AJChE 2002, Vol. 2, No. 1, 75-86

A Review on Fuel Cell as Advanced Power Source

S.K. Kamarudin, W.R.W. Daud, M.S. Ayub, A.W. Mohammad, S. Takriff and S. E. Iyuke*
Department of Chemical and Process Engineering,
National University of Malaysia, 43600 UKM Bangi, Selangor, Malaysia.
*Department of Chemical and Environmental Engineering,
University Putra Malaysia, 43400 Serdang , Selangor, Malaysia.

Fuel cells are making headlines across the globe in almost all arenas of power production. While the technology for these electrochemical power plants was invented around 1839 and has been in use for nearly 150 years, it is only recently that fuel cells have gained popular recognition and reckoned for serious consideration as a power zone for the future. Despite their relatively new arrival on the popular scene, fuel cells have already found their way into pre-commercial testing in domestic, commercial, industrial and mobile applications. Fuel cells convert chemical energy of a fuel gas directly into electrical work, and are efficient and environmentally clean, since no combustion is involved. Fuel cells are presently under development for a variety of generation application in response to the critical need for a cleaner energy technology. The use of fuel cell systems has been strongly promoted in Japan and the United States for medium-scale co-generation plants. Nowadays, this interest has been extended to the smaller scale, in particular at the residential area level. All fuel cells currently being developed for near term use in electric vehicles require hydrogen as a fuel. At the same time, increased interest has arisen for the application of fuel cell systems to automotive propulsion, although there is no clear option on the direct use of hydrogen stored on board or the installation of hydrogen plant on board as of this time. This paper outlines the acute global population growth and the growing need and use of energy and its component as well as its environmental impact. In particular, this paper reviews the existing or emerging fuel cells technologies, limitations, and their benefits in connection with energy, environment and sustainable development relationship. In addition, this paper also explores fuel sources and the various types of fuel cells as well as their applications.

INTRODUCTION

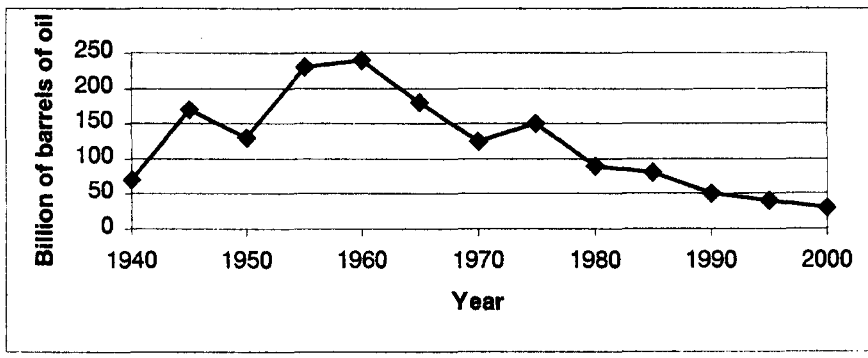
Energy produced from fossil fuel (coal, oil and natural gas) is not environmentally friendly. Apart from this, the availability of fossil fuels become a limiting factor when pollution increases and the demand for alternative energy sources like solar (Lee et.al 2002; Li & Wang 2002; Tiba et.al 2002) nuclear power (Ohnishi 2002; Galy et.al 2002; Schrempel et.al 2002; Meyendorft et.al 2002), wind power (Bansal et.al 2002; Manwell et.al 2002; Eskander 2002; Liu et.al 2002) and hydrogen and oxygen fuel cells become inevitable resource. The amount of energy produced from solar power is limited (Datta et.al 2002) and control problem arises due to variances of PV (Photovoltaic) output power under different isolation levels (Shatter et.al 2002). In addition, energy efficiency is low. In the case of nuclear power, waste generation is very dangerous to both man and environment. For safe and clean energy, fuel cell and wind energy sources are preferred.

