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Fuel Cells: The Fuel for Tomorrow

Debajyoti Bose

University of Petroleum & Energy Studies (UPES) P.O. Bidholi Via-Prem Nagar, Dehradun, Uttarakhand 248007
E-mail: debajyoti1024@gmail.com

Abstract—*Energy security, economic growth and environmental protection are the three paramount entities that encompass the proliferation of a nation's forthcoming. The dwindling community of fossil fuels apart from leaving us with its destructive cumulative effects will put an enormous strain on energy infrastructure and life itself. Such catastrophic outcomes require efficient and effective solutions. Hence debates on low carbon alternatives are now being a harbinger for the society. Fuel cells offer some important benefits over other low carbon technologies. Unwavering cost reductions through innovation are bringing fuel cells close to commercialization with hydrogen as the key fuel in several countries. Compared to natural gas hydrogen is a zero carbon alternative, thus making it the smarter choice for future energy conversion. Fuel cells are the key to enabling technologies for the future hydrogen economy. The story of fuel cells has spanned over two centuries and today it forms an important basis for distributed technology. Fuel cells can be integrated into homes, cars, laptops and cell phones. Automotive propulsion and distributed power generation has already realized its potential. This paper shows the potential this ubiquitous technology has with hydrogen which can react at room temperature, an inherent advantage.*

1. INTRODUCTION

Debates on energy and environment are a common spectacle these days as the global community strives towards low carbon alternatives. During the 19th century the invention of the light bulb led to lighting becoming the first publicly available application of electrical power. Today electrical power influences our lives in every possible way. From heating, refrigeration, telecommunications and appliances it has become vital in everyday life. Production of electricity using fossil fuels has been under the scanner for quite some time now because of their availability and effects on the environment.

Scientists, governments, and industries are witnessing the long-term consequences of energy consumption and foresee catastrophic outcomes if alternative methods of energy production are not developed and utilized to meet the needs of our global economy. Because fuel cells, as electrochemical devices, convert fuels such as hydrogen into electricity without combustion, they create virtually no pollution and hold the key to future prosperity and a healthy global environment. In recent years, the development and commercialization of FC systems for different applications is increasing tremendously and is proposed as a competitive energy policy and a step forward to the target of sustainable development and environmental friendly energy source. Fuel cells are also considered a promising energy conversion technology of the future owing to inherent advantages of electrochemical conversion over thermal combustion processes [1]. The one successful area right now is aerospace, every space shuttle, vehicle has a fuel cell on board as it is the best source to produce electricity and water in space. For automobiles and houses combustion technologies have dominated and to compete with them is a major challenge. Given the fundamental crisis of energy conversion which the world suffers from today fuel cells emerge out as a viable option and an eventual step towards the expected Hydrogen economy.

Enhanced lifestyle and energy demand rise together and the wealthy industrialized economies which contain 25% of the world's population consume 75% of the world's energy supply [2]. Global demand for energy services is expected to increase by as much as an order of magnitude by 2050, while primary-energy demands are expected to increase by 1.5 to 3 times [3]. World oil production will decline in the next 20–40 years and dependence on energy from fossil fuels is also reaching its limits

(Figs. 1 and 2) [4], the development of new power generation technologies will represent the next frontier of energy conversions. With fuel cells and hydrogen concepts relating to sustainable development and restoring the balance of nature can be speculated.

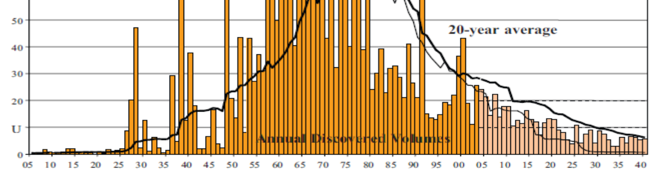

Fig. 1: Confronting the supply challenges, annual discovered volume of oil (1905-2040).

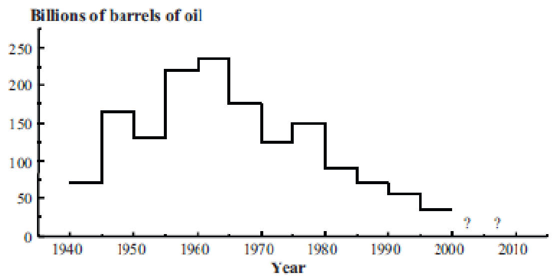

Fig. 2: Volume of oil discovered worldwide every 5 years.

