An Introduction to Fuel Cell Technology and Application: Alternative Energy System for Future

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Abstract— A fuel cell is most interesting new power source because it solves not only the environment problem but also natural resource exhaustion problem. In this paper a description of fuel cell operating principles is followed by a comparative analysis of the current fuel cell technology together with issues concerning various fuels. Appropriate applications for current and perceived potential advances of fuel cell technology are discussed. A brief account on evolution and working of different fuel cells namely SOFC, PEMFC, DFMC, PAFC, MCFC and AFC followed by their comparative analysis The potential application of fuel cells can be used in automotive vehicle in low cost that gives high performance and high efficiency. This investigation examines the economics of producing electricity from fuel cell systems under various conditions, including the possibility of using fuel cell vehicles (FCVs) to produce power when they are parked at office buildings and residences. The analysis shows that the economics of both stationary fuel cell and FCV-based power vary significantly with variations in key input variables such as the price of natural gas, electricity prices, fuel cell and reformer system costs, and fuel cell system durability levels. The Grid-connected FCVs in commercial settings can also potentially supply electricity at competitive rates in some cases producing significant annual benefits particularly attractive is the combination of net metering along with time of- use electricity rates that allow power to be supplied to the utility grid at the avoided cost of central power plant generation. FCV based power at individual residences does not appear to be as attractive, at least where FCV power can only be used directly or banked with the utility for net metering and not sold in greater quantity, due to the low load levels at these locations that provide a poor match to automotive fuel cell operation, higher natural gas prices than are available at commercial settings, and other factors. In the long term, a hydrogen-based economy will have an impact on all these sectors. In view of technological developments, vehicle and component manufacturers, transport providers, the energy industry, and even householders are seriously looking at alternative energy sources and fuels and more efficient and cleaner technologies – especially hydrogen and hydrogen-powered fuel cells. At the end of the paper some potential application of fuel cell that are capable of catalyzing revolutionary impact on energy scenario are being discussed, along with the advantages and disadvantages/ limitations of fuel cells.

Key words: Fuel Cell, PEMFC, SOFC, DMFC, AFC, PAFC, Hydrogen, Fuel Cell Vehicle

I. Introduction

In 1839, William Grove conducted the first known demonstration of the fuel cell. It operated with separate Platinum electrodes in oxygen and hydrogen submerged in a dilute sulfuric acid electrolyte solution, essentially reversing a water electrolysis reaction. High temperature solid oxide fuel cells (SOFC) began with Nernst's 1899 discovery of the still-used yttria-stabilized zirconia solid-state ionic conductor (Nernst, [1899]), although little additional practical development occurred until the 1960's. Low temperature polymer electrolyte membrane (PEM) fuel cells were first developed by General Electric in the 1960's for NASA's Gemini space program. Both PEM and solid oxide fuel cell systems made slow progress until recently. Fueled by technology advances allowing greatly enhanced performance, continuing environmental concern, and a need to develop future power systems that are independent of petroleum fuel stock, interest in all types of fuel cell systems for stationary, automotive, and portable power applications is now very high. In all of these applications, there is a need for reduced system cost, high reliability, and acceptable performance. While the performance of many systems has made the greatest strides, there is still much work to be done. The use of fuel cells in both stationary and mobile power applications can offer significant advantages for the sustainable conversion of energy. Benefits arising from the use of fuel cells include efficiency and reliability, as well as economy, unique operating characteristics, and planning flexibility and future development potential. By integrating the application of fuel cells, in series with renewable energy storage and production methods, sustainable energy requirements may be realized. A principal motivation for creating policies to allow net metering has been to make better use out of intermittent renewable generating systems, such as solar PV and wind power generators.

II. Fuel cell fundamentals

A fuel cell is conventionally defined as an "electrochemical cell which can continuously convert the chemical energy of a fuel and an oxidant to electrical energy by a process involving an essentially invariant electrode-electrolyte system" [1]. For a hydrogen/oxygen fuel cell the inputs are hydrogen (fuel) and oxygen (oxidant) and the only outputs are dc power, heat, and water. When pure hydrogen is used no pollutants are produced, and the hydrogen itself can be produced from water using renewable energy sources such that the system is environmentally benign. In practice hydrogen is the best fuel for most applications. In addition to hydrogen some fuel cells can also use carbon monoxide and natural gas as a fuel. In these reactions, carbon monoxide reacts with water producing hydrogen and carbon dioxide, and natural gas reacts with water producing hydrogen and carbon monoxide, the hydrogen that is produced is then used as the actual fuel.