The problem with energy supply and use is related not only to global warming but also to

Table 1: Population, Energy and Electricity demands (Million of barrels per day of oil equivalent)

Year	Population (billion)	Energy demands, MBDOE	Electricity demands, % Energy demand
1940	2.4	70	-
1960	3.0	90	-
1970	3.6	100	6
1985	4.8	200	12
1995	5.3	300	15
2000	6.1	350	30
2001	7.2	410	50

Source: World Energy Council 1998



(Source: United State Department of Energy Review 2001)

Figure 1: Volume of oil discovered world wide every five years

environmental concerns such as air pollution, acid precipitation, ozone depletion, forest destruction and radioactive substance emission. World population keeps increasing at 1.2-2% per year, such that it is expected to reach 12 billion in 2050 (Stambouli et.al 2002). Therefore, economic development will almost certainly continue to grow. Global demand for energy services is expected to increase by as much as an equal order of magnitude by 2050, while primary-energy demands are expected to increase by 1.5 to 3 times (World Energy Council 1998; refer to Stambouli et.al 2002) as seen in Table 1.

As world wide supplies dwindle (Figure 1), the development of new power generation technologies will become increasingly important. Simultaneously, interest will likely increase regarding energy-related environmental concerns. Indeed, energy is one of the main factors that must be considered in the discussion of sustainable development. In response to the critical need for a cleaner energy technology, some potential solutions have envolved. This includes energy conservation through improved energy efficiency, reduction in the consumption of fossil fuels, and an increase in the supply of environment–friendly energy, such as renewable sources and fuel cells. Electricity from fuel cells can be used in the same way as grid power.

TYPE OF FUEL CELL

A fuel cell, by definition, is an electrical cell, which unlike storage cells, can be continuously fed with a fuel so that the electrical power output is sustained indefinitely. Fuel cells function on the principle of electrolyte charge/exchange between a positively-charged anode plate on a negatively-charged cathode plate.

When hydrogen is used as the basic fuel, reverse hydrolysis occurs, yielding only water and heat as byproducts while converting chemical energy into electricity, as shown in Figure 2. Pollutant emission is practically zero.

Overall reaction:
$2H_2 \text{ (gas)} + O_2 \text{ (gas)} \rightarrow 2H_2O + \text{energy}$

Fuel cells are generally categorized by electrolyte material. As shown in figure 2, there are five main types of fuel cells.

Table 2 present the summary of different fuel cell technologies, their principle characteristics,

Table 2: Different Fuel Cell Technologies and Main Technical Characteristic.

Type of Fuel Cell	Operating Temperature (°C)	Electrolyte	Type of Electrolyte	Fuel	Oxidant	Water generated	Efficiency (%)
Alkaline (AFC)	50-200	Potassium hydroxide, generally in aquas solution, at 35% in weight	Liquid: circulating or in a matrix	Pure hydrogen, or hydrazine	O_2/Air	Anode	50-55
Direct Methanol (DMFC)	60-200	Proton exchange membrane (e.g. Nafion)	Solid: polymer which has to be moistened	Liquid methanol	O_2/Air	Cathode	40-55
Phosphoric acid (PAFC)	160-210	Pure Phosphoric acid	Liquid: in a porous matrix of silicon carbide	Hydrogen from hydrocarbons and alcohol	O_2/Air	Cathode	40-50
Sulfuric acid (SAFC)	80-90	Pure Sulfuric acid	Liquid: in a porous matrix of silicon carbide	Alcohol or impure hydrogen	O_2/Air	Cathode	40-50
Proton Exchange Membrane (PEMFC)	50-80	Proton exchange membrane (e.g. Nafion	Solid: polymer which has to be moistened	Less pure hydrogen from hydrocarbons or methanol	O_2/Air	Cathode	40-50
Molten Carbonate (MCFC)	630-650	Old generation: Li_2CO_3/K_2CO_3 New generation: Li_2CO_3/Na_2CO_3	Liquid: in a porous matrix of lithium aluminates	Hydrogen, carbon monoxide, natural gas, propane, marine diesel	CO_2/O_2/ Air	Anode	50-60
Solid Oxide (SOFC)	600-1000	Ceramic as stabilized zirconium and doped perovskite	Solid (ceramics)	Natural gas or propane	O_2/Air	Anode	45-60

