3$
Interconnector	Doped $LaCrO_3$	NiAl / Al_2O_3

The following are the design specification attributes that would be typical:

Operating Temperature:	800 - 1000°C
Stack Power Density:	1 kW/kg[111]
	0.9 kW/L[111]
Operating Pressure:	Atmospheric (up to 5 bar for larger sizes)
Sulphur Tolerance:	At least 10 ppm

7.7.2 PEM Cell Stack Assembly

The electrolyte is a solid polymer material, and has traditionally been based on perfluorinated sulphonic acid membranes, such as Nafion. The catalyst used is predominantly platinum.

For several years, conventional PEM fuel cell bi-polar plate technology used machined graphite plates that were heavy, expensive and large. Accordingly, much research has been focussed on lightweight, low-cost bi-polar plates that will not require machining and can tolerate fuel cell corrosive operating conditions. The current leading technologies for bi-polar plate designs include: injection moulded carbon-polymer composites, injection moulded and carbonised amorphous carbon, assembled 3-piece metallic and stamped unitised metallic[119].

Individual cells are connected electrically in series, to form a stack. This raises the DC voltage to a level that can be converted directly to the AC level desired, avoiding the need for an additional DC booster. The main parasitic loss associated with a PEM fuel cell system is the loss due to air compression. The compressor may take around 20% of the fuel cell stack power[116]. Using a turbine expander to recover waste energy may reduce losses significantly, but this would be likely to raise the capital cost of equipment further. Such moves cannot be incorporated economically on smaller plant (say <50 kW_e).

One of the main issues for PEM fuel cell reliability is the water (and thermal) management system. An example of this, including air management, is shown below[120]:

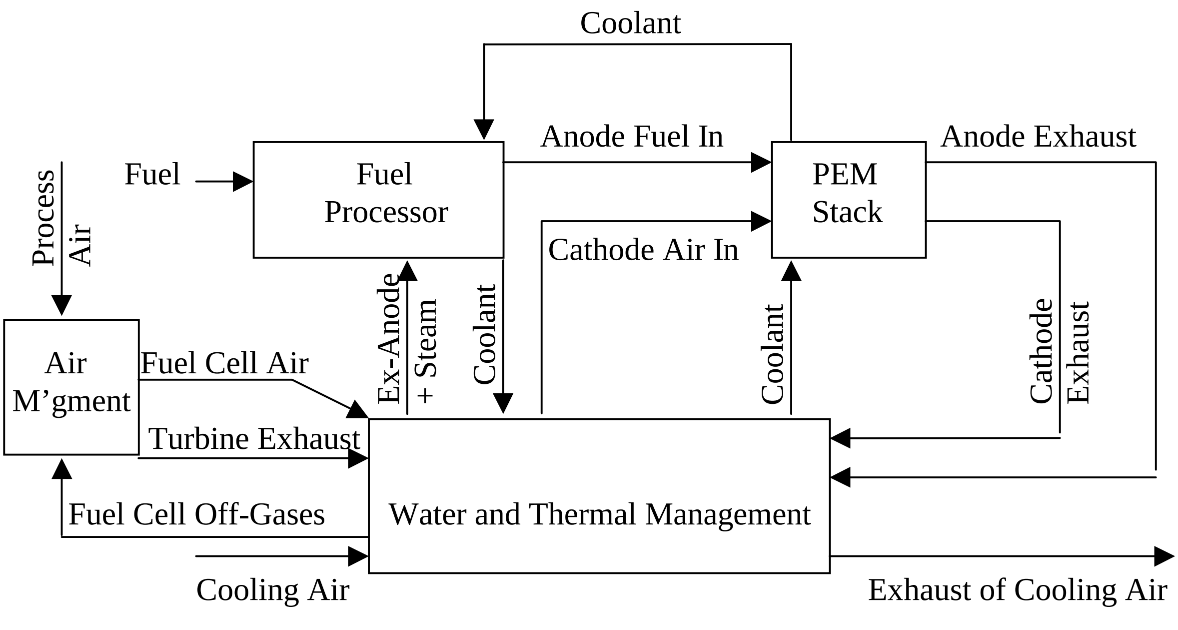

Figure 7.8: Functional Block Diagram of PEM Fuel Cell System

Such a system incorporates numerous fans and pumps. These are required to operate constantly during operation, often in hot or mildly corrosive conditions. Naturally, the reliability of these auxiliaries should be ensured as far as possible, within the acceptable capital cost bounds.

The following design attributes have been recently judged to be achievable for a PEM fuel cell system[116]:

Overall Efficiency:	80%
Hot Water Temp.:	80°C
Electrical Efficiency:	40% LHV
Footprint:	12 m^2 (250 kW)
Volume:	29m^3 (250 kW)
Weight:	12 tonnes (250 kW)
Emissions	
- CO	10-12 mg m^{-3}
- NO	3-5 mg m^{-3}
- HC	10 mg m^{-3}
- SO_x	Negligible
Availability:	95%
Life:	40,000 hours between major overhauls
Maintenance Cost:	0.8p / kWh_e at 100kW size

7.7.3 DMFC Cell Stack Assembly

The DMFC can initially be seen to have many similarities with the PEM fuel cell. A typical design might consists of a Pt-Ru-carbon catalyst anode and a Pt black anode, on either side of a solid polymer electrolyte, such as Nafion. However, one recent design has replaced the machined graphite hardware by non-machined flow-field/bipolar plates, enabling effective air and aqueous methanol solution distribution[121]. In the overall reaction, a direct mixture of methanol and water is transformed to form carbon dioxide, protons and electrons. The protons are conducted through the organic membrane to another platinum catalyst, where they combine with oxygen from the ambient air to form water. Some of this water is recycled back to mix with the methanol, while the excess evaporates into the air.

Storage in liquid form is an important advantage of methanol over hydrogen for portable power applications. The effective energy density of methanol, assuming a DMFC voltage of 0.5V (typical design point) and 90% fuel efficiency, is 2.25 kWh kg^{-1} [121].

Such small fuel cells must operate at relatively ambient pressure and at around room temperature. Also, the methanol concentration must typically not exceed 1 mole L^{-1}. A larger unit of 50W operating at around 60°C has displayed the following characteristics[121]:

Current Density:	150 $mAcm^{-2}$
Cell Voltage:	0.4V
Max. Power Density:	0.2 kW L^{-1}
Energy Density:	200Wh kg^{-1}

7.8 Sub-Model of Power Conditioning Equipment

Of the prime areas considered, the power conditioning equipment here refers primarily to the area of premium power, as the majority of applications considered can use DC power directly. Premium power, however, requires high quality AC power as shall be considered in this section.

The power conditioning sub-system contains several sub-components, as shown below in Figure 7.8. Here it assumed that a voltage booster will not be required to boost the fuel cell DC supply voltage to that required by the inverter, as the stack would have been sized to the requirements for 3 phase voltage. An earlier study has shown that power conditioner efficiencies of around 98% can be achieved if the fuel cell can be configured to provide a voltage high enough to preclude the use of a booster[116].

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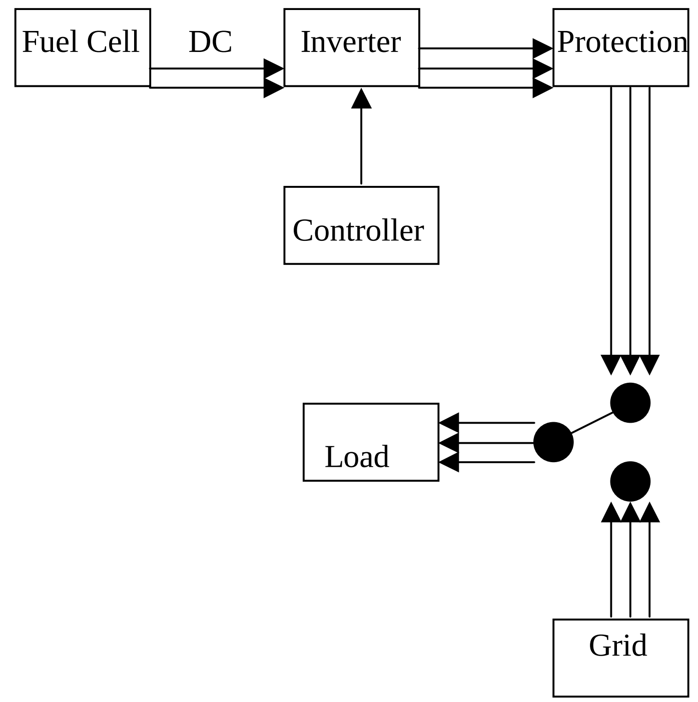

Figure 7.8: Typical Power Conditioner Arrangement

Power supply will generally either be at single phase, 230V AC, or at 3 phase, 400V AC throughout the UK and Europe. Systems of the size required for premium power are most likely to generate at 3 phase, with a voltage tolerance of ±10%. MW-class systems are expected to generate at 11kV, exporting to sub-stations directly. Frequency synchronisation to 50 Hz should be within +1% to –6%, as specified in the G59/1 Guidelines[122].