A. Electrochemistry

The basic physical structure of all fuel cells consists of an electrolyte layer in contact with an anode and cathode electrode on either side of the electrolyte. The electrolyte provides a physical barrier to prevent the direct mixing of the fuel and the oxidant, allows the conduction of ionic charge between the electrodes, and transports the dissolved reactants to the electrode. The electrode structure is porous, and is used to maximize the three-phase interface between the electrode, electrolyte and the gas/liquid, and also to separate the bulk gas phase and the electrolyte. The gas/liquid ionization or de-ionization reactions take place on the surface of the electrode, and the reactant ions are conducted away from or into the three-phase interface [2]. A schematic representation of a fuel cell with the reactant/product gases and the ion conduction flow directions through the cell is shown in Fig.1.

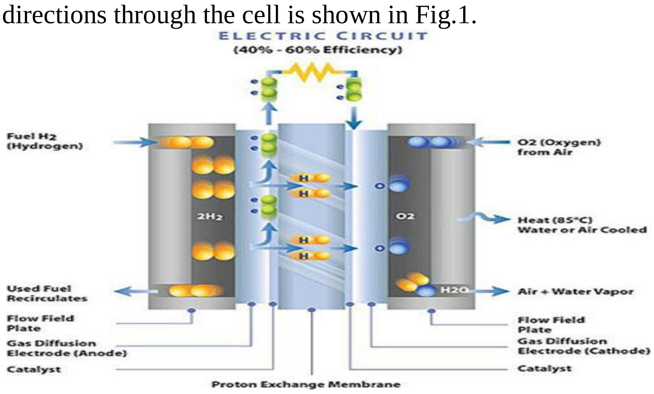

Fig. 1: Basic Working Concepts

In theory a fuel cell is capable of producing an electric current so long as it supplied with fuel and an oxidant. In practice the operational life of the fuel cell is finite, and fuel cell performance will gradually deteriorate over a period of time as the electrode and electrolyte age. However, because fuel cells operate with no moving parts, highly reliable systems are achieved [3].

B. *Efficiency*

The thermal efficiency of the fuel cell can be defined as the percentage of useful electrical energy produced relative to the heat that would have been obtained through the combustion of the fuel (enthalpy of formation). In the ideal case, the maximum efficiency (or thermodynamic efficiency) of a fuel cell operating irreversibly can be expressed as the percentage ratio of Gibbs free energy over the enthalpy of formation, that is,

$$\text{Efficiency} = \frac{\Delta G}{\Delta H}$$

Where D*G* is change in Gibbs free energy and D*H* is the enthalpy of formation of the reaction. For the hydrogen/oxygen fuel cell the thermodynamic efficiency limit at the higher heating value (HHV) is equal to 83% [3]. In practice the efficiency of the fuel cell can be expressed in terms of the percentage ratio of operating cell voltage relative to the ideal cell voltage as

$$\text{Efficiency} = 0.83\frac{V_{\text{cell}}}{V_{\text{ideal}}}$$

Where *V cell* is the actual voltage of the cell and *V ideal* is the voltage obtained from Gibbs free energy in the ideal case. The 0.83 is from the thermodynamic limit (HHV). In the non-ideal case the actual operating voltage is less than the ideal voltage because of the irreversible losses associated with the fuel cell electrochemistry. There are three primary irreversible losses that result in the degradation of fuel cell performance and these are activation polarization, ohmic polarization, and concentration polarization [1-3]. Fig.2 illustrates the effects of the irreversible losses on cell voltage for a low temperature, hydrogen/oxygen fuel cell.

Activation polarization is caused by limited reaction rates at the surface of the electrodes, and is dominant at low current density and increases marginally with an increase in current density.