(Source: Bernay et.al 2002; Stambouli et.al 2002)

Table 3: Current Material of the Different Fuel Cell Technologies

Technology	Anode	Cathode	Bipolar plates
PEMFC	Carbon cloth, carbon particles with high specific area, platinum particles, weight 0.1 $mgcm^{-2}$, PTFE, Nafion©	Carbon cloth, carbon particles with high specific area, platinum particles, weight 0.3 $mgcm^{-2}$, PTFE, Nafion©	Machined carbon or stainless steel
DMFC	Carbon cloth, carbon particles with high specific area, platinum-ruthenium particles, weight 2 $mgcm^{-2}$, PTFE, Nafion©	Carbon cloth, carbon particles with high specific area, platinum-ruthenium particles, weight 2 $mgcm^{-2}$, PTFE, Nafion©	Machined carbon or stainless steel
AFC	Hydrophobic layer (PTFE), carbon catalyst (platinum particles with 0.3 $mgcm^{-2}$ loading or cobalt-based catalyst	Hydrophobic layer (PTFE), carbon catalyst (platinum particles with 0.3 $mgcm^{-2}$ loading or cobalt-based catalyst	Current collection by nickel mesh and distribution of gases, water and electrolyte with plastic frame
PAFC	Carbon cloth as a support, catalyst layer: PTFE + carbon black with high specific area + platinum particles 0.1 $mgcm^{-2}$	Carbon cloth as a support, catalyst layer: PTFE + carbon black with high specific area + platinum particles 0.5 $mgcm^{-2}$	Graphite
MCFC	Nickel-chromium ally with 10wt.% chromium	Porous nickel oxide	Stainless steel with protective layers at the anode and cathodes sides
SOFC	Ni/YSZ cermet of 30% porosity	Strotium-doped lanthanum mangnite of 30% porosity	$LaCrO_3$ or FeCr alloy or stainless steel depending on the operating temperature

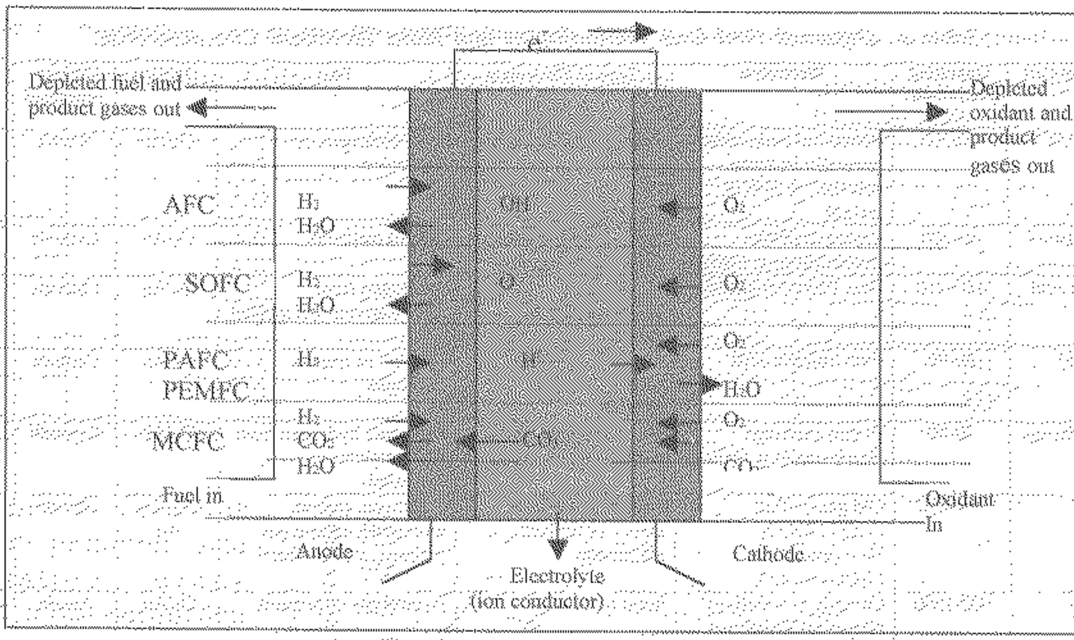


Figure 2: The Five Principal Types of Fuel Cells and their Electrochemical Reactions.

intended applications, worldwide developers and their achieved advanced development. Most often, fuel cells are classified according to the electrolyte used which settles the operating temperature. However, another classification of fuel cells may be set up according to the fuel and the fuel supply used, either direct or indirect.