2. EARLY BEGINNINGS

There is quite some controversy concerning who discovered the principle of fuel cells. According to the Department of Energy of the United States [5], it was the German chemist Christian Friedrich Schonbein, who in 1838 conducted the first scientific research on the phenomenon of a fuel cell, whose work was published in Philosophical Magazine in the January issue of 1839. By contrast, in reference [6] the author asserts that it was Sir William Robert Grove, who introduced the concept of hydrogen fuel cell. Grove discovered that by immersing two platinum electrodes on one end in a solution of sulphuric acid and the other two ends separately sealed in containers of oxygen and hydrogen, a constant current was found to be flowing between the electrodes. Sealed containers contained water together with the respective gases. Grove noted that the water level rose in both tubes as the current flowed. The next step was to realize that combining pairs of electrodes connected in series produced a higher voltage drop, thus creating what he called a gas battery, i.e. the first fuel cell [7].

Present Days: Towards the 21st Century

Modern day fuel cells have the potential to conquer the world of Stationary (supplemental generators, distributed power sources), transportation (fuel cell vehicles, hybrid vehicles) and consumer electronics such as laptops, cell phones and video recorders. There are now many manufacturers working on fuel cell applications of very different nature [8]. It is expected that in the next few years, the opportunity for fuel cells could exceed 1000 MW/year on a global basis [9].

3. THE HYDROGEN ADVANTAGE

In 2003, President Bush announced a program called the Hydrogen Fuel Initiative (HFI). The idea was to develop hydrogen, fuel cell and infrastructure technologies to make fuel-cell vehicles practical and cost-effective by 2020. Pollution reduction was the primary objective and fuel cells powered by pure hydrogen have the potential to be around 80% efficient. Hydrogen is a key fuel because it is everywhere. Not in the raw form but in methane (CH_4), biomass and other plethora of organic dynamics around us. Everywhere on this planet we find hydrogen including water, the key ingredient for life. Then this hydrogen can react at room temperature. Petrol requires higher temperature, so this is the advantage associated. Also emissions are significant in Combustion technologies in terms of CO_X, NO_X, SO_X and other particulate matter. Fuel cells running on hydrogen just doesn't have these issues, hence brings us to a cleaner and better level.

4. FUEL CELLS AS DISTRIBUTED TECHNOLOGY

Bold claims are made in regard to fuel cells having the potential to replace fossil fuels based power stations. The idea is we don't need power stations, we need fuel cells. It is a good example of distributed technology like solar or wind power but those are intermittent. Fuel cells run on gas, with it one can generate their own power and heat, have significant reduction in bills and in the end much less emissions going into the atmosphere. So, global warming is reduced.

5. PRINCIPLE OF OPERATION

The basic requirement to make a fuel cell involves:

- Anode.
- Cathode.
- Electrolyte.
- Catalyst.
- Fuel (Hydrogen rich or pure hydrogen).

Fuel cells consist of two electrodes separated by an electrolyte, such as phosphoric acid or molten carbonate. Oxygen passes over one electrode and H_2 passes over the other. As the H_2 is ionized, it loses an electron. The H_2 and the electron take separate paths to the second electrode before combining with the oxygen. The H_2 migrates through the electrolyte and the electron moves through an external circuit [10].

As shown in Fig. 3 [11], it gives off pure water as byproduct with some heat. Hence, renewable environment friendly ways of producing hydrogen in the future are being considered.

More than 2500 fuel cell systems have been installed worldwide in hospitals, shelters, centers for elderly care, hotels, offices and schools. In these cases, the fuel cell system is connected to the grid to provide additional electrical power to the plant [12], or as an independent system of the grid to generate electricity in remote or isolated areas [13–16].

6. TYPES OF FUEL CELLS

6.1 Alkaline Fuel Cell (AFC)

Operates on compressed hydrogen and oxygen, The AFC is one of the earlier fuel cell system employed for NASA's space missions. It uses an aqueous solution of the potassium hydroxide as an electrolyte. It transports negative charged ions from anode to cathode and releases water as its by-product.

This type of fuel cells is used in transportations such as fleet vehicles and boats and space shuttles. In the case of fuel cells with liquid electrolyte, the electrolyte circulates continuously between the electrodes. In fuel cells with fixed electrolyte, the electrolyte is a thin paste adhering to a porous matrix of asbestos. The operating temperature ranges from 65 and 220°C and pressure of 1 atm. Each cell can deliver about 1.1–1.2 V. Operating temperature is 50 to 100°C [17].