Ohmic polarization is caused by the resistance to the flow of ions in the electrolyte and to the flow of electrons through the electrode materials. This loss is directly proportional to the current density.

Concentration polarization is caused by a loss of concentration of the fuel or oxidant at the surface of the electrodes. These losses are present over the entire current density range but become prevalent at high limiting currents where it becomes difficult to provide enough reactant flow to the cell reaction sites.

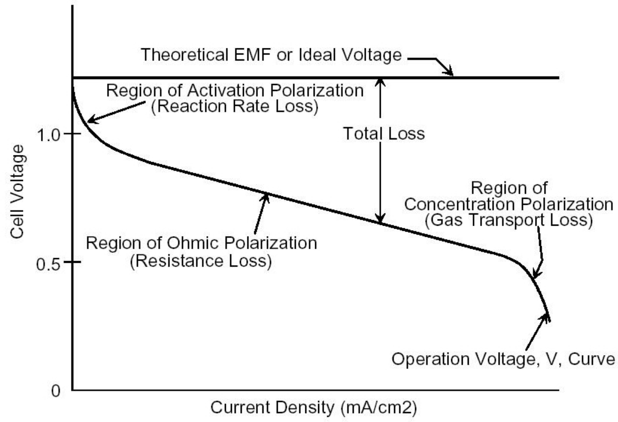

Fig. 2: Ideal and actual voltage/current curves of a low temperature hydrogen/oxygen fuel cell (From [2, 3])

III. FUEL CELL SYSTEMS FOR DISTRIBUTED POWER GENERATION

Fuel cell technology holds the promise to produce electricity at local sites from a wide range of fuels, and with high efficiency. Most types of fuel cells operate on hydrogen fuel, but this hydrogen can be produced from natural gas, liquid hydrocarbon fuels including biomass fuels, landfill gases, water and electricity (via the process of electrolysis), biological processes including those involving algae, and from gasification of biomass, wastes, and coal. Fuel cells are being proposed for use in powering electric vehicles, providing remote power for buildings and communication facilities, providing power as distributed generation (DG) in grid-connected applications (as either primary power or backup power), and for small electronic devices such as laptop computers and cell phones. One principal attraction of fuel cell technology, as evidenced by this diverse array of potential applications, is that fuel cells can produce power with high efficiency in a wide range of system sizes. This feature is a function of the modular design of fuel cell systems (where individual cells are compiled into ''stacks'' to achieve higher voltage and power levels), as well as the fuel cell operating principle that allows electricity to be produced without combustion. Several types of fuel cells are currently being developed, including proton-exchange membrane (PEM) fuel cells, solid-oxide fuel cells (SOFCs), alkaline fuel cells (AFCs), phosphoric acid fuel cells (PAFCs), molten-carbonate fuel cells (MCFCs), and direct-methanol fuel cells (DMFCs). Low temperature PEM fuel cells are considered the leading contenders for automotive and small stationary applications, with SOFC, PAFC, and MCFC operating at higher temperatures (from 2001C to 10001C) and expected to be used for larger stationary applications, and DMFC s for portable electronics and possibly for future electric vehicles. There are several potential operating methods for using both stationary fuel cells and fuel cell vehicles (FCVs) as distributed generating resources.

These Systems could be used to:

- produce power to meet the demands of local loads;
- provide additional power to the grid in a net metered or electricity buy-back scenario, helping to meet demands in times of capacity constraint;
- provide emergency backup power to residences, offices, hospitals, and municipal facilities;
- provide ‘‘peak shaving’’ for commercial sites, reducing demand charges;
- Provide buffering and additional power for grid independent systems that rely on intermittent renewable.