TABLE 4: Power Range And Field Of Application Fuel Cell Stationary Plant

	Electrical power	Field of Application
Small Power	1-5 kW 5-10 kW	Micro power-domestic (housing power system)
Medium Power	50-1000 kW	Cogeneration, production of electric energy and heat, power system (stores, flats, buildings)
Large Power	5-20MW	Remote power stations, power systems

Source: Cacciola et.al. (2001)

Table 3 shows the electrolyte, electrode and bipolar plate materials currently used for the different fuel cell technologies.

APPLICATION OF FUEL CELLS

Fuel cell may potentially be used to produce electricity for homes, business and industries through stationary power plants ranging in size from 100 watts (enough to power a high bulb) to several megawatts (enough to power about 1000 homes). A survey of the electricity production market for possible fuel cell application shows some niche application which can be grouped (Table 4) as: small power plant for residential application (less than 10 kW), medium/large plant for industrial and commercial use (from 50 to 1000 kW) and large power plants (up to 20 MW).

Table 5 shows the recent development, intended application and main developer of various types of fuel cells.

Residential

For residential applications, small fuel cell power plants could be installed for power production of both heat and power to remote residential entities that have no access to primary grid power. This application is more common in developing countries where demand for increased power generation capacity in regions yet to be reached by electric wires is largest. For residential application, the PEM and the SOFC appear to have the highest potential (Heizel et.al 2002) in terms of general development stage and specific development stage for this market. The PAFC and AFC have not been developed for this market, not so much for technical reasons but rather from historical perceptions (Sammes & Boersma 2000).

TABLE 5: Intended Application And Main Developers

Symbol	Intended Application	Development advance	Principal developer/companies
PEMFC	Vehicle (drive) Stationary (housing, cogeneration), portable	Prototype of vehicles, demonstration of housing system and 200 kW systems	Balard (Canada(, Nuvera (Italy/US), IFC (USA), H.Power (USA), Plug Power (USA), Avista (USA), Energy Partners (USA)
AFC	Vehicle (hybrid), spatial	Development: London taxis and small vehicles used for 30 years by NASA in space flights	IFC/UTC (USA), Zetek (GB), Astris Energy (Canada)
DMFC	Vehicle (hybrid) portable	Prototype of 5KW systems and small vehicles, telephones and computers	Balard (Canada), Daimler-Chrysler, Motorols (USA), with US laboratories, laboratory partner ship in Japan including Nissan
PAFC	Stationary (cogeneration)	Marketing of cogeneration systems 200kW (ca. 200 worldwide)	ONSI (joint venture IFC-FUJI-Toshiba, USA-Japan), Fuji (Japan), Toshiba (Japan)
MCFC	Stationary (cogeneration, power plant)	Demonstration of power station 250 kW to 2 kW	FCE (USA), MTU (Germany), IHI)Japan), Hitachi (Japan), Ansaldo (Itally)
SOFC	Vehicle (APU) stationary (housing, cogeneration	Exhibition of housing 1 kW and cogeneration systems 200kW	Siemens-Westinghouse (Germany-USA), Global Thermoelectric (Canada) Suzer Hexis (Switzerland), Mitsubishi (Japan)

Source: Bernay et.al. (2002)

Vehicle

A key commercial application of fuel cells is their potential to replace the internal combustion engine in automobiles. As early as 2004, fuel cell engines could be implemented in more than 100,000 automobile sold around the world (http:www.nfcrc.uci.edu/journal/article/fcarticle.index.htm). All major automobile manufacturers and several other companies are developing prototype fuel cell vehicles to investigate this possibility (Bird 1996; Cacciola et.al 2001; Doss et.al. 2001; Francesco & Arato 2002; Han et.al 2000; Handley et.al 2002; Lin 2000; Ogdean 1999; Panik 1998; Shim & Lee 2000).