Other areas of prime importance for power conditioning equipment connected to the grid are harmonics, power factor and DC injection. These are covered in the following sub-sections, and refer directly to information from the G77 Guidelines[123] for the grid interconnection of photovoltaic plant (solid state electronics) under 5 kW.

7.8.1 Harmonics

Harmonics can be viewed as a form of electrical pollution on the distribution network since they provide no useful benefits, but their existence can interfere with the correct operation of certain types of systems connected to the network. Excess harmonics can also result in network plant having to be operated at reduced ratings. Thus, it is in the interest of both Distribution Network Operator (DNO) and consumers alike to minimise the levels of harmonics present on the network.

7.8.2 Power Factor

"Useful work" is only done by the "real" part of the power (the residential meter measures only "real" power). So, since for a sustained island to occur there needs to be a match of both real and reactive power components, restricting grid connected residential inverters to only exporting real power dramatically reduces the chances of the necessary conditions for islanding being met. This is why the technical guidelines document restricts inverters to export between unity power factor and 0.95 leading (i.e. importing VArs). Note, this refers to reactive current exported to the network, and does not restrict the inverter from supplying reactive power to the loads within the same premises as the residential generator. However, the simpler inverter designs (for smaller systems) are not likely to be able to distinguish between power exported to the network and power taken by the load. In this case, the inverter output will be restricted to operate between unity power factor and 0.95 leading.

7.8.3 DC Injection

The purpose of the electricity distribution network is to distribute electrical power at 50Hz AC. The presence of anything else on the network, such as harmonics, transients and DC is therefore regarded as pollution. However, current standards make no reference to DC other than to say its presence is not approved. This effectively says that DC should be zero. This requirement can be easily met if all connections to the network are made to linear devices (such as resistors, capacitors or inductors) or via a transformer. However, with the development of modern power electronic devices it is possible to design inverters whose power devices can interface directly to the electrical network. This can remove a costly component from the inverter design, but it does mean that there is likely to be some residual DC output component from the inverter, however small. Thus, in the absence of a defined limit for DC within existing standards, technical guidelines state a maximum value of 5mA DC for a single installation for systems below 5 kW. This is in line with limits set for harmonic currents and is less than the sensitivity levels used in RCD protection devices (typically 25mA AC).

8. Initial Environmental Assessments

This section gives an initial environmental assessment of the likely environmental benefits of fuel cell systems in comparison with their conventional power source alternatives. The section is split into two main sub-sections:

- Manufacturing, replacement and disposal impacts
- Routine operational impact

The former area looks at any environmental issues from the materials involved in the construction of the fuel cell, its associated equipment and the current technology. In particular the benefits and disadvantages that may accrue from the avoidance or use of specific toxic materials are addressed in comparison to conventional power sources. Section 8.1 and 8.2 identify the impacts of replacing the principal competitive power source with fuel cells, with respect to the materials used in construction. Therefore, the power sources are listed first in section 8.1, followed by the material implications in section 8.2.

The latter area (routine operational impact) looks at the different levels of routine emissions from a fuel cell and the current technology that it might replace. This is covered in section 8.3, and fuel infrastructure is also covered as appropriate. Section 8.4 summarises the findings.

8.1 Impact of Use of Materials – Power Sources

The niche markets considered are listed in table 8.1 with the likely fuel cell, the main conventional competitor, the fuel cell fuel of choice and the world-wide sales of conventional technology units. The table summarises earlier information needed for section 8.2.

Table 8.1: Niche Market Fuel Cell Types and Fuels

Market	Fuel Cell Type(s)	Conventional Technology	Fuel Cell Fuel	World-wide Market (Units sold / yr.)
P'table electronics - Cellular phones - P'table computers - Video cameras	 DMFC DMFC DMFC	 Li-ion Li-ion Li-ion	 Methanol Methanol Methanol	 300 million units 19 million units 62 million units
UPS	PEM	Lead-acid	Hydrogen	1.2 million (small) 0.8 million (large)
Navigational aids	PEM (DMFC)	Diesel, mains, battery, solar and wind	Natural gas, hydrogen, methanol	100,000 total 20,000 – 40,000 / yr.
Medical Applications	PEM (DMFC)	Non-rechargeable, Ni-Cd / Li-ion	Hydrogen, methanol	$650 million and $450 million
Power Tools	PEM	Ni-Cd	Hydrogen	$6,400 m Approx. 30 m tools.
Television Outside	PEM or	Ni-Cd	Hydrogen,	Negligible.

Broadcast	(DMFC)		methanol	
DC Power Supplies for Traction	PEM / (SOFC)/ (MCFC)	Mains electricity and rectification	Natural gas	Unlikely to be an early market
Premium Power	PEM	IC engine / lead-acid	Natural gas	$1 billion
Stand-by Power	PEM + methanol (or H_2)	Diesel generator	Natural gas, hydrogen	N/A
Portable Power	PEM	Diesel and gas engines	Hydrogen	385,000 units, Capacity: 34800MWe
Chemical Industry	MCFC, PAFC or PEM	Normally flared	The gas normally flared	600 MWe available from Chlor-alkali
Coal Gasification	MCFC	IGCC	Coal	Few plants
Marine Auxiliary Power	PEM / (SOFC) / (MCFC)	Diesel generators	Diesel	1000 units
Low to Medium Power Personal Transport	PEM	Lead-acid Lead-acid Lead-acid 60% Petrol IC 40%	Hydrogen, methanol	- 300,000 power assisted bicycles - 300,000 invalid carriages - 250,000 golf carts
Auxiliary Power	SOFC and (PEM)	Gas turbine Alternator Alternator	Aviation fuel Diesel, H_2 Gasoline	900 aircraft 125,000 coaches 5 million luxury cars
Mechanical Handling and Industrial Vehicles	PEM	Lead-acid or IC engines	Hydrogen	300,000 units / yr.
Ground Support Equipment	PEM	Lead-acid or IC engines	Hydrogen	$300 million annual sales of power source c. 300,000 kW/yr.
Education	PEM	N/A	Hydrogen	250,000 /yr.
Leisure - Boating - Garden Equip.	 PEM PEM	 Diesel Gasoline/ mains	 H_2, (diesel) H_2, (methanol)	 2m kW / yr. 20m kW / yr. (50/50)

The overall comparison can be simplified according to scale. The following section, 8.2, places each application in a like category as determined by size, fuel cell type and the conventional technology replaced.

8.2 Impact of Use of Materials – Material Implications

This section will be sub-divided as follows:
8.2.1 Portable Electronics and Education
8.2.2 Small / Medium PEMs for Battery Replacement
8.2.3 Small / Medium PEMs for IC Engine and Mains Electricity Replacement
8.2.4 Larger Applications

8.2.1 Portable Electronics and Education

The market has been judged to consist of:

• Cellular phones	300m units/yr.	rated at 4W
• Portable computers	19m units/yr.	rated at 90W
• Video cameras	62m units/yr.	rated at 22W
• Education	250,000units/yr.	rated at 100mW

This would require a total of 4.3GW of direct methanol fuel cell capacity to be built each year, replacing the conventional technology of rechargeable batteries. The education market is very small by comparison, and as such, the additional environmental impact of the materials used is judged to be negligible.

A direct comparison between fuel cells and batteries cannot be entirely accurate, as fuel cell outputs are measured in Watts, whilst batteries are usually restricted by storage or Ampere hours (Ah). However, to compare materials used, power output (Watts) will be used.

The portable electronics market has been identified as being most suitable to being supplied by DMFCs. Here lithium-ion batteries are the power sources most likely to be replaced by DMFCs. The use of Ni-Cd batteries has already largely been phased out due to the long-term toxicity of the cadmium, with its replacement, NiMH already being largely displaced by Li-ion. The comparison carried out here is therefore with Li-ion batteries.

Lithium-ion batteries [124] contain lithium cobalt oxide as the active layer in the positive electrode, carbon in the negative electrode and an organic solvent. Both lithium and cobalt are commonly occurring metals and should pose little direct environmental hazard. Indeed, cobalt has been used for colouring glass for 4000 years and is also a vital trace element in animal nutrition.

Methanol fuel cells contain no environmentally sensitive materials. As mentioned in section 7, the DMFC is relatively similar in principle to the PEM, employing a solid polymer membrane, but an additional material to platinum is used in the catalyst material, ruthenium. Ruthenium is a highly flammable metal in powder form emitting toxic fumes during combustion. However, it should not be viewed as posing any direct environmental hazard.

Extraction & Supply Issues: There would not appear to be any significant issues from the extraction and supply of materials, primarily due to the small size of the fuel cells involved. The main material used would be the fuel, methanol. As shown in section 8.3, it is anticipated that methanol powered portable electronics could consume 4TWh of power per year from methanol (calorific value). This equates to around 800 million litres or almost 700,000 tonnes per year of additional capacity required from the existing infrastructure.

Manufacturing Issues: As mentioned in section 2.1, a fuel cell for portable electronics has already been developed with an energy density of over 10 times that of conventional rechargeable batteries. Measuring 25mm x 25mm x 2mm, a cellular phone fuel cell would consume minimal amounts of material. It is therefore anticipated that fuel cells in portable electronics should give a significant overall reduction in the quantity of raw materials used.

