

*Review Article***Proton Exchange Membrane Fuel Cell Technology: India's Perspective**

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India, with over a billion people and a growing economy, is one of the countries, which will shape the energy supply and demand scenario in the 21<sup>st</sup> century. With high growth rates of the Indian economy, energy needs are also growing rapidly. A growing global concern over environmental issues and the need for energy security of the country requires India to pursue all options for diversification of fuels and energy sources. In the coming decades, hydrogen is poised to become a major component in India's energy mix for meeting the growing energy needs of the economy. India's national energy policies acknowledge hydrogen as a promising energy storage option, which will provide clean and efficient energy to meet the requirements in power and transportation sectors. A National Hydrogen Energy Roadmap, setup by National Hydrogen Energy Board, India for the development of hydrogen energy related technologies including fuel cells, has been covered in detail. The most promising of all fuel cell technologies developed is proton exchange membrane fuel cell (PEMFC), which operates at a lower temperature. The variant of PEMFC is direct alcohol fuel cell (DAFC), which is direct fed with methanol and ethanol as fuel instead of hydrogen. The road map is an industry-driven planning process that offers long-term hydrogen energy based solutions to India's energy sector. A section of this article provides detailed information about the R&D activities on PEMFC, DAFC and high temperature PEMFC in India. This covers developmental work carried out by the government research institutes, universities and private sector organizations. A majority of organizations are involved in fundamental research, for e.g. polymer membranes electrolyte, anode and cathode catalysts and membrane electrode assembly and hydrogen storage with very few involved in manufacturing and technology. Some institutions are involved in more application-oriented research such as stack and balance of plant development and fuel cell bus demonstration program. The market potential for fuel cell based applications in India is discussed at the end. India, with a growing economy and a suitable national energy policy is a huge prospective market for fuel cell based applications. Stationary markets for fuel cells in India range from backup power for residential applications to captive power generation for industrial applications. This article includes discussion on potential of fuel cell based power generation in luxury hotels, process industries, chlor-alkali and dairy industry and telecommunication and information technology industry. Fuel cell applications in the Indian automotive sector are of great prospects. Initial penetration in this sector will be in buses due to their centralized operation, maintenance and refuelling. Light duty vehicle market also shows potential for fuel cell technology implementation. India has a large number of organizations in the light duty vehicle category, i.e. passenger car sector.

**Keywords:** Energy Scenario; Hydrogen Energy; Fuel Cell; Proton Exchange Membrane Electrolyte; Anode; Cathode and Catalyst; Fuel Cell Application

**Introduction**

In recent years, global energy shortage and ecological pollution problems have created opportunities for fuel cells to replace the existing technologies in a variety of applications. Some common areas of application

of fuel cells include power for stationary, portable and transport applications. They are used to provide electricity and heat in large stationary applications. They are also used to provide power in areas that are difficult to serve by the national grid. In sectors such

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as telecom, they find use in providing backup power. Another promising area of application is their use in portable devices such as mobile phones. Due to their light weight and higher operating times, they are seen as a good alternative to solid batteries. Their application in transport finds its roots in their ability to meet the stringent emission norms. As far as the world fuel cell industry is concerned, most of the activities are concentrated in regions of North America, Europe, Japan and Korea. The areas of expertise range from R&D to component manufacture and system integration. Fundamental and applied R&D is carried out in universities as well as by commercial players. A large number of corporations are involved in component manufacturing and system integration. The governments in these regions provide strong funding for the development of the fuel cell sector.

India's fuel cell industry is not quite developed as compared to the above mentioned regions. Even then, it can be considered a very important and emerging market. An economy growing at a fast pace and a country in need of energy to sustain the growth are the factors that strengthen India's position as a prospective market for fuel cells. New national energy policies of the country that promote the growth of hydrogen and fuel cell technologies add to the market potential of fuel cells in India.

### **India – A Growing Economy**

India is the second most populous country in the world and the fourth largest economy by purchasing power parity. India has seen dramatic economic growth over the last decade with GDP growth rates going as high as 9% in 2007-08 (Fig. 1). Although due to the global economic slowdown, Indian economy has also slowed (GDP growth rate of about 6.1 %) down from its high performance; it was one of the few economies where impact of this downturn was minimum. India's growth rate was among the highest in the world along with China.

This high growth rate essentially signifies upliftment of large number of population from poverty to India's growing middle class. This growing middle class is causing a consumer boom in Indian market which is contributing to India's growth.

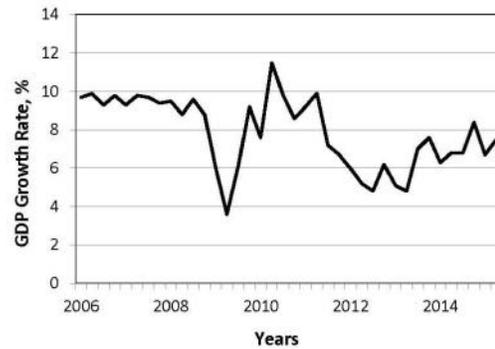


Fig. 1: India's GDP growth rate over the years (WWW.TRADINGECONOMICS.COM | MINISTRY OF STATISTICS AND PROGRAMME IMPLEMENTATION (MOSPI))

Agricultural sector still employs about 60% of the population. A growing service industry is the largest contributor to India's GDP followed by industrial and agricultural sectors. Despite robust economic growth, India continues to face many major problems. One of the major challenges that India is facing to sustain its high levels of economic growth is lack of an effective infrastructure that can support its large population. A provision for reliable power supply and a network for energy supply to India's industrial and transportation sectors are the two key issues that need to be addressed.

### **Energy Landscape**

India is the world's sixth largest energy consumer, accounting for almost 3.4% of the global energy consumption. Due to continuous high growth rates seen over the last few years, the demand for energy has been constantly growing in the economy. To sustain the growth rate for the next 20 years, India needs to increase its primary energy supply to 3-4 times. By 2030, the power generation capacity must increase to about 8,00,000 MW from the current levels of about 1,60,000 MW (Planning Commission Report, 2006). A look at the current energy landscape shows India's dependence on fossil fuels for its energy needs.

About 76% of the electricity produced in India is generated by thermal power plants, 21% by hydroelectric power plants and almost 2-3% by nuclear power plants. India's fuel mix is heavily dependent on hydrocarbons. Fig. 2 shows the

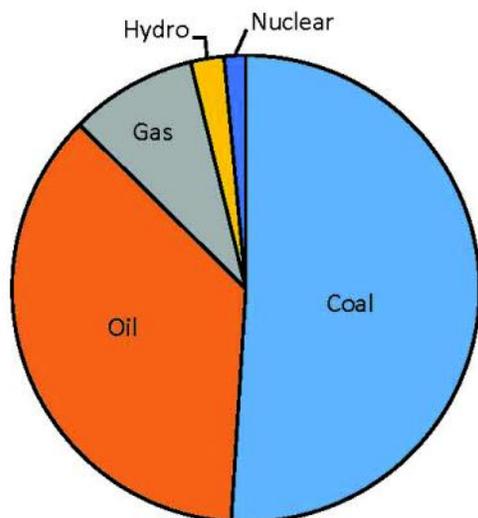


Fig. 2: India's fuel utilization for electricity generation

contribution of various fuels in the supply of energy. This heavily fossil fuel dependent fuel mix of India raises concerns over the energy security of India, particularly regarding imported oil. The main challenge facing India's energy sector is to increase and improve the delivery of energy services to various sections of the economy. A problem of disparity in demand and supply of energy is another big issue that needs to be addressed.

### *Electricity Demand Supply Situation*

Access to electricity is limited in India, even after rural electrification programme and increased power generation capacities are put in place. Even though the electricity line is provided to 80% of the Indian villages, electricity is available to merely 44% of rural households. There is a huge gap between electricity demand and supply in India, amounting to 16% (according to government figures) and 25% (according to industry estimates). Planning Commission of India estimated that around 600 million people are not even on the national grid. This number is even higher than the population of the European Union. Some states are even facing a worse situation. For example, 90% of the rural households in poverty-hit Jharkhand have no electricity and still use oil lamps for light.

India's industry incurs a direct loss of nearly 9 billion USD due to shortage of power. The loss amounts to 1% of India's GDP. The power-intensive

sectors suffer the highest losses. Manufacturing sector alone accounts for 35% of the total loss. The other main sectors include small and medium enterprises at 16%, hospital and hotel, retail at 12%, real estate and infrastructure at 10%.

According to KPMG estimates, India will face a rise in demand of power to 90 GW by 2012 (Fig. 3) and there will be only 65 GW increase in the installed capacity. To sustain the GDP growth rate of 8%, India would need to increase its installed capacity to 220 GW by 2012 from around 130 GW in 2007. Apart from high levels of disparity in demand-supply situation, India has other challenges in its overall energy landscape. These include pollution and growing concerns over energy security. Air pollution in particular is a concern in India's some big cities such as New Delhi, Mumbai, Kolkata, Chennai, Bangalore, Hyderabad and some other urban cities. Measures such as restraining the use of gasoline and diesel vehicles had been adopted to address the environmental degradation problems. New Delhi has converted its public transport system including city buses and 3-wheelers to CNG. This CNG is derived from domestic natural gas, providing energy security. Similarly, cities of Kolkata and Chandigarh have also converted their large auto rickshaw fleets to run on LPG. Still, measures to build a more sustainable energy infrastructure should be adopted and this has been realized by the Indian government.

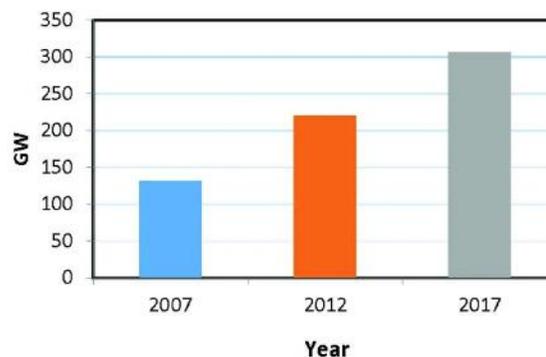


Fig. 3: Installed capacity requirement for power (Planning Commission)

### *Policy Landscape*

The Ministry of New and Renewable Energy (MNRE) largely governs India's policy regarding fuel cells and

hydrogen technology development. The authority being quite active has set up a National Hydrogen Energy Board and a roadmap in 2006. The board set up five expert groups on hydrogen production, storage, power, transport and systems integration. It provided an integrated blueprint for the long-term public and private efforts required for hydrogen energy development inside the country. This roadmap was one of the measures taken in a series to improve the energy supply situation in India. The 2003 Electricity Act was responsible for developing an overall framework for renewable energy. The 2005 National Electricity Policy recognized renewable energy as a key option for areas where national grid is not feasible or cost effective.

The broad objectives of India's National Hydrogen Energy Program are as follows:

1. Reduce dependence on imported petroleum products
2. Promote use of diverse, domestic and sustainable new and renewable energy sources
3. Provide electricity to remote, rural and far flung areas
4. Promote hydrogen as a fuel for transport and power generation
5. Reduce carbon emissions from energy production and consumption
6. Increase reliability and efficiency of electricity generation

The National Hydrogen Energy Roadmap proposed two major initiatives in its Vision 2020 – Prioritized Action Plan (Table 1). The Green Initiative for Future Transport (GIFT) aims to develop hydrogen-powered IC engine and fuel cell vehicles ranging from small (cars, 3-wheelers) to big vehicles through different phases of development and demonstration. The Green Initiative for Power generation (GIP) was to develop hydrogen-powered turbine and fuel cell based decentralized power generating systems.

### What is a Fuel Cell?

Before going into details of fuel cell technology development in India and its further scope, let us first discuss the science of fuel cell technology. The fuel cell is an electrochemical device that converts the chemical energy of the reactants directly into electrical energy. The free energy of the chemical reaction is converted into electrical energy by redox reaction. The essential difference between a fuel cell and a battery is that the fuel cell can continuously generate power as long as the fuel is supplied. Further, the electrode material in fuel cell works as catalyst to facilitate redox reaction and the electrodes do not take part in the reaction or they do not get exhausted. Fuel cell has two electrodes, cathode and anode, which act as current collector as well as catalyst and thus they are also called electro-catalyst. Every fuel cell has an electrolyte in between the electrode, which carries ions from one electrode to the other. Electrons are produced at anode through fuel oxidation reaction.