In general, stationary fuel cells are expected to operate nearly continuously (with the exception of those used for emergency backup), and they also have the potential to act as cogenerates, simultaneously producing electricity and useful waste heat. FCVs would provide power more intermittently, when parked at suitable locations for obtaining fuel and discharging electricity. The fuel cell systems in FCVs would likely be less readily usable for cogeneration (also known as combined heat and power or CHP) than stationary fuel cells due to the additional cost and complexity of trying to capture the waste heat from these systems, for uses inside nearby buildings. Depending on the type of fuel cell system, waste heat is available at different temperatures and can be used for various heating and cooling applications. For PEM fuel cells, the waste heat is available at only about 80–901C. Some other types of fuel cells run much hotter, up to 9001C or even 10001C. The low grade of waste heat from PEM fuel cells is suitable for heating water and/or providing space heating, thereby displacing energy that is otherwise used for that purpose, while higher grade waste heat from other fuel cell types can be used to produce steam and to drive absorption cooling systems.

IV. NET METERING OF FUEL CELL SYSTEMS

There are two basic ways in which commercial fuel cell systems could be ‘‘net metered’’. First, they could be net metered in a manner analogous to current net metering programs, whereby overall billing would be assessed on a monthly or annual basis and the customer could have a zero balance, a negative balance, or in the case where credit is awarded to net excess generation, even a positive balance. One argument against including fuel cell systems in these traditional net metering programs is that while PV and wind systems tend to have peak availability in the daytime and afternoon periods, coincident with the grid peak, to the extent that fuel cell systems are sized to meet most or all of the peak building electrical loads, much excess fuel cell power may be available off-peak when the grid is running mainly from base load power plants. However, net metering policies could be designed to work in conjunction with ‘‘real time’’ electricity meters that are currently being installed at many commercial sites to allow excess generation to only be credited at peak hours of the day when the grid is employing peak power plants. In theory, use of fuel cell systems in this way could reduce the need to operate peak power plants and to construct new ones to meet peak demand growth.

V. FUEL CELL CLASSES

There are five primary classes of fuel cells, identified by their electrolyte, which have emerged as viable systems [2]. Although the most common classification of fuel cells is by the type of electrolyte used, there are always other important differences as well. Each fuel cell class differs in the materials of construction, the fabrication techniques, and the system requirements. The potential use for different applications is inherent in the main characteristics of each fuel cell class [2].

Solid Oxide (SOFC): The solid oxide fuel cell operates between 500-1000°C. The electrolyte in this fuel cell is a solid, nonporous metal oxide and the charge carriers are oxygen ions. The electrolyte always remains in a solid state adding to the inherent simplicity of the fuel cell. The solid ceramic construction of the cell, can minimize hardware corrosion, allows for flexible design shapes, and is impervious to gas crossover from one electrode to the other. Due to the high temperature operation, high reaction rates are achieved without the need for expensive catalysts and also gases such as natural gas can be internally reformed without the need for fuel reforming. Unfortunately the high operating temperature limits the materials selection and a difficult fabrication processes results. In addition the ceramic materials used for the electrolyte exhibit a relatively low conductivity, which lowers the performance of the fuel cell.

Polymer Electrolyte Membrane (PEMFC): The polymer electrolyte membrane fuel cell operates at 50-100°C. The electrolyte in this fuel cell is a solid ion exchange membrane used to conduct protons. Hardware corrosion and gas crossover are minimized as a result of the solid electrolyte and very high current densities as well as fast start times have been realized for this cell. However due to the low temperature operation, catalysts (mostly platinum) are needed to increase the rate of reaction. In addition heat and water management issues are not easily over come in a practical system, and tolerance for CO is low.

Alkaline (AFC): The alkaline fuel cell operates between 50-250°C. The electrolyte in this fuel cell is KOH, and can be either mobile or retained in a matrix material. Many catalysts can be used in this fuel cell, an attribute that provides development flexibility. The ACF has excellent performance on hydrogen and oxygen compared to other candidate fuel cells. The major disadvantage of this fuel cell is that it is very susceptible to CO2 and CO poisoning and hence its use with reformed fuels and air is limited.

Phosphoric Acid (PAFC): The phosphoric acid fuel cell operates at 200°C with phosphoric acid (100%) used for the electrolyte. The matrix universally used to retain the acid is silicon carbide, and the catalyst is Platinum. The use of concentrated acid (100%) minimizes the water vapour pressure so water management in the cell is not difficult.

The cell is tolerant to CO_2 and the higher temperature operation is of benefit for co-generation applications. The main limitation of the PAFC is the lower efficiency realized in comparison with other fuel cells.