The advantage is the low operating temperature and the simple configuration of the device.

Application includes the field of military and space.

6.2 Proton Exchange Membrane Fuel Cell (PEMFC)

The operating temperature of these fuel cells is relatively low (around 60–80 8C), so the boot is faster than in high temperature fuel cells. They have high power density and can vary with relative speed their operation point to deliver the required power demand. Among their applications include automotive systems, buildings or portable applications to replace the rechargeable batteries. The maximum power supplied by these batteries ranges from 50W to 75 kW [18]. The PEMFC uses a solid polymer electrolyte (teflon-like membrane) to exchange the ions between two porous electrodes, which is an excellent conductor of protons and an insulator for electrons. A major breakthrough in the field of PEM fuel cells came with the use of Nafion membranes by DuPont. These membranes possess a higher acidity and also a higher conductivity and are far more stable than the polystyrene sulfonate membranes. A general overview on polymer electrolytes was published in 1997 [19]. Low operating temperature and quick start up suitable for cars and mass transportation.

6.3 Phosphoric Acid Fuel Cell (PAFC)

The most commercially developed type of fuel cell is the PAFC, already installed at hospitals, nursing homes, hotels, office buildings, and utility power plants. PAFCs generate power at more than 40% efficiency and about 85% of the steam produced is used for cogeneration. Liquid phosphoric acid is the electrolyte used in PAFCs and platinum is the required catalyst for the electrodes. The chemical reaction involved in this fuel cell is same as PEM fuel cell where pure hydrogen is used as its input fuel. The efficiency of this type of fuel cells reaches 40% in electricity production and 85% in cogeneration. They work about 150–200 8C and pressure of 1 atm. Each cell can produce around 1.1 V. It is mainly used in stationary power plants ranging from dispersed power to on-site generation plants. Power plants based on PAFCs are being installed worldwide with outputs ranging from 5-20 MW supplying towns, cities, and shopping malls or hospitals with electricity, heat, and hot water [20-24].

6.4 Molten Carbonate Fuel Cell (MCFC)

The MCFC, operating at high temperature, has an internal reforming capability. It separates the hydrogen from carbon monoxide fuel and decomposition of hydrogen is taken through the water shift reaction to produce hydrogen, then the result of reaction is taken same as PEMFC to produce electricity. It also consists of two porous electrodes, in contact with a molten carbonate cell, and having a good conductivity. Uses high-temperature compounds of salt carbonates as electrolyte, operates around 630-650°C and has around 60% efficiency. In view of their ability to work with different types of fuel, MCFC are of great interest.

The electrical and operating properties of these fuel cells are sufficient for building economically justified stationary power plants with relatively large power output. The only problem so far is an insufficiently long period of trouble-free operation. The minimum length of time a large (and expensive) power plant should work until replacement is 40000 h (4.5–5 years). In this sense, intense research and engineering effort have made it possible to build individual units that have worked several hundreds and thousands of hours [25].

6.5 Solid Oxide Fuel Cell (SOFC)

The SOFC are basically high temperature fuel cells and a separate reformer is not required to extract hydrogen from the fuel due to its internal reforming capability. It uses a hard, ceramic compound of metal oxides as electrolyte. Operating temperatures are about 1,000 degrees C, so no reformer is required for extracting hydrogen from fuel. Additionally it has solid electrolyte, so the membrane cannot dry out as with PEMFCs or liquid cannot leak out as with PAFCs [26]. SOFCs are the most efficient (fuel input to electricity output) fuel cell electricity generator currently being developed world-wide. SOFCs are attractive for utility and industrial applications due to several features. They have high tolerance to fuel contaminants, and the high temperature of reactions does not require expensive catalysts, allowing direct fuel processing. Because the electrolyte is solid, problems such as electrolyte flooding and electrolyte migration are avoided. SOFCs promise efficiencies of 60% in large applications such as mid-sized power generating stations and large industrial plants. This type of fuel cell uses a ceramic material, rather than a liquid electrolyte, because the ceramic lends itself well to the high operating temperature (1000°C) and fuel flexibility expected in a SOFC.