Power Storage

Another aspect of power production for which fuel cells are well suited is power storage. These can be used to store energy for future use in power production (Hojo et.al 1996; Watanebe et.al 1996; Kasahara et.al 2000). Such a system can be used in conjunction with solar cells (Shatter et.al 2002; Ahman 2001; Winkler & Lorenz 2002; Asmus 2001; Lior 2001; Ando et.al 2001; Hirsch et.al. 2001; Beck & Ruetschi 2000; Snook 2000) to store energy during the day and produce power at night or with conventional power plants to store energy during off peak hours and help meet load requirements during periods of high electricity demand (Dufour 1998; Lee et.al 2002; Vanhanem 1998; Wallmark 2002 Weiner 1998).

Telecommunication

Interest in using fuel cells to power portable equipment for commercial application is relatively recent. This is perhaps partly due to the success of Li-based batteries in powering laptop computers, mobiles phones, personal digital assistants, game devices and music systems (Dyer 2002). The demand for energy storage devices that will allow the devices to operate for longer times without being plugged into an electrical outlet (Chang et.al 2002; Chu et.al 2001; Meyer & Maynard 2002; Palo et.al 2002). Small fuel cells could be used to power telecommunication satellites, replacing or augmenting solar panels. Micro-machined fuel cells could provide power to computer chips. Finally, a minute fuel cell could safely produce power for biological application (Karyakin et.al 2002; Tributsch 1997; Sebastian et.al 1996) such as hearing aids and pacemakers.

Auxiliary Power Source

Until now, fuel cells are planned mainly for the drive application. However, other vehicle applications may be considered for this power source as an auxiliary power source. The present trend is to increase the electrical requirement of the vehicle auxiliaries, reduction of consumption and emission and safety devices. A fuel cell power plant can be used as an auxiliary source of power or APU capable of supplying the power to vehicle auxiliary devices. This would allow the required battery power to be reduced, as well as, in the long term, to suppress the alternator. (Bernay et.al 2002, Cacciola et.al 2001)

FUEL SOURCE

Fuel choice and fuel processing technology choice will be fundamental factors in the success of fuel cell vehicles. Linking fuel cell vehicle entry strategies on a specific alternative fuel with expansive infrastructure cost will ultimately create fuel cost burdens than exceed the cost targets for fuel cell power plants themselves. Natural gases is the feedstock which both methanol and hydrogen are made most economically but steam reforming natural gas on board vehicles requires high temperature that demand long start up times and a significant reduction in the vehicle's fuel economy. One alternative source is a fuel cell operating on stored hydrogen, which currently offers energy densities ranging from 500 to 1000 Wh/kg. A second alternative, with a much higher energy density, is a fuel cell system fueled by a liquid hydrocarbon.

Hydrogen

Hydrogen is the lightest, the simplest and one of the most abundant elements in nature. It always comes combined with other elements and has a variety of good properties. Both production and utilization of hydrogen can be emission–free. It can also be obtained from a variety of feed stocks (fossil, renewable energy, nuclear). Besides the unquestionable advantages of hydrogen, several problems occur in developing the required technologies: diffusion of hydrogen as an energy carrier lacks safe, efficient and cost-effective storage and the separation and sequestration of the CO_2 produced during H_2 production, is also a point of concern if not stored in safe locations. A key issue is how to provide hydrogen to the fuel cell. There are two options: either to store it on board the vehicle or to produce the hydrogen on the vehicle by means of a fuel processor (Bernay et.al 2002, Bird 1996; Cunha & Azevedo 2000; Han 2002, Edwards et.al 1998; Hey et.al 2000; Hohlein et.al. 1996; Rampe et.al. 2002). The storage of hydrogen in chemicals has the disadvantage of the production step and the reformation into hydrogen. Vehicles with on board steam reforming of methanol or gasoline have about two-thirds the fuel economy of direct hydrogen vehicles (Ogdean et.al 1999). The efficiency is also lower because of the conversion losses in the fuel processor (losses in making hydrogen from another fuel), reduced fuel cell performance on reform rate, added weight of fuel processor components, and effects of dual processor response time (Francesco & Arato 2002). Even though the storage of hydrogen at high pressure in the gas phase results in a high volume, it is an economical and simple way to store hydrogen (Emonts et.al 2002; Heizel et.al 2002; Strobel et.al 2002)