Molten Carbonate (MCFC): The molten carbonate fuel cell operates at 600°C. The electrolyte in this fuel cell is usually a combination of alkali carbonates retained in a ceramic matrix. At the high temperature of operation the alkali carbonates form a highly conductive molten salt, with carbonate ions providing ionic conduction. The high reaction rates remove the need for noble metal catalysts and gases such as natural gas can be internally reformed without the need for a separate unit. In addition the cell can be made of commonly available sheet metals for less costly fabrication. One feature of the MCFC is the requirement of CO_2 at the cathode for efficient operation. The main disadvantage of the MCFC is the very corrosive electrolyte that is formed, which impacts on the fuel cell life, as does the high temperature operation. In addition to the five primary fuel classes, there are two more classes of fuel cells that are not distinguished by their electrolyte. These are the Direct Methanol Fuel Cell (DMFC), distinguished by the type of fuel used, and the Regenerative Fuel Cell (RGF) distinguished by its method of operation.

VI. FUELS FOR FUEL CELL

A. *Fuel Requirements*

In theory, any substance that is capable of being chemically oxidized at a sufficient rate at the anode of the fuel cell may be used as a fuel. In the same sense, any substance that is capable of being reduced at the cathode of the fuel cell at a sufficient rate may be used as an oxidant [2]. In practice, hydrogen is the best fuel for most applications. The low-temperature fuel cells such as the AFC, PEMFC, and PAFC, are electrochemically constrained to hydrogen fuel use only, while the high temperature fuel cells such as MCFC and the SOFC, in addition to hydrogen can also use carbon monoxide and natural gas as a fuel. In these reactions, carbon monoxide reacts with water producing hydrogen and carbon dioxide, and natural gas reacts with water producing hydrogen and carbon monoxide, the hydrogen that is produced is then used as the fuel. Similarly, oxygen is the most common oxidant because it is readily and economically available from air.

B. *Advantages of Hydrogen*

The wide spread use of hydrogen as the fuel choice for fuel cells has the following benefits [1, 5]:

- High electrochemical reactivity when suitable catalysts are used, and high energy content (kJ/kg),
- The oxidation of hydrogen is a simple and environmentally benign reaction that makes zero emissions power systems possible,
- The source of energy production is not constrained to any particular fuel type and hence provides the basis for a rapid progress towards a sustainable transportation and electricity system,
- An increase in retail price competition as a result of the many fuel sources available.

C. *Sources of Hydrogen*

Unfortunately, hydrogen does not occur naturally as a gaseous fuel and must be produced from another source. Potential sources of hydrogen include, such as fossil fuels (coal, oil, or natural gas), a variety of chemical intermediates (refinery products, ammonia, methanol), and alternative resources such as bio-mass, bio-gas, and waste materials. Hydrogen can also be produced by water electrolysis, which uses electricity to split hydrogen and oxygen elements [6]. The electricity for the water electrolysis can be generated from conventional sources or from renewable sources. In the longer term, hydrogen generation could be based on photo-biological or photochemical methods [7].

D. *Fuel Processing*

Some fuel processing will almost always be required in order to produce useful hydrogen rich gas from another source. Most of the hydrogen currently produced on the industrial scale is through the steam reforming of natural gas, which produces carbon dioxide as a byproduct. While this method of hydrogen production is generally the most economic, it is not sustainable in the long term and can serve only as an intermediate step, as is the same for all fossil fuels. However the sustainable production of hydrogen can be achieved with current technology through bio-fuels or by the electrolysis of water using renewable energy sources such as hydro-power, solar energy or wind energy [4,8].