**Table 1: Initiative due to National Hydrogen Energy Roadmap: Vision – 2020**

Green Initiative for Future Transport (GIFT)	Green Initiative for Power Generation (GIP)
Hydrogen Cost at delivery point at Rs. 60-70 per kg	Hydrogen bulk storage methods and pipeline to be in place
Hydrogen storage capacity to be 9 weight %	Support infrastructure- large number of dispensing stations
Development of safety regulations, legislations, codes and standards	1000 MW hydrogen based power generating capacity setup
1, 000, 000 hydrogen-fuelled vehicles on road	- 50 MW small IC engine standalone generators
- 750,000 two/three wheelers	- 50 MW standalone fuel cell power packs
- 150,000 cars/taxis	- 900 MW aggregate capacity centralized plants
- 100,000 buses and vans	

**Source:** NHERM (2006) Report, Ministry of New and Renewable Energy

These electrons take the least electrical resistive path and move from anode to outer circuit to do useful work such as powering an electric motor or illuminating a light bulb. The electron after traversing through the load or outer circuit reaches the cathode and participates in the reduction reaction to complete the process. Similarly, ions produced at the anode takes the least ionic resistive path for the ion and move from anode to cathode via electrolyte and participate in the reduction process to complete the reaction (Basu 2007). To make it clear, if we assume that hydrogen gas is fed at the anode and oxygen gas at the cathode of a fuel cell, with an acidic electrolyte in between the anode and cathode, the following individual and overall reaction would occur:



There are several types of fuel cells, and each operates differently based on different redox reactions, fuels, electrode materials, electrolytes and operating temperature. A brief description of different types of fuel cells is given in Table 2 (Basu, 2007). The table

shows the different types of fuel cells along with the details of their vital components, application, system output, efficiency, and advantages, etc.

In this article, low temperature fuel cell, namely, polymer electrolyte or proton exchange membrane fuel cell based on hydrogen and alcohol fuels (methanol and ethanol) are discussed in detail in subsequent sections.

### **Proton Exchange Membrane Fuel Cells (PEMFC)**

The proton exchange membrane (PEM) fuel cell shown in Fig. 4 uses a solid polymer electrolyte (perfluorosulphonic acid membrane, Nafion®) in the form of a thin, permeable sheet for the transport of proton ( $\text{H}^+$ ) (Basu, 2007). Generally, platinum (Pt-black or Pt/C catalyst) is used as anode and cathode catalysts.

The perfluorosulphonic acid membrane (Nafion®, Dupont USA) is sandwiched between anode and cathode catalysts, which are supported on gas diffusion layer made of carbon cloth or carbon paper. The composite structure is known as membrane electrode assembly (MEA) and it is the heart of the PEMFC. Gas diffusion layers work as substrate for

**Table 2: Different types of fuel cells and their attributes**

	PEMFC	DMFC	AFC	PAFC	MCFC	SOFC
Primary applications	Automotive and stationary power	Portable power	Space vehicles and drinking water	Stationary power	Stationary power	Vehicle auxiliary power
Electrolyte	Polymer (plastic) membrane	Polymer (plastic) membrane	Concentrated (30-50%) KOH in $\text{H}_2\text{O}$	Concentrated 100% phosphoric acid	Molten carbonate ceramic matrix of $\text{LiAlO}_2$	Yttrium-stabilized Zirconia
Operating Temp. Range	50-100°C	0-60°C	50-200°C	150-220°C	600-700°C	700-1000°C
Charge carrier	$\text{H}^+$	$\text{H}^+$	$\text{OH}^-$	$\text{H}^+$	$\text{CO}_3^-$	$\text{O}^-$
Prime Cell Components	Carbon-based	Carbon-based	Carbon-based	Graphite-based	Stainless Steel	Ceramic
Catalyst	Platinum	Pt-Pt/Ru	Platinum	Platinum	Nickel	Perovskites
Primary Fuel	$\text{H}_2$	Methanol	$\text{H}_2$	$\text{H}_2$	$\text{H}_2$ , CO, $\text{CH}_4$	$\text{H}_2$ , CO
Start-up Time	Seconds-minutes	Seconds-minutes		Hours	Hours	Hours
Power Density $\text{kW/m}^3$	3.8-6.5	~0.6	~ 1	0.8-1.9	1.5-2.6	0.1-1.5
Combined cycle fuel cell Eff.	50-60%	30-40% (no combined cycle)	50-60%	55%	55-65%	55-65%

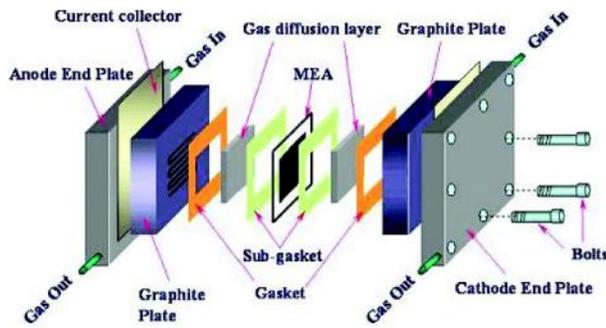


Fig. 4: Schematic of Polymer Electrolyte Membrane Fuel Cell showing different components (Basu, 2007)

catalyst and ensure the proper distribution of reactants over the catalyst. MEA is sandwiched between two bipolar plates (graphite), one in the anode side and the other one at the cathode side. Hydrogen molecules are stripped at the anode by the electro-catalyst into electrons and protons ( $H^+$ ). Electrons generated at the catalyst-carbon paper (GDL) interface are conducted through GDL, having high electron conductivity, to the bipolar plate and to the outer circuit. The bipolar plate, made of graphite, also has channels to supply the reactants over the diffusion layer. The protons permeate through polymer electrolyte membrane and reach the cathode side, where it reacts with conducted electrons from the outer circuit and oxygen from air to produce water. The continuous flow of electron from the outer circuit through a load is nothing but the generation of electricity, which performs electrical work. The polymer electrolyte membrane allows protons to pass through it and restricts the passage of electrons as it is not a conductor. The migration of proton in membrane is promoted by sulphonate group present in the membrane structure through the formation of hydronium ion. The membrane needs to be hydrated for efficient transport of proton in the form of hydronium ion. Hence, the PEM fuel cell cannot be operated above  $90^\circ C$  because of water loss from the membrane and subsequent poor conduction of proton. The reaction scheme for proton exchange membrane fuel cell is shown by Eqs. (1-3). In Fig. 4, one single cell is shown, which generates reversible voltage equals to 1.23 V. The reversible voltage is related to change in Gibbs free energy of the overall reaction

(Eq. 3) by the following expression:

$$\Delta G = -n F E \quad (4)$$

where,  $\Delta G$  is the Gibbs free energy change due to fuel cell reaction (Eq. 3),  $n$  is the number of electron transfer per mole ( $n = 2$ ) of hydrogen reacted,  $E$  is the reversible potential and  $F$  is the Faraday constant. The hydrogen-oxygen fuel cell reaction (Eq. 3) has a Gibbs free energy change of  $-237$  kJ/mole under standard condition. The change in Gibbs free energy for any electrochemical or chemical reaction is calculated from definition of the Gibbs free energy at constant temperature, which is given in difference form as:

$$\Delta G = \Delta H - T\Delta S \quad (5)$$

Where,  $\Delta H$  is the change in enthalpy during the reaction and  $T$  is the temperature and  $\Delta S$  is the change in entropy during the reaction and the product formation;  $\Delta H$  and  $\Delta S$  of reaction can be determined from the difference in enthalpy and entropy of formation of the products, less the formation of enthalpy and entropy of the reacting species at the reaction temperature. Using Eq. (4), at the standard state condition, one can determine reversible voltage,

$$E^{\circ} = -\frac{\Delta G^{\circ}}{nF} = \frac{-237,000 \frac{J}{mole}}{2 \text{ mole electrons/mole of reactants} \times 96500 \frac{C}{mole}} = 1.23 \text{ V}$$

The superscripted 'o' denotes the standard state ( $298$  K and  $1$  bar). Although each cell is capable of generating standard state reversible voltage (also known as standard state open circuit potential) equal to  $1.23$ , in actual operation due to Nernst loss (to incorporate the effect of reacting and product species concentration and temperature) and during fuel cell operation, when current is drawn, due to presence of overpotentials, for e.g., activation, ohmic and mass transport, the operating voltage is much less than that of  $1.23$  V. Normally, estimate of voltage generation at reasonable current density ( $700$  mA/cm<sup>2</sup>) in PEMFC is  $0.5$ - $0.7$  V volt. The fuel cell operation typically

characterized by current-voltage characteristics, which is explained in fig. 5, with dominant regions of losses identified. The current is specified in terms of unit area of electrode, which essentially signifies the reactor area. The power out may be calculated by,  $P = V \times I = 0.6 \times 700 \text{ mA/cm}^2 = 420 \text{ mW/cm}^2$ . To increase output voltage (or wattage), several MEAs in between bipolar plates are stacked in replicated fashion in a fuel cell unit. The schematic of such a fuel cell stack is shown in Fig. 6. It shows the alternative hydrogen and oxygen (air) in flow into the channels of the bi-polar plates. When cells are stacked in series, the total voltage may add up to 40-80 V depending upon the number of unit cells stacked. In parallel and series stacking combination, both voltage and current can be increased. The details are available in O'Hayre *et al.* (2006) and Larminie and Dicks (2003). It may be noted that from fuel cell, DC voltage is generated, which needs to be conditioned to change it to AC at higher voltage using DC-DC and DC-AC converter using electronic circuits.

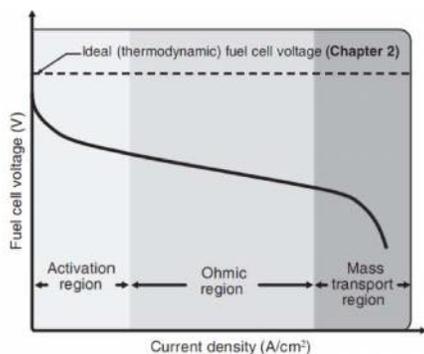


Fig. 5: Typical V-I characteristics of fuel cell showing various losses

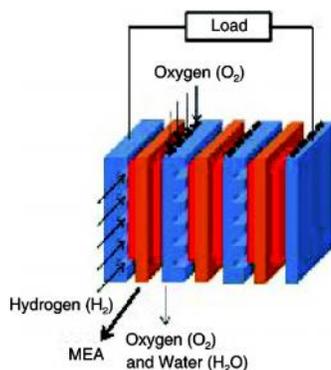
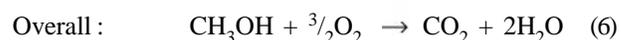


Fig. 6: Schematic of fuel cell stack showing repetition of unit cell with MEA and inflow of hydrogen and oxygen

### Direct Methanol Fuel Cell (DMFC)

Direct alcohol fuel cell (DAFC) is a variant of PEM fuel cell. In case, methanol is used as fuel, it is called direct methanol fuel cell (DMFC); and similarly in the case of ethanol, it is called direct ethanol fuel cell (DEFC). In general, when a fuel cell uses PEM as electrolyte, it is termed as DAFC; and in the case of anion exchange membrane electrolyte, it is called direct alcohol alkaline fuel cell or direct alcohol AEM fuel cell (DAAFC). It is well-known that fuel oxidation and oxygen reduction kinetics is faster in the presence of alkaline medium than acidic medium (Basu 2007). In the recent past, AEM-based DAFCs have become popular as fuel crossover is absent, which is predominantly present in PEM-based DAFCs.

As mentioned earlier, DMFC uses methanol instead of hydrogen gas. The methanol dissociates into electrons, protons and carbon dioxide at the anode. The protons diffuse from anode to cathode through the polymer electrolyte membrane and electrons migrate toward the cathode through an external circuit. At the cathode, the electrons, hydrogen ions and oxygen from the air react to form water. The reactions involved in direct methanol fuel cell are shown here (Basu 2007):



Methanol is a readily available and a low-cost liquid fuel that has an energy density comparable to the gasoline. If methanol can be used as a fuel, then all the problems of storing or generating hydrogen for fuel cell may be solved. The fuel cell system would be simpler to use and very quick to refill. These are the main advantages of DMFC. However, the main problem associated with DMFC is that the methanol electro-oxidation reaction at the fuel electrode (anode) is very slow as compared to hydrogen. This leads to a far lower power for a given size of fuel cell. The second major problem is the methanol crossover from anode compartment to cathode compartment through the polymer electrolyte membrane. Both these problems markedly reduce the performance of the DMFC compared to PEMFC.