6.6 Direct Methanol Fuel Cell (DMFC)

This technology is relatively new and often not considered in the types of fuel cells. DMFCs working at low and intermediate temperatures (up to 150 °C) and employing solid protonic electrolytes have been postulated as suitable systems for power generation in the field of electrotraction [27-32]. The DMFC as a relatively new technology uses polymer electrolyte like PEMFC but uses liquid methanol or alcohol as fuel instead of reformed hydrogen fuel. During chemical reactions, the anode draws hydrogen by dissolving liquid methanol (CH_3OH) in water in order to eliminate the need of external reformer. At the cathode, the recombination of the positive and negative ions takes place, which are supplied from anode through external circuit and it is combined with oxidized air to produce water as a by-product. They show efficiencies around 40% and work at temperatures around 130°C. Applications are employed in small and medium size, to power mobile phones and laptops. The overall chemistry of the fuel cells is given in Fig. 3 [33].

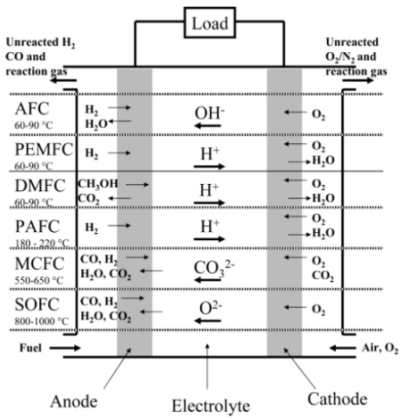

Fig. 3: Types of Fuel cells

7. FUEL PRODUCTION METHOD AND APPLICATIONS

The main fuel for fuel cells is hydrogen (a general scheme for the production of hydrogen is shown in Fig. 4 [34]) but the storage of it is a major and important issue. Hydrogen has been stored in materials such as nanotubes, carbon fibres, metal hydrides, and glass microspheres.

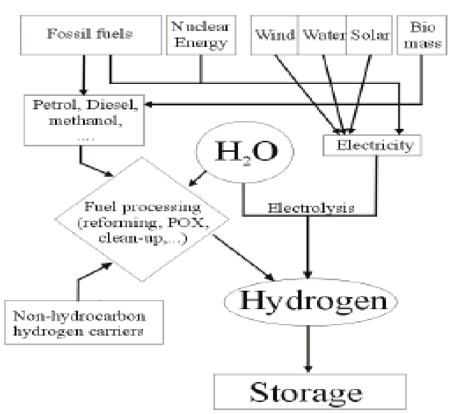

Fig. 4: Possible production paths for hydrogen

Hydrogen storage in alcohols or hydrocarbons, such as methanol or methane gas, can also be an considered. Such hydrocarbons/alcohols can be reformed into hydrogen-rich synthesis gases by several methods. The main processes for hydrogen production are: Partial Oxidation, Catalytic Steam Reforming, and Auto thermal Reforming. The key for hydrogen is that it can react at room temperature hence can be used for commercial applications such as in laptops. Fuel cells are an enhanced form of battery, except a battery eventually goes dead while a fuel cell, with a regular supply of the fuel it keeps running.

Being a clean energy source combined with low noise makes fuel cells the fuel for the future fuel and an important step towards the hydrogen economy.

If we see the trend that we started from using coal then petroleum, natural gas and methane and an eventual shift towards the hydrogen economy.

Problems associated with fuel cell involves the cost of the catalyst (usually Platinum), durability at high temperatures, concerns related to the Hydrogen Infrastructure, these are typical problems which can be expected to be overcome by science.

8. CONCLUSION

Today, numerous fuel cell–based power plants have been built and operated successfully, on a scale of both tens of megawatts and tens or hundreds of kilowatts. A great many small fuel cell units are in use that output between a few milliwatts and a few watts. Fuel cells are already making an important contribution to solving economic and ecological problems facing humankind.

There can be no doubt that this contribution will continue to increase. Hydrogen is the most abundant element in the Universe and therefore is a prime contender for our energy conversion purposes. Fuel cells offer that media which can harbor this reality which promises clean energy.

Large scale research and development efforts concerning the development and application of fuel cells are conducted today in many countries, in national laboratories, in science centers and universities, and in industrial establishments. Advances in automobiles may promise less pollution, but it does not reduce the operation upstream which is extraction of fossil fuels, with fuel cells and newer technologies like renewable electrolysis a significant reduction can take place in aforementioned upstream operations. Today several hundred publications in the area of fuel cells appear every month in scientific and technical journals. And they all seem to aim at the same purpose. We are not moving away from the age of carbon, we are made of carbon. Conversion of biomass and other feedstock sources to energy using fuel cells indicates that the science of tapping into the carbon and hydrogen chemistry is reaching a better level of understanding which will be in every sense a beautiful step forward. There is nothing complicated about it, it is just beautiful chemistry.

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