Gasoline and methanol

Gasoline and methanol are considered as the two most promising energy carriers for fuel cell vehicles. Among the different alcohols, methanol is the most promising organic fuel because its use as a fuel has several advantages in comparison to hydrogen: high solubility in aqueous electrolytes, liquid fuel availability at low cost, easily handled, transported and stored, and high theoretical density of energy (6 kWh/kg) comparable to that of gasoline (10-11kWh/kg).

Methanol, like hydrogen is also capable of delivering power directly in fuel cells without the need for reforming and this clearly simplifies hardware and response characteristics. Other alcohols, such as ethanol, ethylene, glycol, propanol, etc have also been considered for use in a fuel cell, but until now very few direct alcohol fuel cells (DAFC) (Lamy 2002) have been demonstrated, the most advanced system being the direct methanol fuel cell (DMFC) (Cacciola et.al 2001; Priestnall et.al. 2002, Qi & Kaufman 2002; Park et.al & Park et.al 2002; Shukla 2002). But their performance are still limited because of several problems: (1) the low activity of the state-of-the-art electro-catalysts, which can only be enhanced by increasing the operating temperature, (2) anode poisoning by strongly adsorbed intermediates (mainly CO) formed during methanol oxidation, and (3) the high extent of methanol cross-over through the Nafion® type membranes, which depolarizes the air cathode, (4) the power density and efficiency are several time lower than for hydrogen (or methanol reforming) system because a large fraction of the input methanol crosses over the membrane and is oxidized at the cathode without producing useful power (Bird 1996), (5) Enhancement of the electrochemical process (Hassmann & Ripple 1998). Moreover, methanol has a particular disadvantage, e.g., it is relatively toxic, inflammable with a low boiling point (65°C), and it is not a primary fuel nor a renewable fuel (Lamy 2002).

ENVIRONMENT IMPACT

Emission of carbon dioxide (CO_2), the main green house gas (GHG) from human activities, is subjected of a worldwide debate about energy sustainability and the stability of global climate. Carbon dioxide is essential for life on our planet. Animals and plants, volcanoes, oceans and forest control—in a delicate system of complex equilibrium—the CO_2 concentration in the atmosphere: too low or two high values can lead to global climate changes and then, to a cooling or warming of the earth (Conte et.al 2001).

TABLE 6: Total CO_2 emissions by top industrial Nations per unit GNP

Rank	Nation	CO_2
1	Russia	7591
2	China	4015
3	USA	740
4	Canada	708
5	UK	549
6	Germany	477
7	Italy	366
8	Japan	271
9	France	255

Source : Stamboulli 2002

Table 6 shows the total CO_2 emissions of the top industrial nations by unit Gross National Product (GNP). These can be reduced through efficiency improvements and fuel switching measures.

Fuel cells have long been recognized as having excellent features such as high efficiency energy conversion, low CO_2 emissions (refer to Table 7) and potential applicability to both small and large-scale plants. Therefore, fuel cells have been intensively developed all over the world for higher efficiency and lower environmental impact. The worse effective parameters for global warming are energy consumption and CO_2 emission. These features show that researchers and engineers in any energy-related industry should sincerely consider long-term strategies for keeping the earth's environment healthy for future generations (Watanabe et.al. 1996; Conte et. al 2001; Francesco & Arato 2002).

Both petrol and diesel have been modeled by Hart & Hormandinger (1998). The outcome of the model calculations is summarized in Figure 3. The environmental benefits of fuel cell cars are clear: CO, SO_x, NO_x and PM emissions are down by one to two orders of magnitude. For the natural gas-fueled fuel car, PM emissions are almost entirely absent. CO_2 emission for the methanol car are 62% of the petrol car, 40% for the natural gas-powered fuel cell car. Methane emissions rise by around half, from a low base of 0.04 g/km. This is a fuel switching effect but it is important, as methane is a greenhouse gas; nevertheless reductions of up to 60% in CO_2 cause the overall global warming potential (GWP) to drop significantly.