End of Life Disposal Issues: As the use of toxic materials is not anticipated in fuel cells for portable electronics, there are not anticipated to be any significant disposal issues. With the current moves to encourage the recycling of all electronic equipment, the recycling of small fuel cells will doubtless need to be addressed. Naturally, some interest will focus on the recovery of the platinum used, though the amounts used are likely to be measurable in milligrams only. Therefore, recovery might only be economic if fuel cells were stripped out of old appliances and recycling performed in bulk quantities.

8.2.2 Small / Medium PEMs for Battery Replacement

This section includes the following product areas:

• UPS	2m units/yr.	rated at 10kW (av.)
• Medical Applications	N/A	
• Power Tools	30m units/yr.	rated at 25W (est. av.)
• TV & Outside Broadcast	N/A	
• Personal Transport	0.3m units/yr.	rated at 250W (av.-bicycle)
	0.3m units/yr.	rated at 600W (invalid carriage)
	0.25m units/yr.	rated at 4kW (golf carts)
• Mech. Handling / Ind.	0.3m units/yr.	rated at 5kW
• Ground Support Equip.		300,000 kW/yr.

For this section of the report, the areas of medical and TV / outside broadcast have been considered too small to be of significance. The remaining categories could collectively necessitate the production of up to around 14 GW of PEM fuel cell capacity, the majority of which would be for the UPS market. The fuel for the PEM fuel cell would probably be bottled hydrogen and the conventional technology to be replaced is generally the rechargeable lead-acid battery. The power tool battery to be replaced is likely to be the lithium-ion battery.

Extraction & Supply Issues: The units considered are larger units than before, up to 10 kW. Once again, there would not appear to be any significant issues from the extraction and supply of materials. Using bottled hydrogen, no gas clean-up catalysts would be required, with the only catalyst used the platinum in the fuel cell stack. The main supply issue would be the supply of the fuel, bottled hydrogen. Whilst some infrastructure exists, around 80 TWh of hydrogen could be consumed per year, equating to around 22 billion m^3 at standard temperature and pressure (STP). The source of this hydrogen would either be natural gas, or it could be generated from renewable sources, such as wind power, using electrolysis. Apart from this, the main environmental gain would be the reduction in use of lead from the replacement of lead-acid batteries.

Manufacturing Issues: As these PEM fuel cells are anticipated to replace largely lead-acid batteries, it is likely that there should be an overall reduction in the quantity of raw materials used. The main issue is the reduction in the amount of lead used. Assuming lead-acid batteries have an energy density of around 30 Wh/kg (taken from table 4.15), and the replacement market is around 35 TWh (table 8.6), this would amount to a reduction in the amount of lead-acid batteries produced of 1.2 billion tonnes. Clearly this is a significant issue.

End of Life Disposal Issues: As the use of toxic materials is not anticipated in PEM fuel cells for battery replacement, there are unlikely to be any significant disposal issues. Again, some interest will doubtless focus on the recovery of the platinum used, as the amount used per unit is likely to be measurable in grams. Current platinum loadings, reducing through 1 g/kW [125], would indicate that recovery would probably still be economic.

8.2.3 Small / Medium PEMs for IC Engine and Mains Electricity Replacement

This area generally covers PEM fuel cells replacing non-battery applications. As such, the applications tend to be larger. The applications are listed below:

• Navigational Aids	N/A	-	
• Premium Power	$1billion market	8 TWh	around 1 GW_e
• Stand-by Power	N/A	-	
• Portable Power	0.4m units/yr.		35 GW_e
• Coach APU	125,000 units/yr.	rated at 10 - 15 kW	1.6 GW_e
• Car APU	5m units/yr.	rated at 5kW	25 GW_e
• Boating			2 GW_e
• Garden Equipment			20 GW_e

For the purposes of this section, the areas of navigational aids and stand-by power have been considered too small or too inaccessible to be of significance. The remaining categories could collectively necessitate the production of over 80 GW of fuel cell capacity. Of this, almost 60 GW would be PEM fuel cells, whilst the balance might be SOFCs for APUs. The fuels used require further explanation, so table 8.2 below lists the relevant data:

Table 8.2: Small / Medium PEMs for IC Engine and Mains Electricity Replacement

	Fuel Cell Type	Fuel	Total Capacity [GW]
Premium Power	PEM	Natural Gas	1
Portable Power	PEM	Hydrogen	35
Coach APU	SOFC (PEM)	Diesel / Hydrogen	1.6
Car APU	SOFC (PEM)	Gasoline	25
Boating	PEM	Hydrogen (Diesel)	2
Garden Equipment	PEM	Hydrogen (Methanol)	20

As can be seen from the table above, the majority of the applications by capacity are for hydrogen fuelled PEMs. The remainder are largely SOFCs, with 1GW of natural gas fuelled PEMs. These technologies largely replace IC engines, alternators and some network electricity.

Extraction & Supply Issues: The units considered are mostly sized up to 10 kW, with some portable power units sized up to 200 kW and premium power units up to 1 MW. Once again, there would not appear to be any significant issues from the extraction and supply of materials. Using bottled hydrogen, no gas clean-up catalysts would be required, with the only catalyst used the platinum in the fuel cell stack. For those units not running on hydrogen, gas clean-up, reformer and shift reactor catalysts are required as detailed in section 7. The catalysts generally consist of common metals and oxides, though the use of chromium, a heavy metal, can be required in the high temperature shift reactor.

The main supply issue would again be the supply of the fuel. In particular, the portable power industry could use over 700 TWh per year of bottled hydrogen, dwarfing the other categories considered so far. This would require additional infrastructure for an additional capacity of over 200 billion m^3 per year (at STP) which is clearly a major issue.

Manufacturing Issues: As these fuel cells are anticipated to replace largely IC engines, it is more useful to anticipate the types of materials replaced, rather than the quantities. Clearly there would be a reduction in use of materials such as steel and aluminium used in constructing engine blocks and cylinder heads. There would also be the elimination of engine oil, though anti-freeze in coolant may well be required in most fuel cells.

Major increases in manufacturing materials would cover supplies of stacks, catalysts and power electronics, with fans, pumps and heat exchangers also in demand. Use of stainless steels might also increase. For SOFCs using yttria, it should be noted that it is a hygroscopic substance, classed as harmful. Once incorporated into the zirconia as a solid, it should be considered as a ceramic material. In all, there are no particular toxicity issues anticipated.

End of Life Disposal Issues: The main issue is the disposal of catalysts, particularly in the shift reactors. It should be noted that these catalysts, which are likely to be iron/chromium and copper/zinc based (see section 7.6), react strongly with air giving a highly exothermic reaction. Consequently, these may require specialist disposal, involving gradual oxidation. It should also be noted that any chromium used in the high temperature shift reactor should not be committed to landfill. The recovery of platinum used in PEM fuel cells would probably still be economic, though recycling of SOFC fuel cell stacks would not.

Another disposal issue is that of any water treatment resins or other materials required. PEM fuel cells in particular will require regular disposal of materials used to filter and sometimes de-ionise water. Such materials are already dealt with by an established water treatment industry.

8.2.4 Larger Applications

The larger applications cover the following areas:

- DC for Traction — Not an early market
- Chemical Industry — Not an early market
- Coal Gasification — Not an early market
- Marine APUs — 1000 units/yr. rated at 5 – 10 MW
- Aircraft APUs — Not an early market

Many of these larger applications have been deemed unsuitable for early market penetration. However, one exception is marine auxiliary power. Whilst there would only seem to be potential for 1000 units per year, they would be rated generally at the Megawatt scale, giving an annual capacity build of 5 to 10 GW. This could be made up of PEM fuel cells, SOFCs or MCFCs, depending on emerging technologies. There may however be concerns about using molten carbonates at sea, and solid electrolytes may be preferred. At this scale, high temperature fuel cells may well be pressurised and integrated with expansion turbines to raise efficiency. This would either reduce fuel load or extend range.

Extraction & Supply Issues: There would not appear to be any significant issues from the extraction and supply of materials, primarily due to the low numbers of fuel cells involved. The main issue is likely to be fuel, as fuel cell units would need to compete with large diesel IC engines. In particular, section 8.4 shows this market to provide the largest market for the use of fuel at 1900 TWh, partly due to long operating hours and long unit lifetimes. This does highlight the potential for supply of replacement modules throughout long lifetimes to increase manufacturing capacity. Also if this fuel cell market were to accelerate, there would doubtless be a push for cleaner diesel to reduce fuel processor maintenance.

Manufacturing Issues: There are no major manufacturing issues, due to low unit numbers. Indeed, manufacturing is likely to be far less of an issue than fuel. Otherwise manufacturing issues are as covered in section 8.2.3. Another issue is that at these low manufacturing levels, orders would be likely to arrive at irregular periods, providing considerable uncertainty for manufacturers, as is frequently seen in the ship building industry.

End of Life Disposal Issues: Disposal will be influenced by the means of disposal of the ship. Currently ships are supplied to breakers for scrap, and they would need to be educated to the best means of disposal of the fuel cell power plant. Current legislation puts the onus on the fuel cell manufacturer to supply this information when supplying the equipment originally. However, vessels can change hands many times, so contact details should be stamped on the equipment.