Equation (4) shows the methanol oxidation reaction in which 6 electrons are generated by electro-oxidation of a methanol molecule. The reversible cell potential at standard condition of a DMFC is calculated as 1.199 V. The methanol electro-oxidation reaction is a complex multi-step process. It is a very slow reaction and the reaction may proceed through many routes. Fig. 7 shows the possible routes of the complete oxidation of the methanol (Larminie and Dicks 2003). In one of the routes, first, the methanol is oxidized to formaldehyde, which is further oxidized to formic acid. In the final step, formic acid is oxidized to carbon dioxide. Some of the methanol may take another route, which forms carbon monoxide as an intermediate product. The carbon monoxide acts as a poison to the generally used platinum catalyst at the anode of the DMFC. Therefore, to reduce platinum catalyst poisoning, ruthenium (Ru) is used along with the platinum catalyst in a 2:1 ratio. Ruthenium helps to oxidize carbon monoxide into carbon dioxide.

Methanol solution, which is used as fuel at anode

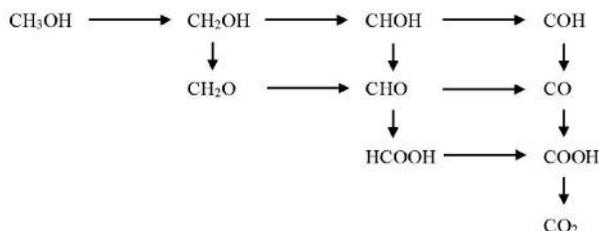


Fig. 7: Possible routes of methanol electro-oxidation

side of DMFC permeates through the electrolyte to the cathode side and this short-circuits the fuel cell, i.e., methanol oxidation at Pt cathode. There have been significant efforts towards the development of polymer electrolyte membranes for DMFCs in order to reduce the methanol crossover and increase their operating temperature (Kerres 2001). There are a few standard approaches for reducing the methanol crossover: (a) use of active anode catalyst results in complete methanol oxidation and not being available to diffuse through the electrolyte; (b) controlled use of methanol to the anode so that at the time of low current there is no excess methanol available, which can diffuse through the membrane; (c) use of thick electrolyte, that may reduce the fuel crossover but it should not be at the expense of the electrolyte

resistance; (d) use of composite polymer electrolyte membrane that may reduce the methanol crossover.

The development of polymer electrolyte membrane with reduced methanol crossover is an active area of research for DMFC. Efforts to develop the desired membrane for DMFC include modification of the conventional polymer electrolyte membrane (Nafion<sup>®</sup>) properties by incorporating organic or inorganic materials (composite Nafion<sup>®</sup> membrane) or by developing alternative PEM (Savadogo 1998). In an effort to modify the existing Nafion<sup>®</sup> membrane properties, inorganic solid acids have been incorporated with the objective of serving the dual functions of improving water retention as well as providing additional acidic sites (Malhotra and Datta, 1997). Composite membranes containing finely dispersed hygroscopic inorganic oxides (zirconium phosphate) effectively show decrease in methanol permeability with increasing (upto a certain extent) infiltrated oxides with a simultaneous increase in proton conductivity at a higher temperature (Daiko *et al.*, 2006). Yang *et al.*, (2001) demonstrated that composite Nafion<sup>®</sup>/Zr(HPO<sub>4</sub>)<sub>2</sub> membrane reduced the methanol crossover for DMFC operating at temperature close to 150°C. Hygroscopic oxides such as SiO<sub>2</sub>, Zirconium phosphate, and TiO<sub>2</sub> have been used for Nafion<sup>®</sup> modification (Watanabe *et al.*, 1996). Moreover, different composite membranes such as PVA/MMT, ErTfO/Nafion<sup>®</sup>, SPEEK with silicotungstic acid, etc., are under study for DMFC and DEFC. Recently, Barborá *et al.* (2009) produced ErTfO/Nafion<sup>®</sup> composite membranes, which showed higher proton conductivity and lower methanol or ethanol permeability than those of pure Nafion<sup>®</sup> membrane. The permeability was reduced by 77 % and 80 % for ethanol and methanol using 1% ErTfO/Nafion<sup>®</sup> composite membrane. The tensile strength and oxidation stability of 1% ErTfO/Nafion<sup>®</sup> was the highest among all the membranes under study. The results showed that the ErTfO/Nafion<sup>®</sup> composite may be a suitable membrane for direct alcohol fuel cells; exhibiting decreased fuel permeability, increased tensile strength and chemical stability, and decreased membrane swelling, without compromising proton conductivity.

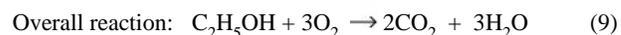
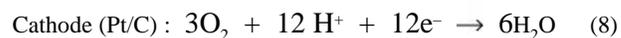
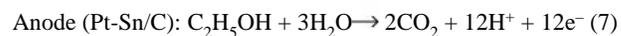
### Direct Ethanol Fuel Cell

During the last decade, many studies have been conducted on the electrochemical oxidation of alcohols, especially methanol, in DMFC. However, recently it has been shown that ethanol is more advantageous and convenient compared to methanol and other higher alcohols. The focus of researchers has shifted from methanol to ethanol in the recent past, mainly due to its low toxicity and volatility as compared to methanol. Moreover, methanol is not considered as primary fuel. Ethanol is renewable owing to the fact that it can be produced in large quantity by fermentation of sugar-containing biomass resources. There exists a strong distribution network for ethanol in most of the countries. Also, ethanol as a fuel has higher theoretical mass energy density than methanol (8 versus 6.1 KWh/kg). All these advantages make ethanol more favourable as fuel in DEFC (Basu 2007, Pramanik and Basu 2007).

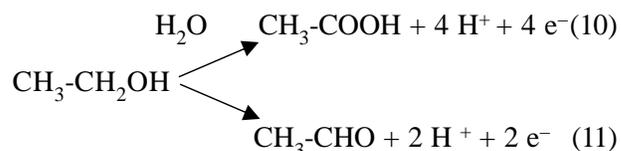
Different platinum-based electrodes, for e.g., Pt-X alloys (with X = Ru, Sn, Mo, Ir, Re, and W) have been investigated by Lamy *et al.* (2001) to study the electrocatalytic oxidation of ethanol. Among these, the most effective electrocatalysts were found to be Pt-Ru and Pt-Sn for DEFC. Since complete oxidation of ethanol requires breaking of C-C bond, its electro-oxidation is more difficult than that of methanol. It was confirmed in the review of the infrared reflectance spectroscopy and gas chromatography experimental data that electro-oxidation of ethanol leads to the formation of intermediate products with C-C bonds and adsorbed CO poisoning species (Lamy *et al.*, 2001). Analysis of the detailed electro-oxidation reaction mechanism of ethanol and the role of catalyst, for e.g., bi-functional mechanism of Pt-Ru/C, at the anode was first proposed by Lamy *et al.* (2002, 2004). Recently, ethanol electro-oxidation on carbon-supported Pt, Pt-Ru and Pt<sub>3</sub>Sn electrocatalysts in the temperature range of 70-120°C was studied by Colamati *et al.* (2006). They pointed out that Pt-Ru and Pt<sub>3</sub>Sn show about the same performance in a DEFC at 70°C.

In order to attain maximum energy from electro-oxidation of ethanol, it is necessary that the oxidation

reaction goes to completion. The complete oxidation of an ethanol molecule involves release of 12 electrons at the anode, as given by



The reversible cell potential at standard condition of a DEFC is calculated as 1.145 V. At a higher operating temperature (>100°C), DEFC gives enhanced performance with an increased CO<sub>2</sub> formation. Below 100°C, product analysis by differential electrochemical mass spectrometry (DEMS) or by chromatographic techniques (HPLC and GC) provided a detailed reaction mechanism of ethanol oxidation on Pt electrodes in acidic medium. The ethanol oxidation involves parallel and consecutive reactions as follows:



Reaction (10) occurs at higher electrode potentials ( $E > 0.8$  V vs. RHE), where the water molecule is activated to form oxygenated species at the platinum surface. Reaction (11) occurs mainly at lower potentials ( $E < 0.6$  V vs. RHE) (Hitmi *et al.*, 1994). There have been considerable efforts to develop bi-metallic and tri-metallic anode catalysts such that the complete electro-oxidation of ethanol to CO<sub>2</sub> at low temperature is possible and that there is no crossover ethanol from anode to cathode (Pramanik *et al.*, 2008, Tayal *et al.* 2011, 2012, 2014, 2015). The single direct ethanol fuel cell (DEFC) test at 90°C, 1 bar with catalyst loading of 1mg/cm<sup>2</sup> and 2M ethanol as anode feed showed an enhancement of catalytic activity in the following order. Pt-Re-Sn (20% Pt, 5% Re and 15% Sn by wt) and Pt-Ir-Sn/C (20% Pt, 5% Ir and 15% Sn by wt) exhibited highest performance among all the catalysts prepared with power density of 33 and 29 mW/cm<sup>2</sup> in DEFC, respectively, operating at 90°C (Tayal *et al.*, 2011, 2012). Basu *et al.* (2008) showed that improvement in cell performance may be achieved by adding

sulphuric acid in ethanol feed and using Ni-mesh as current collector at the anode. Goel *et al.* (2014, 2015) showed that performance of DEFC increases to 61.2 mW/cm<sup>2</sup> by using Pt-Ru on mesoporous carbon nitride (MCN) support at the anode. Andreadis *et al.* (2006) and Pramanik and Basu (2010) developed mathematical model for anode of DEFC and complete model for DEFC to estimate the overpotentials, respectively. The model predicted the experiment data on current-voltage characteristics with reasonable agreement. The influence of process parameters such as ethanol concentration and temperature on the cell performance is reflected in the model prediction.

In recent years, the interest in the direct alcohol alkaline fuel cell (DAAFC) rose again because of its better oxygen reduction kinetics in alkali than in acidic environment, simplicity, low cost and comparable efficiency compared to other types of fuel cell. Verma and Basu (2005, 2007a, b) developed direct alkaline fuel cell with liquid potassium hydroxide solution as an electrolyte for the direct use of methanol, ethanol or sodium borohydride as fuel. The typical power density achieved using Pt-Ru (40%: 20% by wt.)/C catalyst at 1 mg cm<sup>-2</sup> is 15.8 mW cm<sup>-2</sup> at current density of 26.5 mA cm<sup>-2</sup> for methanol and 16 mW cm<sup>-2</sup> at 26 mA cm<sup>-2</sup> for ethanol. The typical power density achieved for NaBH<sub>4</sub> is 20 mW cm<sup>-2</sup> at 30 mA cm<sup>-2</sup> using Pt-black as anode. A mathematical model of DAAFC predicted the experimental data well. Oxygen reduction reaction at manganese oxide cathode in alkaline medium is studied using cyclic voltammetry and by measuring volume of oxygen consumed at the cathode (Verma *et al.*, 2005). Single peak in cyclic voltammogram suggests that 4-electron pathway mechanism prevails during oxygen reduction at MnO<sub>2</sub> cathode in alkaline medium. This is substantiated by calculating the number of electrons involved per molecule of oxygen reacted at MnO<sub>2</sub> cathode from the oxygen consumption data for different fuels. A simple DAAFC stack has been developed, which consists of a series of flow channels in anode and cathode chambers (Gaurav *et al.*, 2010). Anode and cathode electrodes used were platinum black and MnO<sub>2</sub>, respectively. The open circuit voltage of the stack made of four cells was nearly 4.0 V. The maximum power density obtained from such a stack

(25°C) was 50 mWcm<sup>-2</sup> at 20 mA cm<sup>-2</sup> for methanol and 17 mA cm<sup>-2</sup> for ethanol.