Table 7: Fuel Cell air emissions from 1-year operation

Air emission*	SOx	NOx	CO	Particles	Organic Compounds	CO_2
Fossil fueled plant	28,000	41,427	28,125	500	468	4,044,000
Fuel Cell	0	0	72	0	0	1,860,000

(Source: Stamboulli & Traversa 2002)

*Pounds of emissions per 1650 MWh from one year full operation

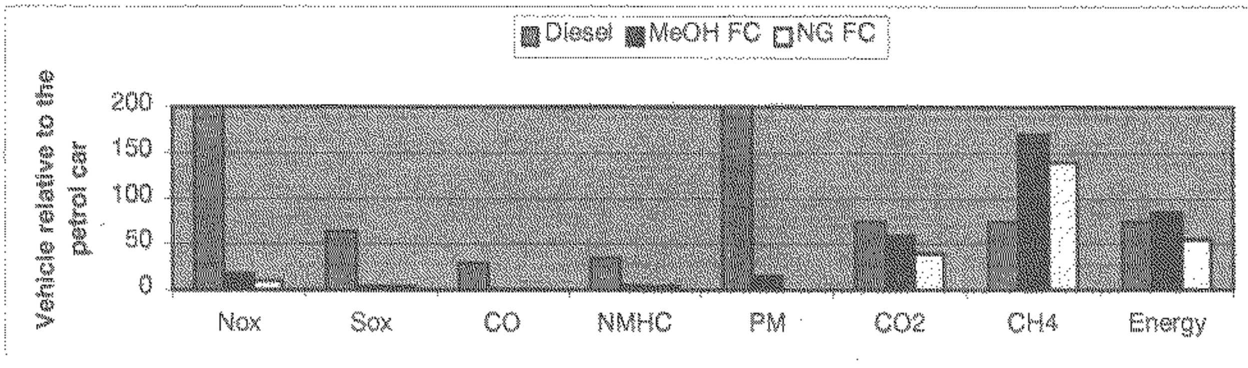


Figure 3: System-wide emission and energy consumption from car relative to those of a petrol car

FUEL CELL BENEFITS & LIMITATION

Fuel cell systems have attracted the attention of those who are interested in energy problems because of their advantageous characteristics as grouped in Table 8. Cost is the major factor and it will become critical as wide spread commercial use of the new broadband devices occurs. There is presently a severe basic cost penalty associated with the use of large batteries, to gain higher energy contents, in particular the popular Li-ion battery. This is due to the relatively higher cost of the basic batteries materials compared with the cost of the fuel for a fuel cell.

The main fuel cell power plant constraint for vehicle application are grouped in Table 9. The challenge for on board fuel cell is the production of an efficient and compact unit to achieve the demanding targets set out for automotive applications; achievement of a short start-up time; and efficiency for hydrogen generation on a small scale. The design should also take into account the thermal and physical integration of components.

CONCLUSION

Over the next 5 years, their development level will reach the realization of plants of significant size for diversified application. Such power plants will use hydrogen produced from reforming and will be integrated with a system for CO_2 sequestration and utilization, as a transitional solution. They can be integrated into advanced generation cycles that combine fuel cells with gas turbine for achieving