E. *Hydrogen Economy*

The emergence of a true hydrogen economy, based upon hydrogen for energy storage, distribution, and utilization would be a major advantage for the wide spread application of fuel cells. Although there is already an existing manufacturing, distribution, and storage infrastructure of hydrogen, it is limited. The infrastructure costs associated with a large scale hydrogen distribution, is often cited as the major disadvantage for the wide spread use of hydrogen as “a major world fuel and energy vector” [3]. In addition there are concerns that because of the relatively low density of hydrogen it is not viable for energy storage, particularly in mobile applications, and there is also concern in regard to the safety of hydrogen [5]. It can be argued however, that with good integration practices for both distributed fuel cell power supplies and mobile power applications, natural gas or off peak electricity can initially be used for hydrogen production, removing the initial requirement for the large infrastructure costs associated with a hydrogen distribution system. In this case, the hydrogen can be produced as needed, in quantities to match the incremental growth of fuel cells applications. The reforming of natural gas, and the use of electricity from coal fired power plants can be used as an intermediate step and does not constrain the hydrogen use to a particular fuel type [5].

F. *Hydrogen storage*

In addition the storage of hydrogen, although not limited to, can be achieved in the simple form of a compressed gas. While the use of compressed hydrogen gas in stationary applications presents a viable option there is concern that the insufficient density of storing hydrogen as a compressed gas limits its inclusion in mobile applications. This is however

not necessarily the case, as is illustrated with the design approach of using compressed hydrogen gas storage in the ultra-light fuel cell vehicles termed hyper cars [5]. Finally, the safe storing hydrogen as a compressed gas are in many ways less stringent than the safe storing of alternative fuels such as methanol, petrol, or natural gas. The hydrogen gas would be stored in extremely strong carbon fiber cylinders. Because of the rapid diffusion of hydrogen any spill will dissipate quickly. Hydrogen is also non-toxic and requires a fourfold higher concentration than petrol to ignite [5].
Additional methods of hydrogen storage include [3]:

- Storage as a cryogenic liquid,
- Storage as a reversible metal hydride,
- The use of metal hydride reactions with water and
- The use of carbon nano-fibers.

The first three methods of hydrogen storage are currently available and are generally well understood processes. The fourth method, which uses carbon nano-fibres for hydrogen storage is not yet practical although considerable efforts are being invested into making this a feasible technology

VII. Some Potential Applications of Fuel Cells

In present scenario fuel cell got enormous application which can be broadly classified into three categories.

A. Stationary (A.C. Applications)

- Power plants
- Home use
- Hospitals
- Hotels
- Isolated rural areas
- Military applications

B. Transportation (D.C. applications)

- Personal Vehicles (ZEV's -Zero Emission Vehicles)
- Public Transportation
- Commercial and Military Vehicles

1) Advantages of Fuel Cells

The basic advantages common to all fuel cell systems are as follows:-

- Potential for a high operating efficiency (up to 50-70%), that is not a strong function of system size.
- Zero or near-zero greenhouse emissions, with level of pollution reduction depending on the particular fuel cell system and fuel option.
- Efficiency - Fuel cells are generally more efficient than combustion engines as they are not limited by temperature as is the heat engine
- Low emissions - Fuel cells running on direct hydrogen and air produce only water as the by-product

2) Limitations of Fuel Cells

In practice of successful market penetration, however, the following limitations common to all fuel cell systems must be overcome:

- Alternative materials and construction methods must be developed to reduce fuel cell system cost to be competitive with the automotive combustion engine (presently priced at about $20/kW), and stationary power systems (presently priced up to $1,000/kW). The cost of the catalyst no longer dominates the price of most fuel cell systems.
- Manufacturing and mass production technology is now a key component to the commercial viability of fuel cell systems.
- Fuel storage and delivery technology must be advanced if pure hydrogen is to be used.
- Fuel reformation technology must be advanced if a hydrocarbon fuel is to be used for hydrogen production.

VIII. Conclusion

In summary the significant areas identified for further research relate to the storage of hydrogen, the integration of fuel cells with renewable energy sources, and the modeling and methodology for system optimization and design. Net metering policies can have a significant impact on the economics of FCV-based power , Typical applications that have been proposed include replacing internal combustion engines with 75-80 kW PEFC stacks; using 1-5 kW stacks to power individual homes; using 250 kW and larger stacks to provide highly reliable power to installations such as credit card clearing centers and hospitals; developing 1-100 W methanol fueled stacks to power consumer electronics such as cellular phones and laptops (replacing rechargeable batteries); and developing methanol fueled portable power for military applications.

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