### Approaches to PEMFC and DAFC Challenges

Proton exchange membrane fuel cells and direct methanol fuel cells currently use platinum-based catalysts at the anode and cathode. It would be difficult for the fuel cell technology to become competitive with other energy conversion technologies unless the overall materials cost is reduced significantly. For example, (Gasteiger *et al.*, 2004) reported that approximately one-fifth of the platinum loading is needed in PEMFC stack for mass commercialization of fuel cell powered automobiles. One method to decrease the cost of the materials in the catalytic layers of a membrane electrode assembly is to engineer catalysts with ultra-low precious metal loadings that still meet performance specifications. Researchers are currently engineering nano-structured supports such as carbon nano-tubes to increase the dispersion of the precious metal catalyst and enhance transport in the active layer (Jeng *et al.*, 2007; Priyanka *et al.*, 2009; Kannan *et al.*, 2009; Gao *et al.*, 2010). Others are attempting to reduce the catalyst cost. Two approaches to reduce catalyst cost are being actively pursued: one is to reduce Pt loading, and the other is to explore non-noble catalysts. In the short-term, catalysts containing low amounts of Pt are the priority and also practical, but in the long term, non-noble metal catalysts would be the better solution. Tremendous efforts have been made towards the finding out low Pt loading anode catalysts and non-noble metal catalysts (Vojislav *et al.*, 2007, Lim *et al.*, 2009). While Vojislav (2007) developed low metal loading nano-scale Pt-bimetallic catalyst for anode of a PEMFC with much higher power density, Lim *et al.*, 2009) developed Pd-Pt bimetallic nanodendrites PEMFC cathode with high activity towards oxygen reduction reaction. A team of scientists at the U.S. Department of Energy (DOE), Brookhaven National Laboratory, in collaboration with researchers from the University of Delaware and Yeshiva University, have synthesized a ternary PtRhSnO<sub>2</sub>/C electrocatalyst by depositing platinum and rhodium atoms on carbon-supported tin dioxide nanoparticles that is capable of oxidizing ethanol with high efficiency and holds great

promise for resolving the impediments to developing practical direct ethanol fuel cells (Kowal *et al.*, 2009). This electrocatalyst effectively splits the C–C bond in ethanol at room temperature in acid solutions, facilitating its oxidation at low potentials to CO<sub>2</sub>, which has not been achieved with existing catalysts.

Analysis of literature shows that over the last few years, tremendous progress towards improvements of activity and stability of non-platinum catalysts has been achieved. Some of the notable catalysts are tabulated in Table 3.

Thermal and water management issues should be handled with great care in the case of new types of gas diffusion layer (GDL), for e.g., metallic/carbon cloth or carbon paper for better electron conductivity and mass transfer of the reactants and products. A well-defined electron transfer through solid metallic structure and fluid flow path in GDL would reduce polarization losses. GDL is the key component of membrane electrode assembly (MEA). It should be such that activation polarization at anode and concentration polarization at cathode are minimal. GDL should keep a balance between water drying condition (decrease of proton conductivity in membrane) and water flooding condition (increase of mass transport resistance hence loss in voltage). Designing of thinner bipolar plate of low resistive

material or highly conductive material for excellent stack performance is the key to success for higher efficiency and minimization of cost of fuel cell. In general, investigators have been focusing on efficient development membrane and electrode-catalyst development. Following Fig. 8 on cost components of a typical PEMFC stack, it becomes obvious that commercialization of PEMFC highly depends on the development of GDL with high conductivity and high surface area with uniform distribution of pores and cheaper, efficient, highly conductive bipolar plate (Kamarudin *et al.*, 2006; Jayakumara *et al.*, 2006). Investigators are working on development of carbon fibre doped with metals, new carbon material and carbon nano-tubes and mesoporous carbon nitride.

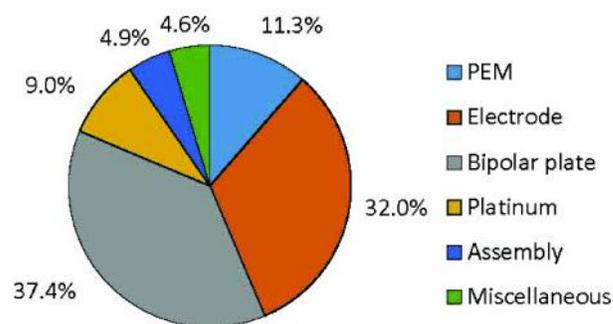


Fig. 8: Percentage share of PEMFC cost components

Table 3: Few Pt and non-Pt metal catalysts of interest to PEMFC and DAFC

Purpose	Catalyst	References
Hydrogen electro-oxidation	WC; WMC (where M= Co, Ni); Ir; IrO <sub>x</sub> ; IrM (where M=Ru, Mo, W,V)	Wiesener 1989; Zagal <i>et al.</i> , 1992; Faubert <i>et al.</i> , 1996; Alves <i>et al.</i> , 1999; Lefevre and Dodelet 2003; Schulenburg <i>et al.</i> , 2003; Olson <i>et al.</i> , 2008; Serov and Kwak, 2009
Methanol electro-oxidation	Pd/C; Pd/Ni/C; Fe-MnO <sub>x</sub> ; Ni-MnO <sub>x</sub>	Hwu <i>et al.</i> , 2001; Zellner and Chen 2005; Liu <i>et al.</i> , 2003; Ganesan and Lee 2005; Weigert <i>et al.</i> , 2007; Serov and Kwak, 2009
Ethanol electro-oxidation	RuNi; Pd/C, PdAu/C; PtSn/CeO <sub>2</sub> -C; (PtSnPd)/SnO <sub>2</sub> ; PtSn/C-Rh; PtSn/C-CeO <sub>2</sub> ; IrSn/C; Pt-Sn-W/C; CuNi, CuNiPt	Tarasevich <i>et al.</i> (2005); Xu <i>et al.</i> 2010; Neto <i>et al.</i> 2008; Antolini <i>et al.</i> 2009; De Souza <i>et al.</i> 2010; Cao <i>et al.</i> (2007); Ribeiro <i>et al.</i> 2008; Gupta <i>et al.</i> (2004)
Oxygen electro-reduction	Fe-N/C; Co-N/C; MnO <sub>2</sub>	Wasmus and Kuver 1999; Batista <i>et al.</i> , 2001; Shobha <i>et al.</i> , 2003; Savadogo <i>et al.</i> , 2004; Atwan <i>et al.</i> , 2005; Verma <i>et al.</i> (2005); Lima <i>et al.</i> , 2005; Wang <i>et al.</i> , (2007); Mustain <i>et al.</i> , (2007)

It has been found that the development of non-noble metal catalysts and GDL is comparatively simpler when they are used at higher temperature. However, with the present technology and use of PEM in the PEMFC and DAFC, it is not possible to use the fuel cells at an operating temperature above 90°C. Therefore, development of high temperature PEMFC and DAFC is being studied. A brief discussion on high temperature polymer electrolyte membrane is provided in the subsequent section.

### ***High-temperature Polymer Electrolyte Membrane Fuel Cells (HT-PEMFC)***

The interest in development of high temperature polymer electrolyte membrane fuel cells (HT-PEMFCs) has risen due to the numerous advantages of PEMFC technology operating above 100°C (Lobato *et al.*, 2007; Scott *et al.*, 2007; Li *et al.* 2008): (i) kinetics of both the electrode reactions are enhanced, (ii) tolerance of the Pt electrodes to carbon monoxide is increased, (iii) non-noble metal catalysts may be used, (iv) the integration of reformer technology is simpler, and (v) the cooling system for facilitating heat dissipation is simplified.

A suitable polymer electrolyte membrane is an important step for the development of HT-PEMFC. So far, perfluorosulphonic membranes such as Nafion® (DuPont), Dow (Dow Chemicals), Aciplex (Asahi Chemicals), and Flamion (Asahi Glass Co.) are the most widely used in fuel cell research and development. However, these membranes are not suitable for temperature higher than 100°C due to insignificant proton conductivity of the membrane for fuel cell purpose as the water content of the membrane at higher temperature, required for the conductivity, reduced appreciably. Therefore, three different types of membranes have been investigated for the fuel cell at temperature higher than 100°C: (i) modified perfluorosulphonated membranes, (ii) alternative sulphonated polymers and their composite and (iii) acid-base polymer membranes and their composites.

It is necessary to prepare polymer structure with higher glass transition temperatures, which can solvate the mobile cations in a polar phase containing the anions and the solvation groups. The solvation groups being

developed worldwide include imidazoles, which are tethered to the polymer matrix (Schuster *et al.*, 2005). Phosphoric acid doped polybenzimidazole, which is an alternative to Nafion® membrane, and works at a higher temperature suffers from leaching problem in water environment. It is therefore required to carry out investigation to provide a solid-state membrane with no leachable components. PolyFuel offers a new membrane, which works at a higher temperature (175°C) without much deterioration to reactants and by-products forms (Ashley 2005). Other new membranes such as sulphonated poly-(arylene thioether sulfone) (PATS), sulphonated poly (arylene ether sulphonate) (BPSH), and sulphonated poly (imide) (SPI) copolymers are found to be as good as Nafion® in many respects (Hickner and Pivovar 2005). Recently, high temperature proton exchange polyimide electrolyte membranes having sulphopropoxy and fluorenyl groups with higher proton conductivity are tested by Zhou *et al.*, (2005).

The polybenzimidazole (PBI) doped with phosphoric acid is a serious candidate for being used in HT-PEMFC. This acid-base membrane has low-cost and can work efficiently at high operational temperature of fuel cell. PBI membrane doped with phosphoric acid works at temperature up to 180°C without humidification and making it possible for the fuel cell to tolerate the use of H<sub>2</sub> having impurity of CO up to 3% with only small power loss. There are various other membranes for the HT-PEMFC such as PBI/PTFE, PBI composite membrane, SPEEK/PBI, pyrophosphate-based inorganic membrane, etc. on which active research is being conducted (Wu *et al.*, 2008; Verma and Scott, 2010).

The question is whether ceramic membrane can be developed as in solid oxide fuel cell (SOFC) as substitute for PEM, which operates at a temperature range of 150-200°C. Normally, ceramic material and metal oxides are used in high temperature SOFC. Impregnation of nano-metals in perfluorosulphonic acid membrane may help in proton transport. The membrane should have the following characteristics: chemical and mechanical stability for higher durability, control over undesired side reactions, greater tolerance to contamination caused by impure fuel or

by-products, low electro-osmotic drag and high proton conductivity.

Most of the points covered for PEMFC are also true for DAFC. Some additional issues are discussed further. Normally portable electronic equipment work at room temperature. However in some extreme cases at outdoor conditions, for e.g., sub-zero temperature or very high temperature, electronic equipment are used. In such conditions, the start-up time for the stack should be a few seconds such as 5-10 s. In DAFC, the main hurdle to be overcome is the development of membrane such that it does not allow crossover of fuel, for e.g., methanol and ethanol, through the membrane restricting fuel oxidation at cathode and minimizing over voltage loss.

PEMFC stack engineering and control is the next biggest hurdle once the component level improvements are achieved. The biggest challenge is in the computer controlling of fuel cell stack with load variation, minimum response time, better heat removal, less fuel flow resistance, by-products removal, decrease in stack mass per volume and weight and cyclic endurance.

### Commercial Development of PEMFC

In 1955, W. Thomas Grubb of General Electric (GE) introduced the concept of using a sulphonated polystyrene ion-exchange membrane as the electrolyte in a PEMFC. Three years later, another GE chemist, Leonard Niedrach, devised a method of depositing platinum catalyst directly onto the polymer electrolyte membrane. Both these technologies were used by GE to develop the fuel cell system for Gemini Spacecraft. This can be considered as the first commercial use of fuel cell. In 1959, British engineer Francis Thomas Bacon successfully developed a 5 kW stationary fuel cell. During the same time, a team led by Harry Ihrig built a 15 kW fuel cell tractor for Allis-Chalmers and it was demonstrated across the United States. Pratt and Whitney, in late 1960, licensed Bacon's U.S. patents for use in the U.S. space program to supply electricity as well as drinking water.