Table 8: The Fuel Cell Benefits

High energy security	reduce oil consumption, cut oil imports, and increase the amount of the country's available electricity supply
Reliability	achieve operating times in excess of 90% and power availability 99.99% of the time
Low operating cost	efficiency of the fuel cell system reduces drastically the energy bill (in the case of a mass production of fuel cells)
Constant power production	Generate power continuously unlike backup generators, diesel engines or Uninterrupted Power Supply (UPS)
Choose of fuel	allow fuel selection: hydrogen may be extracted from natural gas, propane, butane, methanol and diesel fuel
Clean emissions	100-1000 times cleaner than the 1998 American bus standards (15 ppmv of CO_2) and compared with traditional combustion power plants, stops NOx and SOx from being released into the environment, eliminates 20,000 kg of acid rain and smog-causing pollutants from the environment and reduces the carbon dioxide emissions by more than two million kg per year
Quiet operation	quiet enough to be installed indoors, normal conversation possible near fuel cells and hearing protection is not required as for combustion engines
High efficiency	converts up to 50-70% of available fuel to electricity (90%) with heat recovery and reduces fuel cost and conserves natural resources

potentially higher efficiencies and lower emissions than the individual system separately. Electrical conversion efficiencies of over 70% are calculated for these hybrid configurations. The following key areas need to be addressed to produce successfully the desired high performance, lightweight, ambient temperature and pressure, fuel cell system (Chu et.al 2001): (1)Thermal and heat transfer management; (2) Water management; (3) Environment factors; (4) Hydrogen storage conditions; (5) Determination of the optimum stoichiometry of fuel and oxidant; (6) System integration for high-performance PEMFCs.

Several kinds of fuel cell exist but the most important is the PEMFC. This fuel cell uses an acidic membrane electrolyte and gives excellent results, but the price is too expensive and limits the development of this kind of cell. So many systems have been considered to check the possibility of using an anomic exchange membrane or an alkaline solid polymer electrolyte in the fuel cell (Agel et.al. 2002; Agel et.al 2001). For a fuel other than hydrogen, the sensitivity of the PEMFC to CO requires the installation of at least two reforms rate purification stages, which results in increasing the volume and complexity of the fuel supply system. The cost of a PEMFC drive train is still expansive as compared with the traditional engine. Lately a direct methanol fuel cell (DMFC) based drive train has been demonstrated in a prototype by Daimler-Chrysler and solid oxide fuel cell as a power unit by BMW.

PEMFC is an emerging technology, which offers many advantages over conventional methods of electricity generation. PEMFC is under development for both transportation and stationary power application. Research efforts are presently focused on issues such as stack performance (Brujin et.al 2002; Lee et.al 2002; Qi et.al 2002; Michael et.al 2002; Jiang & Chu 2001; Dohle et.al 2001, Robert et.ak 2000; Scholta et.al 1999, Chu & Jiang 1999; Lee & Lalk 1998), durability (Ahn et.al 2002; Handley et.al 2002, Peter et.al 2000; Jiang & Chu 2001), and cost (Dufour 1998; Teagean et.al 1998; Makkus et.al 2000; Teagen et.al 1998; Ayoub Kazim 2002; Xue & Dong 1998;). Information on the present status of PEMFC development can be found in (Bar-On 2002; MacKerron 2000; Bird (1996); Stone & Morrison 2002; Bernay et.al 2002;; Escudero et. al 2002; Handley et.al 2002, Ogdean et.al 1999 Yang et.al 2001).

Further more, these systems offer the best solution for reducing pollution to zero in city centers. Other advantage of PEMFCs include: (1) the flexibility with respect to power and capacity-achievable devices for energy conversion and energy storage, (2) the long lifetime and service life, (3) the good ecological balance, and (4) very low self-discharge.

Table 9: Fuel Cell Power Plant Constraint for Vehicle Application

Power plant Constraints	Corresponding single cell and stack constraints (possibly power, if significant)
Mass, Volume	Single cell and stack power density, stack-operating pressure, fuel cell power plant density
System efficiency	Stack and fuel power plant efficiency
Cost	Fuel cell stack raw material and process cost, corresponding system cost, potential stack fuels
Kind of fuel	Acceptable stack contaminant percentage and associated single cell or stack performance decrease and reversibility
Emission	Pollutants at the fuel cell stack outlet
Lifetime and maintenance operations	Fuel stack lifetime and maintenance operation, fuel stack operating temperature
Starting and response	Stack, system and power plant thermal management, stack problems associated with start, stop, sudden power change, stack performance
Safety and reliability	Stack stop of operation, electrolytes loss, mixing of H_2-O_2, etc

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