Other disposal issues are as covered in section 8.2.3.

8.3 Routine Operational Impact

This section looks at the routine operational impact of operating fuel cells in the niche markets considered. Therefore this section will be sub-divided as follows:

8.3.1 Power Outputs
8.3.2 Efficiencies
8.3.3 Fuel Logistics and Supply
8.3.4 Emissions

8.3.1 Power Outputs

The niche markets considered are listed in table 8.4 together with the likely fuel cell, the power consumed by the appliance, an approximate energy output per annum and the number of world-wide sales. Numbers used throughout consider 100% penetration rates into conventional markets, at the current size of those markets.

Table 8.3: Table of Energy Usage

Market	Fuel Cell Type(s)	Power (In) Consumption & Time Used	Energy Out [kWh/yr.]	World-wide Market (Units sold / yr.)
P'table electronics - Cellular phone - P'table computer - Video camera	 DMFC DMFC DMFC	 3Wh/day 25W for 15m/day 22W for 4m/day	 1.1 2.3 0.5	 300 million units 19 million units 62 million units
UPS	PEM	0.6% in 48hrs 0.6% in 48hrs	3 (at 3kW) 20 (at 20kW)	1.2 million (small) 0.8 million (large)
Navigational aids	PEM (DMFC)	10W always (max.)	90	100,000 total 20,000 – 40,000/yr.
Medical Apps.	PEM	Low use only	Insignificant	
Power Tools	PEM	Low use only	Insignificant	$6,400m - 30m tools
Television Outside Broadcast (camera / OBU)	PEM or (DMFC)	6 hrs / day	50W - camera, 10 to 25kVA for an OBU	Negligible.
DC Power Supplies for Traction	PEM / (SOFC)/ (MCFC)	N/A	N/A yet	Unlikely to be an early market
Premium Power	PEM	95% availability	1 kW to MWs	$1 billion / 1 GW
Stand-by Power	PEM	Irregular use	N/A	N/A
Portable Power	PEM	90kW 2.5hrs/day	82,000 input	385,000 units, Capacity: $35GW_e$/yr.
Chemical Industry	MCFC, PAFC or PEM	N/A	N/A	600 MWe available from Chlor-alkali
Coal Gasification	MCFC	$500MW_e$		Few plants
Marine Auxiliary Power	PEM / (SOFC) / (MCFC)	5MW - 10MW 200 days	36 GWh/yr.	1,000 units

Market	Fuel Cell Type(s)	Power (In) Consumption & Time Used	Energy Out [kWh/yr.]	World-wide Market (Units sold / yr.)
Low to Medium Power Personal Transport	PEM	150W - 400W : 15 m/day 200W - 600W : 3 hrs/day 3kW - 4kW : 4 hrs/day	23 440 5100	- 300,000 power assisted bicycles - 300,000 invalid carriages - 250,000 golf carts
Auxiliary Power	SOFC and (PEM)	300kW - 1MW : 16hr/d 10-15 kW: 6hr/d 5 kW: 1hr/day	3.8 GWh/yr. 27,000 1,800	900 aircraft 125,000 coaches 5 million luxury cars
Mechanical Handling and Industrial Vehicles	PEM	~5kW: 4hr/day	7,300	300,000 units / yr.
Ground Support Equipment	PEM	5 to 300kW : Circa 3m kW in use 4hrs/day	4.4 TWh/yr. for TOTAL market	$300 million annual sales of power source c. 300,000 kW/yr.
Education	PEM	~100mW	N/A	250,000 /yr.
Leisure - Boating	PEM	0.5 -100kW 2m kW_{out} : 2hr/wk	0.21 TWh / yr.	
- Garden Equip.	PEM	up to 10 kW 20m kW_{out} : 15m/wk	0.26 TWh / yr.	

From this table, for the purposes of calculating emissions, several of the categories can be excluded either due to low annual use or poor market penetration being anticipated. These areas are:

- Medical Applications
- Power Tools
- TV Outside Broadcast
- DC Supplies for Traction
- Stand-by Power
- Coal Gasification
- Education

Having eliminated these categories, the following table lists the total energy usage for each remaining area:

Table 8.4: Appliance Energy Output

Market	Annual Energy Output / Unit [kWh/yr.]	Number of Units in Use / yr. (estimate)	Total Energy Output (Estimate/yr.)
Portable electronics - Cellular phones - Portable computers - Video cameras	 1.1 2.3 0.5	 1 billion 100 million 300 million	 1.1 TWh 230 GWh 150 GWh
UPS – large UPS – small	3 20	12 million 8 million	36 GWh 160 GWh
Navigational aids	90	100,000	9 GWh
Premium Power			8 TWh
Portable Power	82,000	4 million	330 TWh
Chemical Industry			5 TWh available
Marine Auxiliary Power	36,000,000	29,000	1000 TWh
Personal Transport - assisted bicycles - invalid carriages - golf carts	 23 440 5100	 1 million 1.5 million 1 million	 23 GWh 660 GWh 5.1 TWh
Auxiliary Power - aircraft - coaches - luxury cars	 3,800,000 27,000 1,800	 13,500 1.25 million 30 million	 50 TWh 34 TWh 54 TWh
Mechanical Handling & Industrial Vehicles	7,300	3 million	22 TWh
Ground Support Equipment			4.4 TWh
Leisure - Boating - Garden Equip.	 0.21 TWh/yr. 0.26 TWh/yr.	 10 x more units 10 x more units	 2.1 TWh 2.6 TWh

The figures for energy output are for output from the appliance itself. They make no allowance for unit efficiency or power storage / conversion efficiency. This is covered in the following section.

8.3.2 Efficiencies

This section considers the efficiencies of the fuel cell plant and the conventional plant to be replaced in the leading niche categories. The following table gives these efficiencies:

Table 8.5: Plant Efficiencies

Application	Fuel	Conventional Efficiency [%]	Efficiency with Fuel Cell [%]
Portable Electronics	Methanol	20	35
PEMs for Battery Replacement	Hydrogen	20	40
Portable Power	Hydrogen	25-30	45
Gardening / Boating	Hydrogen	30 / 25	40
Premium Power	Natural Gas	30-35	40
Coach APUs	Diesel	20-25	40
Car APUs	Gasoline	15	40
Larger Applications (Marine APU)	Diesel	35-40	40-65

Notes:
Portable Electronics: These units are powered originally from network electricity, with a fuel efficiency after transmission and distribution losses of around 40%. Figures from a 1998 report [126] indicate an efficiency of 36.4%, likely now to be rising to 40%. Portable electronics chargers can be particularly inefficient, especially after considering idling time, operating at around 40 to 60% efficiency. Battery operating efficiencies at around 90% give an overall fuel efficiency of around 20%.
PEMs for Battery Replacement: Conventional efficiency as for portable electronics.
Portable Power: The size range considered is mostly for units in the range 1 – 75 kVA. At this size, the diesel generating sets are likely to be 25-30% efficient.
Gardening / Boating: The size of units in this category is from hundreds of Watts to around 10 kW. Conventional gardening equipment is either mains powered (around 40% efficiency) or gasoline powered (around 15-20% efficiency). An average of around 30% is taken for this simple analysis. Boating for leisure generally uses diesel power for propulsion or auxiliary power. These can be assumed to be around 25% efficient.
Premium Power: This area would largely use natural gas or diesel IC engines or perhaps some lead-acid batteries. Efficiencies of 30-35% can be assumed.
Coach APUs: These would replace alternators powered from diesel engines. Diesel engines can perform at efficiencies of up to 35% at this scale, but this assumes optimal running conditions. In reality, coach diesel engines run at around 28-30% efficiency [127] over a wide engine speed range, giving a combined system efficiency at the alternator of 20 – 25%.
Car APUs: Gasoline fuelled engines are inherently less efficient than diesel engines. In new cars, engine efficiencies of around 25% at the crankshaft are to be expected [128], giving an electrical efficiency at the alternator of around 16-20%.
Marine APUs: The conventional technology replaced here is the diesel IC engine. At the Megawatt scale, efficiencies of 35-40% can be expected.

8.3.3 Fuel Logistics and Supply

The following table gives a summary of fuel consumption in larger applications:

Table 8.6: Fuel Consumption in Primary Markets

Application	Fuel Cell Fuel	Energy Out [TWh]	Conven-tional Effic-iency [%]	Fuel Currently Consumed [TWh]	Fuel Cell Effic-iency [%]	Fuel Consumed by Fuel Cell [TWh]
Portable Electronics	Methanol	1.5	20	7.5	35	4.3
PEMs for Battery Replacement	Hydrogen	32	20	160	40	80
Portable Power	Hydrogen	330	25-30	1200	45	730
Gardening / Boating	Hydrogen	4.7	30/25	17	40	12
Premium Power	Nat. Gas	8	30-35	25	40	20
Coach APUs	Diesel	34	20-25	150	40	85
Car APUs	Gasoline	54	16-20	300	40	135
Larger Applications (Marine APU)	Diesel	1000	35-40	2700	40-65	1900

What can be seen from the table above is that marine APUs could collectively consume more energy from fuel than all the other applications in total. The figures have been calculated using an electrical efficiency between 40% (for PEM units) and 65% (for SOFC units with expansion turbines). If however SOFCs integrated with expansion turbines were to become preferred, further considerable savings could be achieved.