United Technologies Corporation Power (UTC Power) was the first company to manufacture and

commercialize 2kW stationary fuel cell system (PureCell 200) to use as a powerhouse for hospitals, universities, and large buildings. They are also the sole supplier to NASA till date. UTC Power supplies (PureCell 400 model) complete fuel cell system to Coca-Cola Enterprises, CT Science Center, Fujitsu America, Hilton New York, Mohegan Sun, New York Power Authority, NYPD, Saint Helena's Hospital, Samsung Everland, South Windsor High School, Verizon, Whole Foods Market, etc. In 1983, Ballard Power Systems started development of a PEMFC system. Now, Ballard develops different type of fuel cells both for stationary power generation (FCgen™) and automotive application (FCvelocity™). Ballard fuel cell systems are used by ACME group, BAXI Innotech, FutureE Fuel Cell Solutions, H<sub>2</sub> Logic, Heliocentris Fuel Cells AG, IdaTech, ISE Corporation, New Flyer Industries, Plug power, etc. In January 2007, Daimler AG, with thirty-six experimental units powered by Ballard fuel cells, completed a successful three-year trial in European metropolitan cities. The cities included in that project were Amsterdam, Barcelona, Berlin, Chicago, Hamburg, London, Luxembourg, Madrid, Perth, Porto, Reykjavik, Stockholm, Stuttgart, and Vancouver. Similarly, NedStack has an ongoing project with Akzo Nobel at Delfzijl, Holland. Its 50 kW system recently reached the milestone of 4000 running hours and has delivered over 200 MWh to the grid. Plug Power Inc. has been involved, since 1997, in the design, development, and manufacturing of fuel cell systems for industrial off-road and stationary power markets. The company develops and sells a range of fuel cell products and services, including PEMFC systems for mobile (GenDrive) and stationary power (GenSys). They also develop a high temperature fuel cell system for residential and light commercial co-generation. In 2008, they received full certification to the American National Standards for Stationary Fuel Cell Power Systems (ANSI/CSA FC-1) requirements. Recently, various power requirements in the Oscars red carpet ceremony (2010) were successfully fulfilled by Freedom Power fuel cell systems.

R&D in the fuel cell sector in Europe (Germany, United Kingdom, France, Russia) and Asia (Korea, Japan, China, Taiwan) has progressed as much as in

North America (USA and Canada). In Japan, PEMFC and MCFC technologies are already in the market, PEFC systems for vehicular and mobile applications as well as for standalone systems in residential use are ready for applications. PEMFC technologies started in 1980s, which led to their early commercialization as compared to other fuel cell technologies. Several hundred units including prototype have been sold. Non-noble catalysts based on C, N, O, H alloys and proton exchange membrane based on poly (paraphenylene)S are used leading to higher PEMFC efficiency and durability. Based on this technology, several companies are working on development of FC-based light duty vehicles and back-up power with heating facility for household use. Honda FCX car with twin 100 kW PEMFC stack claiming lifetime of 5000 h, cruising range of 620 km and 60,000 start-stop cycle is one of the finest example of development of FC-based vehicle in Japan. Toshiba, Eneos-Celltech, Ebara-Ballard, Toyota Motors, Panasonic installed 3307 units of 1 kW PEMFC stack work on LPG and LNG using reformer. The 1 kW PEMFC stack works with 40% electrical efficiency, produces hot water with claimed lifetime of 40,000 h and 4000 times start-stop cycles. The cost of both PEMFC operated FCX Honda car and 1 kW PEMFC system is exorbitantly high. The number of 1 kW PEMFC stationary systems sold and installed by different companies are shown in Table 4.

**Table 4: 1 kW PEMFC stationary systems installed in Japan**

Manufacturer	LPG	LNG	Kerosene	Sub total
ENEOS Caltech	1062	191	0	1253
Ebara Ballard	0	396	314	710
Toshiba	554	194	0	748
Panasonic	0	520	0	520
Toyota Motors	0	76	0	76
Total	1614	1379	314	3307

Considerable commercial activity has been seen in the last decade on the development of DMFC as a power source for portable electronic equipment such as laptops and mobile phones. Toshiba and Motorola

demonstrated DMFC-powered laptop and mobile phones in different international exhibitions on fuel cell technology. In a similar manner, DEFC and direct glucose fuel cell development have been undertaken by many investigators (Basu *et al.* 2010, 2011) and Sony Corporation.

However, their commercial viability *vis-a-vis* Li-ion battery in mobile phone and other handheld devices application is not known, but it hold much promise.

### Fuel Cell and Its Application

PEMFC is used for motive power i.e., vehicle application, power generation for portable application as well as powering a building complex and block of houses i.e., utility market in the form of combined heat and power. Hydrogen is the fuel for PEMFC, which can be produced through different pathways, for e.g., utilizing solar and wind power to electrolyse water to produce hydrogen, biomass to synthesis gas and further converting to hydrogen, coal to hydrogen with carbon dioxide sequestration, natural gas to hydrogen with separation of unwanted (CO) gases, nuclear and thermo-chemical reaction route to produce hydrogen. In the initial stage in North America, Europe and Japan, fixed route vehicles, busses, trucks, and delivery vans have been tried to create effective hydrogen dispensing facility and gain experience from it. Internal combustion vehicle, fuel cell vehicle (ICE-FCV) or fuel cell hybrid vehicle (FC-HEV) has been the starting point in these countries to have a smooth transition from ICV to FCV in terms of economy, infrastructure and technology development. India may follow a similar strategy.

DAFC is constructed on basis of proton exchange membrane (PEM) or anion exchange membrane (AEM) technology. DAFC is suitable as a power source to portable electronic equipment, for e.g., laptops, mobile phones, pads, and camcorder replacing the use of Li-ion batteries with possible commercialization in near future. The market for portable application is increasing by leaps and bounds with advancement in microelectronics technology, fore.g., micro-fluidics devices, micro-chemical plants, lab-on-a-chip, etc. Thus, demand for micro Watts to Watt ranges of miniature to portable power packs

will increase and portable fuel cell is a good option as the duration of power supply by fuel cell is much higher than Li-ion battery. The primary candidates as fuel for direct fuel cell technology are methanol, ethanol, formic acid, esters and sugar with improved catalysts and membrane electrolyte technology for the fuel cell.

### Fuel Cell Research in India

The last few years have seen considerable activity in the area of fuel cell research in India. Most of the basic research is done by India's reputed academic institutions and very few industrial organizations are involved in research. A vast majority of this research is funded by the government under new energy policies of the Ministry of New and Renewable Energy. These research institutions are involved in more fundamental research such as catalysis and MEA development. Some institutions are also involved in more application-oriented research such as stack development and Balance-of-Plant(BoP)-related work. Table 5 presents a summary of fuel cell related activities of key R&D institutions in India.

Although, Indian companies are generally regarded as only manufacturers and service providers with less emphasis on R&D, some big corporate houses of India have entered the area of fuel cell research. Most of these industrial houses are carrying out applied research which is concerned with the adaptation of fuel cell technologies in the Indian scenario. Car makers such as Tata and Mahindra & Mahindra are involved in making fuel cells a part of the Indian automobile industries.

Apart from these, several foreign companies have also entered the Indian market since the market is still in a nascent stage. Some of these organizations are focusing on bringing the technologies developed in other countries to India, while some have focused on using Indian expertise and resources to develop a strong R&D base. Some local players are also involved in collaborations with these companies. In the last few years, India has seen a steep growth in fuel cell research activities with several national and international conferences and workshops organized locally. Both academic institutions and private sector

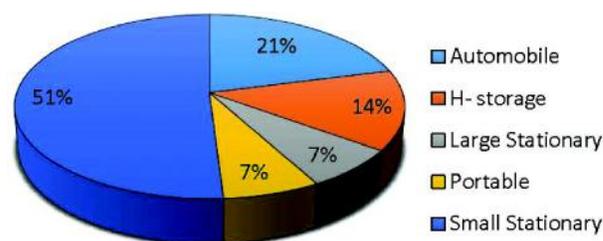


Fig. 9: Distribution of fuel cell organization application-wise in India

companies are actively participating to organize these events. These events have provided a good platform to Indian researchers to interact among themselves and also with researchers from other countries. This is quite important, as no active network of Indian researchers exists in the area of fuel cell research.

A large percentage of organizations involved in fuel cell activities are working on small stationary units (Fig. 10). Power distribution is a big problem in both domestic and industrial sectors in India and fuel cells are being considered as a good option to provide stationary backup power. Several programmes related to stationary applications of fuel cells are being promoted by the government.

Apart from stationary power, automotive sector is also an important focus area for fuel cell research institutions in India. Some of the big industrial organizations are involved in development of fuel cells for automobile applications. Hydrogen storage, portable and large stationary applications of fuel cells are some other important areas of fuel cell research in India (Table 5).

### Markets for Fuel Cells in India

A fast growing economy, with a large gap in demand and supply of power, makes India a good potential market for various power generation technologies including fuel cells. Favourable national energy policies for hydrogen and fuel cell technology development in stationary power and automotive sectors strengthen India's position as a future market for fuel cell based applications. This section of the report describes some of the markets for fuel cells in stationary power and automotive sectors.

**Table 5: Summary of fuel cell R&D organizations in India**

Institute/Organization	Main Focus Area(s)	Achievements/Remarks
CECRI, Chennai	PEMFC, DMFC, DBFC, Hydrogen Generation	Developed a 1 kW PEMFC stack, Developed a 5 kW PEMWE
CFCT, Chennai	PEMFC, Hydrogen Generation	Developed PEMFC stacks- up to 5 kW, Grid independent power systems (3 kW), Fuel cell systems for transport applications with Mahindra Rise and Reva
CGCRI, Kolkata	SOFC	Developed electrode and membrane materials for high performance SOFCs and Low Temperature SOFC. 400 W SOFC stack developed. SOFC technology is discussed elaborately in a separate chapter.
SPIC SF, Chennai	PEMFC, DMFC, Hydrogen Generation	Developed 5 kW PEMFC stacks, 250 W DMFC Stack, PEM-based water and methanol electrolyzers, fuel cell based stationary applications such as UPS
IIT Bombay, Mumbai	PEMFC, DMFC, IT-SOFC, hydrogen generation	PEMFC system development, Catalysts for PEMFC, Working on HT-PEMFC and IT-SOFC, Hydrogen storage in complex hydrides
IIT Delhi, Delhi	PEMFC, DAFC, Hydrogen Generation, SOFC	Developed DEFC with power density of 70 mW/sq.cm, electrode-catalysts, Developed Direct Glucose fuel cells. Non-PGM ORR catalyst and micro fuel cell for MEMS. Anode materials for hydrogen generation using PEM water electrolyzer, working on anode material for Direct Hydrocarbon SOFC and low temperature SOFC.
IIT Madras, Chennai	PEMFC, DMFC, SOFC, Hydrogen Storage	Developed a DMFC with non-noble cathode catalyst with 340 mA/sq.cm (0.6 V) at 80-°C. Non-PGM catalyst for PEMFC, SOFC material research
NCL, Pune	PEMFC	Prepared thermally stable PBI membranes, Demonstrated a 350 W (15 cell) PBI-based PEMFC stack
NMRL, DRDO, Mumbai	PAFC, PEMFC, Hydrogen Storage	Developed and demonstrated 700-1000 W capacity PAFC-based UPS/generators. 1.2 kW PAFC system integrated in an electric vehicle developed under DRDO-REVA joint project. Development work on PEMFC and SOFC and hydrogen generation by autothermal reforming
BARC, Mumbai	SOFC, PEMFC	SOFC material and tubular SOFC under development
BHU, Varanasi	Hydrogen Storage, Hydrogen IC Engines, Hydrogen Production	Developed AB <sub>3</sub> and AB <sub>2</sub> type storage materials with improved storage capacity. Converted existing petrol-driven IC engines to operate with hydrogen as fuel
IISc, Bangalore	PAFC, DMFC, PEMFC	Developed PAFC with power density value of about 560 mW/sq.cm.
Mahindra Rise	Hydrogen IC engines	Developed hydrogen powered Alfa 3-wheeler vehicle. Developing battery-powered electric hybrid vehicle
TATA Motors	Fuel cell technology for transport applications	Developing a fuel cell based city bus, Projects on using hydrogen blends as fuels. TATA teleservices involved in demonstration of fuel cell technology for mobile tower backup power
Indian Oil Corp. Ltd.	Hydrogen infrastructure, hydrogen for transport sector	Setup hydrogen dispensing stations. HCNG usage in 3-wheeled vehicles and light duty buses.
Reliance Industries Ltd.	PEMFC for stationary applications, SOFC	Joined the NMITLI project for Indigenous PEMFC Technology Development as the industrial partner. Established a fuel cell R&D lab in Mumbai
REVA (Own by Mahindra Rise)	Fuel cell based small cars	Developed a car with NMRL with 1 kW PAFC stack on board. Involved in a similar project with CFCT.
BHEL	PAFC, PEMFC,SOFC	Developed a 50 kW PAFC power plant, developed 1 kW PEMFC modules and a 3 kW PEMFC power pack. Partner institute in the development of a 5 kW PEMFC system under the NMITLI project

Nissan India	PEMFC technology for automobile applications	Working on membrane development for PEMFC technology. Studying membrane degradation
ACME Telepower	Fuel cells for backup power	Joint venture with Ballard power systems Inc. and Ida-Tech to set up a high volume low cost fuel cell systems for mobile tower back-up power
Eden Energy (India) Pvt. Ltd.	Hhydrogen for transport sector	Involved in production of Hythane, agreement was signed with Ashok Leyland for the supply of Hythane to be used in natural gas powered buses
Gas Authority of India Limited	Hydrogen Infrastructure	Main player for supply of suitable fuels, including hydrogen, natural gas, propane, butane and methanol
Bloom Energy (India) Private Limited	SOFC	Working on testing and characterization of SOFC technology
Daimler Research Center (DMRC), Bangalore	Fuel cell for transport applications	Setup an outsourcing R&D centre in Bangalore. Considering launching a commercial fuel cell vehicle in India. Final outcome of DMRC is not known to author
Indian Space Research Organization	Application of PEMFC powering automatic weather station. PEMFC use future space station and man mission	100 W PEMFC system is developed for automatic weather station

### **Stationary Power**

Stationary power generation sector in India can be considered to have the most near term potential market for fuel cells. The rapid growth in Indian economy demands for a growth in infrastructure facilities and energy supply. India is suffering from severe power shortages which can affect the growth levels of economy as it affects both the domestic and industrial sectors. In India, several industrial and commercial enterprises use some form of captive power and are potential customers for fuel cell based stationary power plants. An unreliable grid system and prolonged power blackouts in urban areas in India add to the market potential for fuel cell applications in stationary power sector. A study conducted by TERI, Delhi, on the market assessment of fuel cells in India, identified several key markets for fuel cell stationary power plants in India. These include chlor-alkali industry, luxury hotels, paper and pulp industry, dairy industry, telecommunication industry and stationary backup power. The study identified availability of fuel for fuel cell power plant as one of the key factors in selection of potential consumers. Also, potential use of waste heat from fuel cell power plant was another important factor considered in the selection of consumer. Table 6 presents some of the key niche areas for stationary power generation identified from the study.

Another market application for fuel cell base power plants could be in distributed power generation in Indian rural areas. Due to the unavailability of grid connected power supply, these areas can be seen as a potential market for distributed power generation systems. Government incentives and support in this area can be seen as an advantage for the market players.

### **Telecommunication Industry**

India has emerged as one of the fastest growing telecom markets in the world. Mobile services in telecom industry have been growing at a much faster pace mainly in urban areas. Still, the total wireless tele-density remains at around 40.3% which shows a huge untapped potential for market growth. The main future market for these services lies in non-urban areas where penetration of these services remains low.

A growing telecom industry presents itself as a potential market in mobile towers backup power. There are around 2,80,000 mobile telecom sites and it is estimated that about 5,00,000 sites will be required by 2018. One of the main infrastructure requirements for mobile towers is the provision of backup power which is a necessity due to frequent power cuts in both urban and rural areas. The issue of irregular

**Table 6: Summary of key niche markets for stationary power generation in India**

Potential Markets	Power requirement, MW	Potential fuel cell types	Remarks
Luxury Hotels	0.5 -5	PAFC, SOFC, MCFC	Availability of natural gas or LPG a big advantage
Chlor alkali	5-45	SOFC, MCFC, PEMFC	Hydrogen available as a by-product
Pulp and Paper	2-50	SOFC, MCFC	Availability of natural gas is required
Dairy Industry	<5	AFC, PAFC, PEMFC	Use of biogas from rural areas will be economical
Telecom & IT	<5	AFC, PAFC, PEMFC	Fuel availability, a big issue
Weather station	<5	PEMFC, DMFC	Hydrogen and methanol fuel

power supply is more pronounced in the rural sector, where a number of Indian villages either do not have an electricity grid connection or face limited power availability. Mobile towers use backup power in the form of diesel-powered generators. Although the start-up costs for diesel based power generators are low, the operating costs are quite high due to high costs of crude oil in recent times. It is estimated that over 35% of rural cell site's network operating expenses are due to costs associated with electricity and diesel.

Fuel cells are being offered as a viable option to telecom customers in place of diesel generators. Telecom infrastructure companies are willing to pay a premium for reliable power, especially in remote rural areas. Fuel cells offer clean, noise-free and most importantly, they can be run on a variety of fuels. These fuels can be cheap biogas which is available in remote rural areas and thus can provide a solution to telecom companies looking for a replacement to diesel-based generators.

In May 2008, agreement was signed between Ballard Power Systems and ACME Telepower for supply of fuel cell stacks to the telecom's backup power. A development and supply agreement was signed between ACME, Ballard and IdaTech for supply of 5 kW natural gas PEMFC stack 30,000 systems to be delivered by 2013. A minimum order of 10,000 systems is to be completed by 2010, rest of the order after evaluation of this unit. In August 2008, Plug Power demonstrated a LPG-fuelled telecom power backup unit in partnership with Hindustan

Petroleum Corp. Ltd. and Tata Teleservices. However, outcome of the above agreement is not known to the public.

### *Chlor-alkali Industry*

Chlor-alkali industry in India mainly comprises manufacturers of caustic soda and soda ash. In the process of manufacturing caustic soda, some valuable by products are produced. A tonne of caustic soda produces 860 kg of chlorine and 25 kg of hydrogen. Chlorine and hydrogen produced can be combined to prepare hydrochloric acid. These basic chemicals are used by many industries. Table 7 shows the hydrogen-producing capacity of various chlor-alkali plants in India.

The manufacturing process of caustic soda is quite energy intensive (5-45 MW). The load requirements are met by grid supply as well as captive power plants. Hydrogen as a major by-product of the manufacturing process finds little usage in the chemical industry (Table 7). Although some hydrogen is used in the manufacturing of hydrochloric acid and some is sold after compression and storage in bottles, a significant amount does not find any use. Compression of hydrogen and storage into cylinders is a labour and energy intensive process. Also, market for HCL is limited; so, conversion of hydrogen to HCL is restricted by demand. Caustic soda is transported to long distances after it is converted to caustic flakes by an evaporation process, which consumes fuel. Use of hydrogen in this process is also difficult as it requires sophisticated burners and controls. It has also been

estimated that all the hydrogen produced as by-product in the plant cannot meet the energy requirements of the flaking process. So, use of additional fuel is necessary in any case. Due to these factors, use of hydrogen in fuel cells presents itself as a promising option. In recent times, due to liberal import policies of Government of India, domestic chlor-alkali industry is facing stiff competition from overseas manufacturers which sell caustic soda at a significantly lower price. So, domestic manufacturers are looking for technologies which can give them an advantage in terms of overall cost reduction inside the plant. Several domestic manufacturers have switched to more efficient technologies of production namely membrane cell processes and are incurring large capital investments. For fuel cell technology adoption in this market, economics of fuel cell power plant and particularly the capital investment would be of utmost importance. Thus, fuel cells which also generate waste heat in the form of steam can be thought of as a good option as they can satisfy some of the energy needs of the plant. SOFC and MCFC power plants could be the ideal fit in these cases. Steam from the fuel cell power plants can be used in the flaking process of the caustic soda. Benefits of the fuel cell power plants depend on how effectively the waste heat is utilized in the plant.

**Table 7: Hydrogen producing capacity of some chlor-alkali plants in India**

Manufacturer, State	H <sub>2</sub> , Nm <sup>3</sup> /day	Excess H <sub>2</sub> , Nm <sup>3</sup> /day
Century Rayon, Maharashtra	11000	11000
Hukumchand Jute Industries Ltd., M.P.	23100	11100
DCW Ltd., Tamil Nadu	48160	16800
Indian Petrochemicals Corporation Ltd., Gujarat	120000	50000
Grasim Industries. Ltd.	112000	50000
Tata Chemicals, Gujarat	29500	4720
Punjab Alkalies & Chemicals	84000	11866
DCM Sriram, Kota	91000	19000

### **Luxury Hotels**

There is a need for reliable primary and backup power in large commercial premises. The five star hotels of India can be viewed as a prime candidate for the adoption of fuel cell technology in stationary power generation. The load requirements range from 500 kW to 5 MW depending upon the capacity of the hotels. The load is distributed lighting requirements, kitchen load, operation of lifts and mainly space conditioning.

These hotels require heat for various purposes which include hot water for guests, kitchen, and laundry. Some hotels also have sauna baths and health clubs which also require steam. The hotels are well-connected by grid, but due to frequent power cuts, they also maintain some form of captive power generation which can meet the energy requirements. Most commonly diesel-based generators are used as captive power plants in the hotel. Fuel cells which can simultaneously supply electricity, steam and hot water will be an attractive option to hotel owners. PAFC, MCFC and SOFC power plants are best suited for this case. A clean and noise-free energy generation process with ease of operation can be considered as factors which will drive fuel cells entry in this market.

Availability of fuel for such plants will be another important factor in this market. Some of the cities in India, mainly metropolitan cities such as Delhi and Mumbai have a good infrastructure for natural gas distribution. This infrastructure is being extended to commercial hotels in these cities. These large hotels also have a good supply of LPG gas for their cooking requirements. So, availability of fuels is another advantageous factor for the adoption of fuel cell technology in this market.

### **Other Stationary Power Generation Markets for Fuel Cells**

The pulp and paper industry in India have electricity requirement in the range of 2-50 MW. The industry also requires low and medium pressure steam in the chemical processes of cooking raw material for making pulp, drying of paper and evaporation processes. The bleaching plants also require saturated steam at around

200°C. The industry uses captive power generation systems mainly in the form of diesel generators. Sometimes, gas turbines or steam turbines are used for power generation.

Fuel cell system with the capacity to produce heat (PAFC, SOFC and MCFC) can be useful in the industry. Again, the capital cost of the fuel cell systems would be critical in their entry into this market. Another area of fuel cell application in stationary power sector is in the dairy industries most of which are in the western and north-western parts of the country. These industries use diesel generators or gas turbine based captive power generation systems. The dairy industries in western India have easy access to natural gas. Other fuels such as biomass and biogas are also available in these areas. Thus, fuel availability is a major advantage for fuel cell applications in these industries.

Power cuts in the urban area have created a market for standby/back up power generation systems used by domestic users. The backup power load ranges from 0.3 to 5 kW depending upon the requirements of the domestic user. Diesel, petrol and kerosene generators and battery banks (DC to AC inverters) are the most commonly adopted power generation systems used by domestic users. The problem with diesel, petrol and kerosene based generators lies in the pollution and noise caused by these systems. The inverters are also not very efficient while charging and discharging cycles. PEMFC-based systems can be good alternative for domestic users but they face stiff competition from conventional generators in terms of their costs.

Fuel cell power systems designed and developed by Indian Space Research Organization (ISRO) were installed (Fig. 10) at Shillong and Thiruvananthapuram for powering Automatic Weather Stations (AWS). In a first of its kind in the country, the first unit was installed during April 2013 and it has completed one year of operation, successfully. The power systems are based on a 100W class PEM fuel cell stack that operates on hydrogen and air and deliver 12V DC required for the functioning of AWS. The systems are designed to work in fully unmanned and autonomous mode with very simple architecture with



Fig. 10: Fuel cell power system installed by ISRO for powering automatic weather station at Shillong

minimal subsystems, especially, dynamic components. The systems make use of hydrogen from standard gas cylinders and ambient air, directly, and deliver stable electrical output. The work was done as a spin-off application of the systems under development at ISRO, after specific design adaptations. More such installations, which have the potential to enhance our remote sensing and disaster mitigation capabilities, have been planned.

There are a large number of automatic weather stations (AWS) all over the country and these acquire regional weather data, which is then pooled into a common data base, automatically, through a satellite uplink. The AWSs work in fully outdoor conditions and are many of them are located in remote areas without grid power. The units are configured to operate in fully autonomous mode and are normally powered by solar panel-battery combination. The AWSs located in areas with long spells of rain and winter, generally, suffer from insufficient solar intensity for certain periods. This renders them non-functional since the battery tends to run out of charge due to insufficient recharging. Similarly, those located in high altitudes and latitudes are also prone to chronic low solar intensity resulting in under performance of the power system.

Fuel cell power system operates on the stored hydrogen gas and is fully free of all the constraints mentioned. Also, when the system operation is configured in such a way that the refilling of gas

cylinder would be needed once in 3-4 months, it becomes quite manageable. The system provides a fully clean power generation cycle and water is the only by-product. The system thus offers an alternative power system option for AWSs. The new solution based on fuel cells enables AWSs, which provide crucial data on regional weather forecasting and now-casting, to operate free of adverse weather conditions.