Having identified these potential savings in fuel possible by using fuel cells, the table below summarises overall fuel increases or decreases.

Table 8.7: Total Annual Increase (+) or Decrease (-) in Fuel Use

Fuel	Increase [TWh]	Increase – Other Units	Comments
Hydrogen	820	230 billion m^3	Almost entirely for portable power
Methanol	4.3	700,000 tonnes	Portable electronics
Nat. Gas	-5	- 480 million m^3	Premium power only
Gasoline	-170	- 14 million tonnes	Car APU & half gardening
Diesel	-2100	- 170 million tonnes	Portable, marine, coach & boating
Network Electricity	-170	- 12 billion m^3 nat. gas - 26m tonnes coal - 0.8m tonnes fuel oil	Portable electronics, battery replacement and half gardening

These figures assume 37.5 MJm^{-3} for natural gas, 45 $MJkg^{-1}$ for gasoline, 44 $MJkg^{-1}$ for diesel and 20.7 $MJkg^{-1}$ for coal.

Estimated figures of primary energy used in network electricity generation for 1998 [129] indicate 35% of electricity was generated from coal, 31% from natural gas and 2% from oil. The balance was generated from nuclear or renewables. Assuming the 40% generation (at point of use) efficiency mentioned earlier, around 425 TWh of primary fuel would be required. This implies 130 TWh of natural gas would be saved, 150 TWh of coal and around 10 TWh of oil. Integrating these figures for network electricity into the primary fuel totals gives the following table:

Table 8.8: Revised Total Annual Increase (+) or Decrease (-) in Fuel Use

Fuel	Increase [TWh]	Increase – Other Units
Hydrogen	+820	+ 230 billion m^3
Methanol	+4.3	+ 0.7m tonnes
Nat. Gas	-58	- 12.5 billion m^3
Gasoline	-170	- 14m tonnes
Diesel / Fuel Oil	-2100	- 170m tonnes
Coal	-60	- 26m tonnes

From the above table it can be seen that there would be a large decrease in the use of most fuels due to the better fuel economy of these niche fuel cells. The exceptions would be the increases for the no / low carbon fuels of hydrogen and methanol. For hydrogen, clearly new infrastructure would be needed to meet demand. This would be achieved either by reforming natural gas or by electrolysis using off-peak renewable power. The latter route would give by far the greater environmental benefit.

The existing infrastructure for methanol has the capacity to supply around 9 million tonnes per year [130]. The potential increase of 0.7 million tonnes per year should easily be absorbed over time, requiring a total increase of capacity of up to 8%.

8.3.4 Emissions

This section looks at the routine operational discharges in terms of CO_2 and emissions in terms of CO, NO_x, SO_x, unburned hydrocarbons (UBHC) and particulates (PM). Again, only those categories where large quantities of fuel are consumed will be considered. The following table summarises the changes in fuel used and the resulting changes in CO_2 emissions:

Table 8.9: Emissions in Primary Markets

Fuel	**Increase [TWh]**	**Increase [units of fuel in]**	**CO_2 Emissions [m tonnes/TWh]**	**Increase (+) or Decrease (-) in CO_2 Emission [million tonnes]**
Hydrogen	+820	+ 230 billion m^3	N/A	N/A
Methanol	+4.3	+ 0.7m tonnes	0.167	+ 0.9
Nat. Gas	-58	- 12.5 billion m^3	N/A	- 23
Gasoline	-170	- 14m tonnes	0.238	- 40
Diesel / Fuel Oil	-2100	- 170m tonnes	0.315	-660
Coal	-60	- 26m tonnes		-76
TOTAL				798

Notes:
Hydrogen: The numbers for hydrogen are not applicable. It is presumed that the majority will be produced from off-peak renewable sources via electrolysis.
Methanol: It is assumed that the vast majority of all the carbon (0.26m tonnes) is converted to carbon dioxide. Calculations by molecular weight.
Natural Gas: It is assumed that the vast majority of all the carbon in the methane (approx. 8.3m tonnes methane) is converted to CO_2. Calculations by molecular weight.
Gasoline: Figures of 208.81g/km (of CO_2) and 3.16MJ/km were used to give 66g/MJ [131].
Diesel: 315g/kWh (of CO_2) was used [131].
Coal: Figures vary dependant on carbon composition of coal. Carbon content of 80% has been used, giving 21 tonnes of carbon. Calculations of CO_2 were done by molecular weight.
The figures in table 8.9 give the total potential for savings in CO_2 as around 800 million tonnes if the fuel cell niche markets considered achieve full market penetration world-wide.

This table shows a total saving of around 800 million tonnes of CO_2. The majority of this is due to a reduced use of diesel fuel, which is achieved from the portable power and marine APU markets.

The following table lists the non-CO_2 emissions per kilowatt-hour in the niche markets that would consume most fuel:

Table 8.10: Emissions per kWh in Primary Markets

Fuel	Fuels	NO_x [g/kWh]	SO_x [g/kWh]	CO [g/kWh]	UBHC [g/kWh]	PM [g/kWh]
Pt. Electronics	Methanol FC	0	0	0	0	0
	Network	0.907	0.333	0.45	0.169	0.001
PEMs for Battery Replacement	Hydrogen FC	0	0	0	0	0
	Network	0.907	0.333	0.45	0.169	0.001
Portable Power	Hydrogen FC	0	0	0	0	0
	Diesel IC	4.432	0.685	0.222	0.818	0.049
Gardening / Boating	Hydrogen FC	0	0	0	0	0
	D,Gsl,Nk	2.51	0.476	0.801	0.654	0.027
Premium Power	Nat. Gas FC	0.027	0.006	0.010	0.208	0.003
	Nat. Gas IC	1.246	0.006	0.996	0.405	0.001
Coach APUs	Diesel FC	0.021	0.005	0.001	0.202	0.000
	Diesel IC	4.432	0.685	0.222	0.818	0.049
Car APUs	Gasoline FC	0.021	0.005	0.001	0.202	0.000
	Gasoline IC	0.26	0.20	2.31	0.81	0.01
Larger Applications (Marine APU)	Diesel	0.024	0.005	0.005	0.205	0.001
	Diesel	4.432	0.685	0.222	0.818	0.049

Notes:
Network Electricity: Figures for emissions taken from ETSU report [132].
Conventional Gasoline Engine: Figures from ETSU report [133].
Conventional Diesel Engine: Figures from ETSU report [134].
Conventional Gas Engine: Figures from ETSU report [134].
Gardening/Boating Conventional Generation (D,Gsl,Nk): Weighted average of 50% diesel engine, 25% gasoline and 25% network electricity.
Direct Methanol Fuel Cell: Emissions other than steam and CO_2 have been presumed zero. Minute emissions are likely, but would be insignificant due to low operating temperatures. Hydrocarbon emissions may be of significance, but no figures are available.
Hydrogen Fuel Cell: Emissions other than steam and CO_2 have been presumed zero. Minute emissions are likely, but would vary dependent on hydrogen quality and would be insignificant.
Gasoline FC / Diesel FC: Fuel cell (FC) emissions taken as for standard SOFC [134].
Marine APU Diesel FC: Fuel cell (FC) emissions taken as half standard SOFC and half PAFC [134]. PAFC emissions assumed similar to PEM fuel cell emissions.
Premium Power FC: Fuel cell (FC) emissions taken as for PAFC [134]. PAFC emissions assumed similar to PEM fuel cell emissions.

The following table gives total non-CO_2 emissions for the leading niche markets:

Table 8.11: Emissions in Tonnes in Primary Markets

Fuel	Fuels	NO_x	SO_x	CO	UBHC	PM
Pt. Electronics	Methanol FC	0	0	0	0	0
	Network	6800	2500	3000	1300	8
PEMs for Battery Replacement	Hydrogen FC	0	0	0	0	0
	Network	145,000	53,000	72,000	27,000	160
Portable Power	Hydrogen FC	0	0	0	0	0
	Diesel IC	5.3m	820,000	270,000	980,000	59,000
Gardening / Boating	Hydrogen FC	0	0	0	0	0
	D,Gsl,Nk	43,000	8100	14,000	11,000	460
Premium Power	Nat. Gas FC	540	120	200	4200	60
	Nat. Gas IC	31,000	150	25,000	10,000	25
Coach APUs	Diesel FC	1800	425	85	17,000	0
	Diesel IC	660,000	100,000	33,000	123,000	7350
Car APUs	Gasoline FC	2800	675	135	27,000	0.000
	Gasoline IC	78,000	60,000	690,000	243,000	3000
Larger Applications (Marine APU)	Diesel	46,000	9500	9500	390,000	1900
	Diesel	12.0m	1.85m	600,000	2.21m	132,000
TOTAL	Fuel Cells	51,000	10,700	9900	440,000	2000
	Conventional	18.3m	2.9m	1.7m	3.6m	200,000
	Saving	18.2m	2.9m	1.7m	3.2m	200,000

From this table it can be seen that fuel cells can produce large reductions in emissions in the niche markets considered. It should also be noted that marine fuel cell APUs offer by far the largest reduction in emissions due to long operating life and long operating hours.