### **Fuel Cell Markets in Automotive Sector**

The automobile industry in India is one of India's fastest growing industrial sectors. Still, the penetration in this sector is quite low which indicates a huge potential for growth. The Indian automobile industry can be classified as follows:

Light duty 2- and 3-wheeled vehicles, passenger car

Heavy duty vehicles including buses and trucks

The following section discusses the market potential of fuel cells and recent market developments in both these categories.

### **Light Duty Vehicles**

Majority of light duty vehicles in India belong to 2- and 3-wheeler vehicle categories. Two-wheeled scooters and motorcycles are the main mode of transport for the Indian middle class homes which constitute a large market. As per the NHERM, activities related to adoption of hydrogen-based technologies in this vehicle segment have already started. The focus is on the development of hydrogen-powered IC engines rather than adoption of fuel cells. Domestic manufacturers such as Mahindra Rise have developed a hydrogen IC engine based vehicle 'HyAlfa' (Table 5). Bajaj has developed a hydrogen-powered three-wheeler vehicle. Companies are involved in developing hybrid versions of 2- and 3-wheeled vehicles. However, lack of hydrogen infrastructure in majority of Indian cities has kept these vehicles from coming into entering the market. Most of such vehicles are in the demonstration stages in Delhi, where they have developed a hydrogen/CNG infrastructure. Fuel cell application in this area would not be possible in the near term. This is due to high

capital costs associated with fuel cell systems, which makes it hard for the consumers in this category to adopt this technology. Indian middle class consumers would find it hard to invest a substantial amount on a two-wheeler when gasoline-based vehicles are available at substantially cheap prices. Similarly, fuel cell costs may be prohibitively high for an Indian autorickshaw operator. With huge skilled labour force in India for maintenance, it is possible that fuel cell applications in India may not be as sophisticated as that of the developed world, where labour force is dwindling and costly. This may bring down the cost of fuel cell and become competitive with the IC engine based vehicles. Another important issue will be the durability of fuel cell based vehicles given the near continuous operation of 3-wheelers and the bad condition of Indian roads which are often filled with potholes. So, market potential for fuel cell based 2- and 3-wheelers is quite limited in India.

Passenger car market in India presents an interesting picture. This sector is growing at a very rapid pace which has led to many international automobile manufacturers entering the Indian market. Apart from a number of large domestic players, the Indian automobile sector now has several world-known automobile manufacturers, which sell their products in the premium segment of the market. The domestic manufacturers in this market are looking for alternative fuelling options. Various activities regarding the development of alternative fuelled vehicles are being carried out by these car companies.

Again a look at the hydrogen fuel infrastructure condition in India tells us that commercialization of fuel cell based passenger cars is not an immediate-term option. Also, the capital costs related to these systems make it hard to commercialize such vehicles in Indian markets. Although, fuel cell based vehicles can be a good option to battery-based electric vehicles as range extenders which have a very small market in India at present. Delhi government gives tax sops to manufacturers and users of battery-operated vehicles, which is a good sign to start with. Such benefits may be extended to fuel cell operated vehicles in future during implementation stage.

## Heavy Duty Vehicles

Buses in India show a promising future for the adoption of fuel cell technology. A number of manufacturers in this industry in India are showing much interest for the development of fuel cell based demonstration units. Operation of buses in many cities is by state-run enterprises. Also, in many metro cities, the government is planning to impose some environmental constraints on public transport systems of which buses are an integral part. A good example of this is the conversion of city buses in Delhi to CNG-fuelled buses in 2001. In near future, buses seem to be the most promising option for fuel cell technology implementation. Although, high capital costs will still hinder this technology from entering the market, but fuel cell buses for demonstration purposes have sufficient scope.

Two of the biggest manufacturers (Tata and Ashok Leyland) in this sector have started developing buses based on hydrogen technologies. Tata and ISRO are jointly developing a PEMFC-powered bus for demonstration purpose. While they are using Ballard PEMFC stack as power source along with a battery, the system engineering is completely developed by Tata and ISRO. Ashok Leyland is working with Society of Indian Automobile Manufacturers on guidelines of NHERM towards development of low cost hydrogen IC engine technology. In detail, they are discussed here.

Tata Motors Ltd. (TML) is developing a hydrogen-fuelled fuel cell bus which is in line with its corporate policy of designing and developing environment-friendly, sustainable transport solutions. In this endeavour, Tata Motors is developing a fuel cell power train technology to power buses which will be fuelled with hydrogen (Fig. 11). As part of this initiative, Tata Motors has set up a Research Centre, in Society for Innovation and Development at Indian Institute of Science, Bangalore Campus and has created a fuel cell power system test facility there.

A typical low floor Tata Motors Starbus running on CNG-based electric traction was used for the purpose. The CNG electric generator was replaced with a fuel cell power system. The power system



Fig. 11: Tata Motors designed fuel cell Starbus which was displayed during AutoExpo 2010 at Delhi

consisted of a FCvelocity<sup>TM</sup>-1100 Ballard stack capable of 120 kW and a Li-ion battery pack. The battery is placed in the front-end so that it powers the motor and the fuel cell keeps charging the battery. This way, the battery was made to handle the transients. Hydrogen gas was stored under high pressure up to a permissible level of 350 bar on the roof of the bus in a composite high pressure vessel. An air compressor delivered the required quantity of air into the system based on a proprietary control logic evolved for the purpose. Development of a robust gas humidification system by TML was indeed a highlight of the programme. The prototype realized does not envisage recovery of the product water which is exhausted into the atmosphere. However, future vehicles are expected to include water recovery as well. Cooling radiators in bus are mounted on the roof top. The total power system was mounted in the rear module of the vehicle. The bus being developed comprises fuel cell power system, electric traction, hydrogen storage system and controls. Hydrogen is used as fuel, which will be stored on-board in compressed form in light weight composite cylinders. ISRO has provided some of the technology-related hydrogen handling. Electric power is generated by fuel cell power system on-board bus by indirect combustion of hydrogen. Surplus power required during transients is met by the lithium ion traction battery which also absorbs power generated by traction system during braking. Power generated is regulated and controlled by using traction controller. The motive power for the bus is provided by electric traction. Tata Motors has already developed two

prototype buses and trials are being carried out at test facilities. Several cities around the world, consider the fuel cell and battery hybrid bus as the most promising technology to facilitate decarbonisation of public transport.

The other kind of heavy vehicles in India, trucks, show very little scope for fuel cell adoption. These trucks are mostly operated by private owners. Fuel cell operated trucks should be affordable and operation-wise less expensive so that the owners do not incur loss. These owners would not be willing to invest in this technology unless the capital costs become low. Also, the operation of these trucks is very rough and runs for long hours. The fuel cell systems in such vehicles should be rugged and reliable with low maintenance costs. These factors impose further restrictions for the fuel cell technology to be implemented in such vehicles. The only option is to use fuel cells in the auxiliary power unit of trucks with the present state-of-the-art FC technology.

There is a small window for the entry of fuel cells in the niche vehicle market. These vehicles can

be forklift trucks in the warehouses of the industries such as food processing and microelectronics manufacturing. Such industries require zero emissions vehicles and mostly use battery-run electric vehicles to which fuel cell based vehicles will be a good alternative. Also, some airports in the country can switch to fuel cell operated vehicle fleet to decrease noise and air pollution inside the airport premise. Some monumental sites such as Taj Mahal in Agra impose severe restrictions on the use of fossil fuel based vehicles near the premise. Sites such as these can be a good market for fuel cell operated vehicles as they are already using electric vehicles.

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### References

- Alves M C M, Dodelet J P, Guay D, Ladouceur M and Tourillon G (1992) Origin of the electrocatalytic properties for oxygen reduction of some heat-treated polyacrylonitrile and phthalocyanine cobalt compounds adsorbed on carbon black as probed by electrochemistry and X-ray absorption spectroscopy *J Phys Chem* **96** 10898-10905
- Andreadis G, Song S and Tsiakaras P (2006) Direct ethanol fuel cell anode simulation model *J Power Sources* **157** 657-665
- Antolini E, Colmati F and Gonzalez E R (2009) Ethanol oxidation on carbon supported (PtSn) alloy / SnO<sub>2</sub> and (PtSnPd) alloy/SnO<sub>2</sub> catalysts with a fixed Pt/SnO<sub>2</sub> atomic ratio: Effect of the alloy phase characteristics *J Power Sources* **193** 555-561
- Ashley S (2005) On the Road to Fuel-Cell Cars *Sci Am* **292** 62-69
- Atwan M H, Northwood D O and Gyenge E L (2005) Evaluation of colloidal Os and Os-Alloys (Os-Sn, Os-Mo and Os-V) for electrocatalysis of methanol and borohydride oxidation *Int J Hydrogen Energy* **30** 1323-1331
- Barbora L, Acharya S, Singh R, Scott K and Verma A (2009) A novel composite Nafion membrane for direct alcohol fuel cells *J Membr Sci* **326** 721-726
- Basu S (2007) Recent Trends in Fuel Cell Science and Technology Springer New York
- Basu S, Agarwal A and Pramanik H (2008) Improvement in performance of a direct ethanol fuel cell: Effect of sulfuric acid and Ni-mesh *Electrochem Commun* **10** 1254-1257
- Basu D and Basu S (2010) A Study on Direct Glucose and Fructose Alkaline Fuel Cell *Electrochim Acta* **55** 5575-5579
- Basu D and Basu S (2011) Synthesis, Characterization and Application of Platinum Based Bi-metallic Catalysts in Direct Glucose Alkaline Fuel Cell *Electrochim Acta* **56** 6106-6113
- Batista J, Pintar A, Gomilsek J P, Kodre A and Bornette F (2001) On the structural characteristics of gamma-alumina-supported Pd-Cu bimetallic catalysts *Appl Catal A: Gen* **217** 55-68
- Cao L, Sun G, Li H and Xin Q (2007) Carbon-supported IrSn catalysts for direct ethanol fuel cell *Electrochem Commun* **9** 2541-2546
- Colamati F, Antolini E and Gonzalez E R (2006) Effect of temperature on the mechanism of ethanol oxidation on