These niche fuel cells could reduce world-wide NO_x emissions by around 18 million tonnes, SO_x and hydrocarbon emissions by 3 million tonnes each and CO emissions by almost 2 million tonnes. This is in addition to the potential savings in CO_2 emissions of around 800 million tonnes, already identified.

8.4 Summary of Environmental Issues

Materials:

- There are few material concerns. High temperature shift reactors as used in low temperature fuel cells tend to contain chromium, a heavy metal. This should not be disposed of to landfill. Also, the catalysts in the shift reactors can strongly react exothermically exposure to atmosphere. Consequently, specialist contractors should dispose of shift reactors.
- Platinum may well be economically recoverable from low temperature fuel cells.
- PEM fuel cells for battery replacement could reduce the weight of lead-acid batteries manufactured by over 1 billion tonnes. This excludes any reduction in size of car batteries due to APUs.
- In materials for manufacture terms, by far the three largest markets are portable power (35GW), car APUs (25 GW) and garden equipment (20 GW). Portable power and garden equipment would both probable require hydrogen fuelled PEM fuel cells, whilst car APUs seem likely to be supplied by small SOFCs.

Fuel:

- There would be a large decrease in the use of most fuels due to the better fuel economy of these niche fuel cells. The exceptions would be the increases for the no / low carbon fuels of hydrogen and methanol.
- Hydrogen supply would clearly require new infrastructure to meet additional demand of 230 billion cubic metres. This would be achieved either by reforming natural gas or by electrolysis using off-peak renewable power. The latter route would give by far the greater environmental benefit.
- The existing infrastructure for methanol has the capacity to supply around 9 million tonnes per year [130]. The potential increase of 0.7 million tonnes per year should easily be absorbed over time, requiring a total increase of capacity of up to 8%.

Emissions:

- There are potential savings in CO_2 emissions of around 800 million tonnes. The majority of this is due to a reduced use of diesel fuel, which is achieved from the portable power and marine APU markets.
- There are potential NO_x emissions savings of around 18 million tonnes, SO_x and hydrocarbon emissions savings of 3 million tonnes each and CO savings of almost 2 million tonnes.

9 Conclusions

Of the niche markets identified, several would appear to be ideally placed for exploitation, whilst others either have technical reasons why they would be unattractive or the market is simply too small. Of the promising markets identified, the following are the top five:

- Auxiliary Power Units (APUs) for executive cars
- Leisure / Outdoor (including gardening, camping etc.)
- Portable Power
- Portable Electronics (laptop computers, cellular phones and video cameras)
- Custom / Premium Power

Promising Areas for Development and System Designs: *APUs for executive cars* are already being developed. Indeed, BMW are planning the use of a 5 kWe SOFC unit in their 7 series models in the near future and have secured initial supply agreements. Of the *leisure/outdoor* area, lawnmowers and camping appear promising areas. In particular, 3 kW – 4 kWe PEM powered lawnmowers could provide a premium market where electric mowers fed by mains electricity cannot compete. *Portable power* is a large market for products in the range 1 VA to 75 kVA, ideally suited to PEM fuel cells running on hydrogen. This area could be an early market providing considerable emission savings. *Portable electronics*, though a comparatively small market, again could give early penetration this time using direct methanol fuel cells. The *premium power* market, though relatively small, is ideally suited to early niche applications using PEM fuel cells.

Materials: By far the three largest markets are portable power (35GW), car APUs (25 GW) and garden equipment (20 GW). Portable power and garden equipment would both probable require hydrogen fuelled PEM fuel cells, whilst car APUs seem likely to be supplied by small SOFCs. There are few material concerns, though the shift reactors used in low temperature fuel cells should be disposed of by specialist contractors. Replacement of lead-acid batteries could also save over 1 billion tonnes of production.

Fuel: There would be a large decrease in the use of most fuels due to the better fuel economy of these niche fuel cells. Hydrogen supply, however, would require new infrastructure to meet additional demand of 230 billion cubic metres. Also, methanol production capacity would need to increase by around 8%.

Emissions: There are potential savings in CO_2 emissions of around 800 million tonnes. The majority of this is due to a reduced use of diesel fuel, which is achieved from the portable power and marine APU markets. There are also potential NO_x emissions savings of around 18 million tonnes, SO_x and hydrocarbon emissions savings of 3 million tonnes each and CO savings of almost 2 million tonnes. The majority of these savings would be due to the marine APU market.

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Appendix - Key Players

This section identifies those companies and organisations with specific interests in the development, manufacture, supply, application or operation of fuel cell systems in the various niche markets identified. The primary focus has been given to companies and organisations in UK and Europe, North America and Asia Pacific, although note has been taken of specific interests in the rest of the world.

Company name & address	Contact(s)	Email address	Telephone/fax no.	Web site	Comments
Ansaldo srl Via N. Lorenzi 8 16152 Genoa Italy			Tel: +39 10 655 3484 Fax: +39 10 655 3480	www.ansaldo.it	Design, manufacture, market & provide service activities for packaged PC25™ fuel cell power plant. Currently looking at applications in the chemical industry using H_2 by-product and fuel cell powered pleasure boats
Astris Energi Inc. 2175 Dunwin Drive Mississauga Ontario L5L 1X2 Canada			Tel: +1 905 608 2000 Fax: +1 905 608 8222		Developer of small alkaline fuel cells for residential cogeneration and also for powering golf carts.
Ball Aerospace and Technologies Corporation 1600 Commerce Street Boulder Colorado 80301 USA		techops@ball.com	Tel: +1 303 939 6100 Fax: +1 303 939 6104	www.ball.com	Developer & manufacturer of light-weight portable fuel cells. 50W & 100W (PPS-50 & PPS-100) units are available as an alternative to batteries or generators.
Ballard Power Systems Inc. 9000 Glenlyon Parkway Burnaby British Columbia V5J 5J9 Canada			Tel: +1 604 454 0900 Fax: +1 604 412 4700	www.ballard.com	World leader in developing PEM fuel cells for transportation. Jointly developing portable power units with Coleman Powermate utilising Ballard's Mark 900 fuel cell technology. Product could be on the market by 2001.

Company name & address	Contact(s)	Email address	Telephone/fax no.	Web site	Comments
BMW AG Petuelring 130 Munich D-80788 Germany			Tel: +49 893 8224272 Fax: +49 893 8224418	www.bmw.com	Installing and testing Global Thermoelectric's SOFC on board a vehicle this year. Also signed a memorandum of understanding with Renault & Delphi Automotive Systems to develop SOFC APUs.
Case Western Reserve University Ernest B Yeager Center for Electrochemical Science 124 A W Smith Building 10900 Euclid Avenue Cleveland OH 44106-7218 USA	Professor Savinell	rfs2@po.cwru.edu	Tel: +1 216 368 6525 Fax: +1 216 368 3016	www.cwru.edu	Developing miniature fuel cells using advanced microfabrication techniques. Prototype has a volume of $5mm^3$ and produces 5mW. Technology is initially intended for military applications.
Chubu Electric Power Co. 20-1, Kita-seikiyama, Oodaka-cho Midori-ku Nagoya-shi 459-8522 Japan			Tel: +81 52 624 9112 Fax: +81 52 623 5117	www.chuden.co.jp	Working with Ishikawajima-Harima Heavy Industries on hybrid MCFC/gas turbine technology.
Coleman Powermate Inc. 4970 Airport Road Kearney NE 68847-3772 USA		info@colemanpowermate.com	Tel: +1 308 237 2181	www.colemanpowermate.com	Collaborating with Ballard on the development of portable and stand-by power products based on Ballard's Mark 900 fuel cell. Products will be available through Coleman Powermate's network of retailers and distributors.

Company name & address	Contact(s)	Email address	Telephone/fax no.	Web site	Comments
Dais-Analytic Corporation 11552 Prosperous Drive Odessa Florida 33556 USA		info@daisanalytic.com	Tel: +1 727 375 8484 Fax: +1 727 375 8485	www.daisanalytic.com	Developer & manufacturer of small PEM fuel cell power supplies (up to several kW) for back-up, stand-by, UPS, portable power markets etc. Products already available include the FC-150 & FC-200 (150W & 200W).
DCH Technology 27811 Avenue Hopkins Suite 6 Valencia California 91355 USA			Tel: +1 661 775 8120 Fax: +1 661 257 9398	www.dcht.com	Specialises in licensing and converting new ideas into state-of-the-art products. Are developing a portable PEM fuel cell through their wholly owned subsidiary EnAble™ Fuel Cell Corporation.
De Nora Spa Via Bistolfi 35 I-20134 Milan Italy	Michelle Tettamanti Manager - Fuel Cells Division	DENORAspa@mail.skp.it	Tel: +39 02 212 9346 Fax: +39 02 215 4953	www.denora.com	Developer of PEM fuel cell stacks aimed at low cost, mass production for stationary & mobile applications. Niche applications include a prototype 100kW fuel cell module installed on a chlor-alkali plant. Recently merged with Epyx to form Nuvera Fuel Cells.
Delphi Automotive Systems Corporation 5725 Delphi Drive Troy MI 48098 USA			Tel: +1 248 813 2000 Fax: +1 248 813 2523	www.delphiauto.com	World's largest maker of auto parts with 80% of business coming from former parent General Motors. Recently signed a memorandum of understanding with BMW & Renault to develop SOFCs as APUs for cars & trucks.

Company name & address	Contact(s)	Email address	Telephone/fax no.	Web site	Comments
Eco Soul Inc. 18051 Irvine Boulevard Tustin CA 92780 USA		ecosoul@thegrid.net	Tel: +1 714 573 4955	http://ecosoul.org	Manufacturer and supplier of reversible PEM fuel cell learning kits for schools (cost $500 each).
Electric Power Development Co. 15-1, Ginza 6-chome Chuo-ku Tokyo 104-8165 Japan		webmaster@epdc.co.jp	Tel: +81 3 3546 2211 Fax: +81 3 3544 1819	www.epdc.co.jp	Developing an integrated coal gasification fuel cell (IGFC) system. A prototype plant in Kitakyushu is planned to begin a 3 year trial in 2001 with a viable commercial IGFC system by 2008.
Electro-Chem-Technic 81 Old Road Headington Oxford OX3 7LA UK	James Larminie	ectechnic@patrol.i-way.co.uk	Tel: +44 1865 769054 Fax: +44 1865 434799	www.i-way.co.uk/ ~ectechnic	Manufacturer and supplier of small alkaline fuel cells for educational purposes (cost ~ $30 per unit).
ElectroChem Inc. 400 West Cummings Park Woburn Massachusetts 01801 USA		General: fuelcell@fuelcell.com Sales: sales@fuelcell.com	Tel: +1 781 938 5300 Fax: +1 781 935 6966	www.fuelcell.com	Developer & manufacturer of PEM fuel cells for portable power. Products include EC-PowerPak-200 (a 200W unit) & a 45W unit for education/demonstration purposes.
EnAble™ Fuel Cell Corp. 2120 West Greenview Drive Suite 1 Middleton WI 53562 USA			Tel: +1 608 831 6775 Fax: +1 608 831 6835	www.dcht.com	Wholly owned subsidiary of DCH Technology. Developer and manufacturer of portable air-breathing PEM fuel cells under exclusive license from Los Alamos National Laboratory.
Energy Conversion Devices 1675 West Maple Road Troy Michigan 48084 USA		hydrogen@ovonic.com	Tel: +1 248 280 1900 Fax: +1 248 280 1456	www.ovonic.com	Developer of metal hydride hydrogen storage systems for use with portable fuel cells. Also developing a regenerative fuel cell system.

Company name & address	Contact(s)	Email address	Telephone/fax no.	Web site	Comments
Energy Partners Inc. 1051 Northpoint Parkway, Suite 102 West Palm Beach Florida 33407 USA	Dr Frano Barbir Chief Research Engineer Doug Weinberg Vice President Business Development	fbarbir@energypartners.org weinberg@energypartners.org	Tel: +1 561 688 0500 Fax: +1 561 688 9610	www.energypartners.org	Founded in 1990 to research & develop PEM fuel cells for stationary & transport applications. Have converted Gator™ utility vehicles to fuel cell power and tested as airport ground service vehicles.
Energy Related Devices Inc. 127 Eastgate Drive Los Alamos NM 87544 USA	Robert Hockaday Chief MicroFuel Cell Scientist	energyrd@aol.com	Tel: +1 505 662 0660 Fax: +1 505 662 0665	www.energyrelatedevices.com	Contractor to Manhattan Scientifics developing a, high energy MicroFuel Cell™ electrical power system for cellular phones, laptop computers and other portable devices.
Energy Ventures Inc. 43 Fairmeadow Avenue North York Ontario M2P 1W8 Canada			Tel: +1 416 733 2736 Fax: +1 416 733 8407	www.evi.on.ca	Developing direct methanol fuel cells - 150W to 300W prototype expected to be available by 2001. Also looking at small fuel cell units for use in golf carts, electric motorcycles etc.
Forschungszentrum Jülich Institute for Materials and Processes in Energy Systems (IWV) D-52425 Jülich Germany	Professor B Höhlein	b.hoehlein@fz-juelich.de	Tel: +49 2461 613235 Fax: +49 2461 616695	www.kfa-juelich.de	Key European centre for fuel cell R&D especially at a fundamental level. Research areas include both high and low temperature fuel cells. SOFC technology is licensed to Global Thermoelectric.
Fraunhofer Institute for Solar Energy Systems Oltmannsstraße 5 D-79100 Freiburg Germany	Dr Angelika Heinzel Head of the Energy Technology Department		Tel: +49 761 4588194 Fax: +49 761 4588320	www.ise.fhg.de	Developing compact PEM fuel cells for portable electronic equipment such as cellular phones and laptop computers.

Company name & address	Contact(s)	Email address	Telephone/fax no.	Web site	Comments
Freightliner Corporation 2701 NW Vaughn Suite 300 Portland OR 97210 USA			Tel: +1 503 735 8000 Fax: +1 503 735 8921	www.freightliner.com	Leading heavy duty truck manufacturer in North America. Developing fuel cells as APUs for heavy duty trucks in conjunction with Xcellsis. System uses two Ballard PEM stacks.
FuelCell Energy Corp. 3 Great Pasture Road Danbury CT 06813 USA	Jerry Leitman		Tel: +1 203 825 6000 Fax: +1 203 798 2945	www.fce.com	Developer of Direct Fuel Cell™ - molten carbonate fuel cells for utility scale applications. Also looking at MCFCs in combination with coal gasification.
Global Thermoelectric Inc. Bay 9 3700-78 Avenue SE Calgary Alberta T2C 2L8 Canada	Dave Ghosh Vice President Fuel Cell Division	fuelcell@globalte.com	Tel: +1 403 236 5556 Fax: +1 403 236 5575	www.globalte.com	Involved in the commercialisation of solid oxide fuel cell technology from Forschungszentrum Jülich. Supplying BMW with an SOFC later this year to be tested as an APU on board one of their vehicles.
H Power Corporation 60 Montgomery Street Belleville NJ 07109 USA		moreinfo@hpower.com	Tel: +1 973 450 4400 Fax: +1 973 450 9850	www.hpower.com	Developer & manufacturer of low power fuel cells. PowerPEM™ products range in output from 35W to 500W. Demonstrated use of fuel cells for powering invalid carriages, video cameras and portable variable message signs.
H Power Enterprises of Canada Inc. 1069 Begin Street St Laurent Québec H4R 1V8 Canada	Mr Jean-Guy Chouinard General Manager		Tel: +1 514 956 8932 Fax: +1 514 956 5426	www.hpowercanada.com	Developer and manufacturer of EPAC™, a back-up power system based on PEM technology aimed at electrical power utilities. Models from 100W to 1.5kW available.

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H-TEC Wasserstoff-Energie-Systeme GmbH Lindenstraße 48a 23558 Luebeck Germany	Uwe Kueter	info@h-tec.com	Tel: +49 451 8791213 Fax: +49 451 8791215	www.h-tec.com	Manufacturer and supplier of PEM fuel cell kits for demonstration and education purposes. Regenerative and direct methanol fuel cells are also available.
Hydrocell UK Odiham Hook Hampshire UK			Tel: +44 771 4618895 Fax: +44	www.fuelcells.co.uk	Manufacturer and supplier of small PEM fuel cells for educational purposes, military and research laboratories.
Hydrogenics Corporation Inc. 100 Caster Avenue Woodbridge Ontario L4L 5Y9 Canada		sales@hyrogenics.com	Tel: +1 905 851 8866 Fax: +1 905 851 2328	www.hydrogenics.com	Developer of PEM fuel cell portable power generators in the range 15W to 10kW. Portable fuel cell products will be commercially available in 2001.
IdaTech PO Box 5339 Bend Oregon 97759 USA	William A Pledger Vice President Engineering	info@idatech.com	Tel: +1 541 383 3390 Fax: +1 541 383 3439	www.idatech.com	Developing PEM fuel cells & fuel processor technology. Work is underway to integrate its prototype fuel processor with a 1kWe PEM fuel cell to produce a compact and quiet portable power generator.
International Fuel Cells Corporation 195 Governor's Highway PO Box 739 South Windsor Connecticut 06074 USA			Tel: +1 860 727 2200 Fax: +1 860 727 2319	www.internationalfuelcells.com	A division of United Technologies Corporation. Developing PEM fuel cell technology for the transportation, stationary and residential power markets.