- carbon supported Pt, PtRu and Pt<sub>3</sub>Sn electrocatalysts *J Power Sources* **157** 98-103
- Daiko Y, Klein L C, Kasuga T and Nogami M (2006) Hygroscopic-oxides / Nafion® hybrid electrolyte for direct methanol fuel cells *J Membr Sci* **281** 619-625
- De Souza R F B, Tusi M M, Brandalise M, Dias R R, Linardi M, Spinacé E V, Santos M C and Neto A O (2010) Preparation of PtSn/C-Rh and PtSn/C-CeO<sub>2</sub> for Ethanol Electro-Oxidation *Int J Electrochem Sci* **5** 895-902
- Faubert G, Lalonde G, Côté R., Guay D, Dodelet J P, Weng L T, Bertrand P and Dénès G (1996) Heat-treated iron and cobalt tetraphenylporphyrins adsorbed on carbon black: Physical characterization and catalytic properties of these materials for the reduction of oxygen in polymer electrolyte fuel cells *Electrochim Acta* **41** 1689-1701
- Ganesan R and Lee J S (2005) Tungsten Carbide Microspheres as a Noble-Metal-Economic Electrocatalyst for Methanol Oxidation *Angew Chem Int Ed* **44** 6557-6560
- Gao Y, Sun G Q, Wang S L and Zhu S (2010) Carbon nanotubes based gas diffusion layers in direct methanol fuel cells *Energy* **35** 1455-1459
- Gasteiger H A, Panels J E and Yan S G (2004) Dependence of PEM fuel cell performance on catalyst loading *J Power Sources* **127** 162-171
- Gaurav D, A Verma, D Sharma and Basu S (2010) Development direct alcohol alkaline fuel cell stack *Fuel Cell* **10** 591-596
- Goel J and Basu S (2014) Effect of support materials on the performance of direct ethanol fuel cell anode catalyst *Int J Hydrogen Energy* **39** 15956-15966
- Goel J and Basu S (2015) Mathematical Modeling and Experimental Validation of Direct Ethanol Fuel Cell *Intl J Hydrogen Energy* in press doi:10.1016/j.ijhydene.2015.03.082
- Gupta S S, Mahapatra S S and Datta J (2004) A potential anode material for the direct alcohol fuel cell *J Power Sources* **131** 169-174
- Hickner M A and Pivovar B S (2005) The Chemical and Structural Nature of Proton Exchange Membrane Fuel Cell Properties *Fuel Cells* **5** 213-229
- Hitmi H *et al.* (1994) A kinetic analysis of the electro-oxidation of ethanol at a platinum electrode in acid medium *Electrochim Acta* **39** 407-415
- Hwu H H, Kourtakis K, Lavin J G and Chen J G (2001) Potential application of tungsten carbides as electrocatalysts. 1. Decomposition of methanol over carbide-modified W(111) *J Phys Chem B* **105** 10037-10044
- Jayakumara K, Pandiyana S, Rajalakshmi N and Dhathathreyan K S (2006) Cost-benefit analysis of commercial bipolar plates for PEMFC's *J Power Sources* **161** 454-459
- Jeng K T, Chien C C, Hsu N Y, Huang W M, Chiou S D and Lin S H (2007) Fabrication and impedance studies of DMFC anode incorporated with CNT-supported high-metal-content electrocatalyst *J Power Sources* **164** 33-41
- Kamarudin S K, Daud W R W, Md Som A, Takriff M S and Mohammad A W (2006) Technical design and economic evaluation of a PEM fuel cell system *J Power Sources* **157** 641-649
- Kannan A M, Kanagala P and Veedu V (2009) Development of carbon nanotubes based gas diffusion layers by in situ chemical vapor deposition process for proton exchange membrane fuel cells *J Power Sources* **192** 297-303
- Kerres J A (2001) Development of ionomer membranes for fuel cells *J Membr Sci* **185** 3-27
- Kowal A, Li M, Shas M, Sasaki K, Vukmirovic M B, Zhang J, Marinkovic N S, Liu P, Frenkel A I and Adzic R R (2009) Ternary Pt/Rh/SnO<sub>2</sub> electrocatalysts for oxidizing ethanol to CO<sub>2</sub> *Natur Mater* **8** 325-330
- Lamy C, Belgsir E M and Leger J-M (2001) Electrocatalytic oxidation of aliphatic alcohols: Application to the direct alcohol fuel cell (DAFC) *J Appl Electrochem* **31** 799-809
- Lamy C, A Lima, V Lerhun, F Deline, C Coutanceau, J-M and Leger J-M (2002) Recent advances in the development of direct alcohol fuel cells (DAFC) *J Power Sources* **105** 283-296
- Lamy C, S Rousseau, E M Belgsir, C Coutanceau and Leger J M (2004) Recent progress in the direct ethanol fuel cell: development of new platinum-tin electrocatalysts *Electrochim Acta* **49** 3901-3908
- Larminie and Dicks A (2003) Fuel Cell Systems Explained 2<sup>nd</sup> Ed. John Wiley pp 145
- Lefevre M and Dodelet J P (2003) Fe-based catalysts for the reduction of oxygen in polymer electrolyte membrane fuel cell conditions: determination of the amount of peroxide released during electroreduction and its influence on the stability of the catalysts *Electrochim Acta* **48** 2749-2760
- Li M Q, Shao Z G and Scott K J (2008) A high conductivity Cs<sub>2</sub>.5H<sub>0</sub>.5PMo<sub>12</sub>O<sub>40</sub>/polybenzimidazole (PBI)/H<sub>3</sub>PO<sub>4</sub> composite membrane for proton-exchange membrane fuel cells operating at high temperature *J Power Sources* **183** 69-75
- Lima F H B, Giz M J, Ticianelli E A And Braz J (2005) Electrochemical Performance of Dispersed Pt-M (M =V, Cr and Co) Nanoparticles for the Oxygen Reduction Electrocatalysis *Chem Soc* **16** 328-336
- Lim B, Jiang M, J, Camrargo P H C, Cho E C, Tao J, Lu X, Zhu Y and Xia Y (2009) Pd-Pt bimetallic nanodendrites with high activity for oxygen reduction *Science* **324** 1302-1305

- Liu N, Kourtakis K, Figueroa J C and Chen J G (2003) Potential application of tungsten carbides as electrocatalysts: III. Reactions of methanol, water, and hydrogen on Pt-modified C/W(111) *J Catal* **215** 254-260
- Lobato J, Canizares P, Rodrigo M A, Linares J J and Aguilar J A (2007) Improved polybenzimidazole films for H<sub>3</sub>PO<sub>4</sub>-doped PBI-based high temperature PEMFC *J Membr Sci* **306** 47-55
- Malhotra S and Datta R (1997) Membrane-Supported Nonvolatile Acidic Electrolytes Allow Higher Temperature Operation of Proton-Exchange Membrane Fuel Cells *J Electrochem Soc* **144** 23-26
- Mustain W E, Kepler K and Prakash J (2007) CoPdx oxygen reduction electrocatalysts for polymer electrolyte membrane and direct methanol fuel cells *Electrochim Acta* **52** 2102-2108
- Neto A O, Farias L A, Dias R R, Brandalise M, Linardi M and S pinacé E V (2008) Enhanced electro-oxidation of ethanol using PtSn/CeO<sub>2</sub>C electrocatalyst prepared by an alcohol-reduction process *Electrochem Commun* **10** 1315-1317
- O'Hayre R, Cha S, Colella W and Printz F (2007) Fuel Cell Fundamentals. Wiley Inc., New York
- Olson T S, Chapman K and Atanassov P (2008) Non-platinum cathode catalyst layer composition for single Membrane Electrode Assembly Proton Exchange Membrane Fuel Cell *J Power Sources* **183** 557
- Planning Commission Report (2006) Integrated Energy Policy, August 2006
- Pramanik H and Basu S (2007) A Study on Process Parameters of Direct Ethanol Fuel Cell *Can J Chem Eng* **85** 781-785
- Pramanik H, Basu S and Wragg A A (2008) Studies of some operating parameters and cyclic voltammetry for a direct ethanol fuel cell *J Appl Electrochem* **38** 1321-1328
- Pramanik H and Basu S (2010) Modeling and experimental validation of overpotentials of a direct ethanol fuel cell *Chem Eng Process* **49** 635-642
- Priyanka M H and Mathur R B (2009) Improved performance of PEM fuel cell using carbon paper electrode prepared with CNT coated carbon fibres *Electrochim Acta* **54** 7476-7482
- Ribeiro J, dos Anjos D M, Léger J -M, Hahn F, Olivi P, de Andrade A R, Tremiliosi-Filho G and Kokoh K B (2008) Effect of W on PtSn/C catalysts for ethanol electrooxidation *J Appl Electrochem* **38** 653-662
- Savadogo O, Lee K, Oishi K, Mitsushima S, Kamiya N and Ota K I (2004) New Palladium Alloys Catalyst for the Oxygen Reduction Reaction in an Acid Medium *Electrochem Commun* **6** 105-109
- Savadogo O (1998) Emerging membranes for electrochemical systems: (I) solid polymer electrolyte membranes for fuel cell systems *J New Mater Electrochem Syst* **1** 47-66
- Schulenburg H, Stankov S, Schunemann V, Radnik J, Dorbandt I, Fiechter S, Bogdanoff P, and Tributsch H (2003) Catalysts for the oxygen reduction from heat-treated iron(III) tetramethoxyphenylporphyrin chloride: Structure and stability of active sites *J Phys Chem B* **107** 9034-9041
- Schuster M, Roger T, Noda A, Kreuer K D and Maier J (2005) About the Choice of the Protogenic Group in PEM Separator Materials for Intermediate Temperature, Low Humidity Operation: A Critical Comparison of Sulfonic Acid, Phosphonic Acid and Imidazole Functionalized Model Compounds *Fuel Cells* **5** 355-365
- Scott K, Pilditch S and Mamlook M (2007) Modelling and experimental validation of a high temperature polymer electrolyte fuel cell *J Appl Electrochem* **37** 1245-??
- Serov A and Kwak C (2009) Review of non-platinum anode catalysts for DMFC and PEMFC application *Appl Catal B: Environ* **90** 313-320
- Shobha T, Aravinda C L, Bera P, Devi L G and Mayanna S M (2003) Characterization of Ni-Pd alloy as anode for methanol oxidative fuel cell *Mater Chem Phys* **80** 656-661
- Tarasevich M R, Karichev Z R and Bogdanovskaya V A (2005) *Electrochem Commun* **7** 141-146
- Tayal J, Rawat B and Basu S (2011) Bi-metallic and tri-metallic Pt-Sn/C, Pt-Ir/C, Pt-Ir-Sn/C catalysts for electro-oxidation of ethanol in direct ethanol fuel cell *Int J Hydrogen Energy* **36** 14884-14897
- Tayal J, Rawat B and Basu S (2012) Effect of addition of rhenium to Pt-based anode catalysts in electro-oxidation of ethanol in direct ethanol PEM fuel cell *Int J Hydrogen Energy* **37** 4597-4605
- Verma A, Jha A K and Basu S (2005) Manganese dioxide as a cathode catalyst for a direct alcohol or sodium borohydride fuel cell with a flowing alkaline electrolyte *J Power Sources* **141** 30-34
- Verma A and Basu S (2005) Direct use of alcohols and sodium borohydride as fuel in an alkaline fuel cell *J Power Sources* **145** 282-285
- Verma A and Basu S (2007a) Experimental evaluation and mathematical modeling of a direct alkaline fuel cell *J Power Sources* **168** 200-210
- Verma A and Basu S (2007b) Direct alkaline fuel cell for multiple liquid fuels: Anode electrode studies *J Power Sources* **174** 180-185
- Verma A, Scott K and Basu S (2010) Development of high-temperature PEMFC based on heteropolyacids and polybenzimidazole *J Solid State Electrochem* **14** 213-219

- Vojislav R S, Bongjin S M, Matthias A, Karl J J M, Christopher A L, Guofeng W, Philip N R and Nenad M M (2007) Trends in electrocatalysis on extended and nanoscale Pt-bimetallic alloy surfaces *Natur Mater* **6** 241-247
- Wang W, Zheng D, Du C, Zou Z, Zhang X, Xia B, Yang H and Akins D L (2007) Carbon-supported Pd-Co bimetallic nanoparticles as electrocatalysts for the oxygen reduction reaction *J Power Sources* **167** 243-249
- Wasmus S and Kuver A (1999) Methanol oxidation and direct methanol fuel cells: a selective review *J Electroanal Chem* **461** 14-31
- Watanabe M, Uchida H, Seki Y, Emori M and Stonehart P (1996) Self-Humidifying Polymer Electrolyte Membranes for Fuel Cells *J Electrochem Soc* **143** 3847-3852
- Weigert E C, Stottlemeyer A L, Zellner M B and Chen J G (2007) Tungsten Monocarbide as Potential Replacement of Platinum for Methanol Electro-oxidation *J Phys Chem C* **111** 14617-14620
- Wiesener K, Ohms D, Neumann V and Franke R (1989)  $N_4$  macrocycles as electrocatalysts for the cathodic reduction of oxygen *Mater Chem Phys* **22** 457-475
- Wu X, Verma A and Scott K (2008) A Sb-doped  $SnP_2O_7$  Solid Proton Conductor for Intermediate Temperature Fuel Cells *Fuel Cells* **8** 453-458
- Xu J B, Zhao T S, Shen S Y and Li Y S (2010) Stabilization of the palladium electrocatalyst with alloyed gold for ethanol oxidation *Int J Hydrogen Energy* **35** 6490-6500
- Yang C, Srinivasan S, Arico A S, Creti P, Baglio V and Antonucci V (2001) Composite Nafion/Zirconium Phosphate Membranes for Direct Methanol Fuel Cell Operation at High Temperature *Electrochem Solid State Lett* **4** A31-A34
- Zagal J, Paez M, Tanaka A A, Dossantos J R and Linkous C A (1992) Electrocatalytic activity of metal phthalocyanines for oxygen reduction *J Electroanal Chem* **339** 13-30
- Zellner M B and Chen J G (2005) Potential Application of Tungsten Carbides as Electrocatalysts: Synergistic Effect by Supporting Pt on C/W(110) for the Reactions of Methanol, Water, and CO *J Electrochem Soc* **152** 1483-A1494
- Zhou H, Miyatake K and Watanabe M (2005) Polyimide Electrolyte Membranes Having Fluorenyl and Sulfopropoxy Groups for High Temperature PEFCs *Fuel Cells* **5** 296-301.