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Lawrence Livermore National Laboratory 7000 East Avenue L-174 Livermore CA 945551-0808 USA	Fred Mitlitsky	fm@llnl.gov	Tel: +1 925 423 4852 Fax: +1 925 424 3731	www.llnl.gov	Developing small, lightweight PEM-based unitised regenerative fuel cells. These are intended for applications such as solar-powered aircraft, energy storage, remote power sources etc.
Los Alamos National Laboratory PO Box 1663 Los Alamos NM 87545 USA	Ken Stroh	stroh@lanl.gov	Tel: +1 505 667 5061 Fax: +1 505 667 0603	www.lanl.gov	Developing PEM fuel cells for transportation. Also developing small PEM fuel cells in collaboration with Motorola for use in portable electronic equipment.
M-C Power Corporation 8040 South Madison Street Burr Ridge IL 60521-5808 USA			Tel: +1 630 986 8040 Fax: +1 630 986 8153	www.mcpower.com	Developing pressurised molten carbonate fuel cell technology. A 330kW commercial prototype will be available for demonstration testing in the 3rd quarter of 2001.
Manhattan Scientifics Inc. 127 Eastgate Drive Los Alamos NM 87544 USA		informhtx@mhtx.com	Tel: +1 505 662 0660 Fax: +1 505 662 0665	www.mhtx.com	Developing MicroFuel Cell™ with Energy Related Devices. Also, recently acquired NovArs technology - mid-range fuel cells for high current, low voltage applications (e.g. laptops, power tools, invalid carriages, bicycles).
McDermott Technology Inc. 1562 Beeson Street Alliance OH 44601-2196 USA	Rob Privette Business Development Specialist		Tel: +1 330 821 9110 Fax: +1 330 823 0639	www.mtiresearch.com	Developing planar SOFCs and fuel reformers. Working with Ballard on a contract for the US Office of Naval Research and the Naval Sea Systems Command to develop fuel cells for shipboard applications.

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Medis El Ltd 14 Shabazi Street PO Box 132 Yehud 56101 Israel		info@medisel.com	Tel: +972 2 632 0816 Fax: +972 2 632 0817	www.medisel.com	Developing small fuel cells for use in cellular phones, paging devices and computers.
Motorola Inc. Energy Systems Group 1700 Belle Mead Court Lawrenceville Georgia 30043 USA	David DeMuro Manager, Advanced Product Realisation		Tel: +1 770 338 3742 Fax: +1	www.motorola.com	Developing direct methanol fuel cells in conjunction with Los Alamos National Laboratory for use in portable electronic equipment. Commercialisation is expected in 4 to 5 years.
MTU Friedrichshafen GmbH Neue Technologien D-88040 Friedrichshafen Germany			Tel: +49 89 60731525 Fax: +49 89 60731509	www.mtu-friedrichshafen.com	Developing "Hot Module", a molten carbonate fuel cell power plant, in conjunction with FuelCell Energy. System can run on natural gas or synthetic gases such as biogas and coal gas.
National Power Innogy Harwell International Business Centre Harwell Didcot Oxfordshire OX11 0QA UK	John Newton	john.newton@natpower.com	Tel: +44 1235 444925 Fax: +44 1235 444909	www.innogy.com	Developer of Regenesys™ electricity storage system based on regenerative fuel cell technology. Also working with DERA to develop the technology for air independent power on submarines.
NovArs GmbH European Research Headquarters Hauptstraße 6 94124 Buchlberg Germany	Arthur Koschany Chief Mid-Range Fuel Cell Scientist	novars@t-online.de	Tel: +49 8505 91780 Fax: +49		Developing mid-range (2W - 3kW) fuel cell technology for high current, low voltage applications. IPR and exclusive world-wide commercial development rights have been acquired by Manhattan Scientifics. Recently launched the Hydrocycle™, a 670W fuel cell powered bicycle.

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Nuvera Fuel Cells 15 Acorn Park Cambridge MA 02140 USA			Tel: +1 617 498 6732 Fax: +1 617 498 6655	www.nuvera.com	New company formed from merger of Epyx and De Nora. Will produce complete fuel cell systems for both the stationary power and transportation markets.
ONSI Corporation 195 Governor's Highway PO Box 739 South Windsor Connecticut 06074 USA			Tel: +1 860 727 2550 Fax: +1 860 727 2319	www.onsicorp.com	Part of International Fuel Cells Corporation. Developer and manufacturer of PC25™ PAFC plant. Niche markets include stand-by and custom power applications.
Paul Scherrer Institut Electrochemistry Laboratory CH-5232 Villigen PSI Switzerland	Otto Haas	otto.haas@psi.ch	Tel: +41 56 310 2199 Fax: +41 56 310 2199	www.psi.ch	Developing portable PEM generators. 100W units have been tested successfully at various Engineering Colleges in Switzerland. A 300W unit is currently under development.
Physical Sciences Inc. 20 New England Business Center Andover MA 01810 USA	Dr Michael Kimble	kimble@psicorp.com	Tel: +1 978 689 0003 Fax: +1 978 689 3232	www.psicorp.com	Developing a prototype 500W, 24V energy storage system based on its proprietary micro-PEM technology for unmanned aerial vehicles. This work is funded by the US Air Force.
Plug Power 968 Albany-Shaker Road Latham NY 12110 USA			Tel: +1 518 782 7700 Fax: +1 518 782 7914	www.plugpower.com	Developing PEM fuel cells for residential use; commercial sales expected to begin in 2001. Recently unveiled its "House on Wheels", a full size recreational vehicle with a PEM fuel cell system powering all on board electrical appliances.

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Proton Energy Systems Inc. 50 Inwood Road Rocky Hill CT 06067 USA		pes@protonenergy.com	Tel: +1 860 571 6533 Fax: +1 860 571 6505	www.protonenergy.com	Developing and commercialising PEM unitised regenerative fuel cells. Its Unigen™ product is intended for utility, premium power and remote site applications.
Renault SA 34, quai du Pont du Jour Boulogne-Billancourt 92109 France			Tel: +33 1 41045050 Fax: +33 1 41046790	www.renault.com	Recently signed a memorandum of understanding with BMW and Delphi to develop SOFC APUs for vehicles. Agreement covers diesel SOFC reformers for Renault light and heavy duty trucks.
Siemens AG Power Generation Group (KWU) PO Box 3220 D-91050 Erlangen Germany	Albert Hammerschmidt Director Fuel Cells PEM Technology	Albert.Hammerschmidt@erl11.siemens.de	Tel: +49 9131 187030 Fax: +49 9131 187039	www.siemens.de/kwu	Developer & manufacturer of both SOFC and PEM fuel cells. Niche applications include demonstration of fuel cell powered fork lift truck. Also supplying PEM fuel cells to German and Italian navies for powering U-212 submarines.
Still GmbH Schwabacher Straße 494 90763 Fürth Germany			Tel: +49 911 977110 Fax: +49 911 9771126		One of the world's largest constructors of fork lift and service vehicles. Working with Zevco to develop an alkaline fuel cell hybrid fork lift.
Sure Power™ Corporation 30 Main Street Suite 405 Danbury CT 06810 USA		amannion@hi-availability.com	Tel: +1 203 790 8996 Fax: +1 203 743 2182	www.surepowersupply.com	Supplier of UPS systems which incorporate ONSI Corporation's 200kW PC25™ PAFC modules.

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Toshiba Corporation Fuel Cells Systems Division 2-4 Suehiro-cho Tsurumi-ku Yokohama Kanagawa 230-0045 Japan		fuelcell@hby.toshiba.co.jp	Tel: +81 45 510 6009 Fax: +81 45 500 1417	www.toshiba.co.jp	Developing fuel cells for emergency power systems. Also developing compact fuel cells for applications such as vending machines - product is forecast to be marketed by 2003.
US Coast Guard R&D Centre 1082 Shennecossett Road Groton CT 06340-6096 USA	Walt Lincoln Project Manager	wlincoln@rdc.uscg.mil	Tel: +1 860 441 2727 Fax: +1 860 441 2792	www.uscg.mil	Investigating the use of fuel cell power systems at its remote locations and radio-navigation sites.
Warsitz Enterprises Inc. PO Box 408 San Juan Bautista USA		h2man@slip.net	Tel: +1 831 637 7350 Fax: +1 831 637 8338	www.warsitz.com	Started out by developing and providing experimental kits for demonstrating renewable fuel cells. Also offer low power products such as RoamPower™ (30, 60 and 90W units) and HydroGen™, a 150W fuel cell based electric generator.
Xcellsis Corporation 12190 Tech Center Drive Poway CA 92064 USA			Tel: +1 858 679 3270 Fax: +1 858 679 4901	www.xcellsis.com	Parent companies are DaimlerChrysler, Ford and Ballard Power Systems. Developing PEM APUs for cars (with Daimler-Chrysler) & heavy duty trucks (with DaimlerChrysler and Freightliner).
Zentrum für Sonnen-energie und Wasserstoff-Forschung Geschaftsbereich 3 Hemholtzstraße 8 D-89081 Ulm Germany	L Jorissen	ljoeriss@huba.zsw.uni-ulm.de	Tel: +49 731 9530609 Fax: +49 731 9530666	www.zsw.uni-ulm.de	Developing a portable PEM power supply. Hydrogen is supplied from metal-hydride storage cylinders. The fuel cell delivers 200W DC at 12V and the prototype can supply 500Wh of electrical energy.

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ZeTek Power plc 1st Floor Rodwell House 100 Middlesex Street London E1 7HD UK		info@zetek.com	Tel: +44 20 73776199 Fax: +44 20 74744472	wwww.zevco.co.uk	Dedicated to the development, production and installation of zero-emission alkaline fuel cell power. Zevco is concerned with fuel cell systems for commercial vehicles (e.g. airport tow tractors and fork lift trucks). ZeMar is concerned with marine applications; e.g. a 5kW APU for a sailing yacht.