Hydrogen and Microbial Fuel Cells as Alternate Sources of Clean Energy

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Abstract: The incessant power generation failure has grossly affected the economy, seriously slowing down development in rural and sub-rural settlements, with present energy policy mainly benefiting urban dwellers. Hydrogen and microbes are being considered by many countries as a potential energy carrier for green energy generation and for vehicular applications. In this paper, the current status of hydrogen fuel cell (HFC) and microbial fuel cell (MFC) as alternate sources of clean fuels for economic growth and development are reviewed. The use of hydrogen as well as microbes as alternative sources of non-conventional energy are all new technologies, which are generally not widely available, but possesses a good potential for future use, as a clean fuel. Hydrogen-powered fuel cells are not only pollution-free, but a two to three fold increase in the efficiency can be experienced when compared to traditional combustion technologies. These technologies are already in use in countries such as Japan and in Scotland, where buses in Aberdeen have been in use since 2015. Iceland has taken a major lead in this field by envisaging a project that will produce hydrogen from sea water, using the country's renewable energy sources like wind, geothermal, and hydropower. The MFC is a bio-electrochemical system in which microbes are used to catalyze the conversion of organic material into electricity. MFC is eco-friendly and can be used as a substitute to reduce global greenhouse gases emission. Although the implementation of a hydrogen as well as microbial-based economy would clearly take time, the key point is that research and development to address these viable and environmentally friendly ventures must occur now.
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1. Introduction

The pursuit of a clean and healthy environment has stimulated much effort in the development of technologies for the utilization of hydrogen and microbial-based energies (Meregalli and Parrinello, 2001). Fuel cell technologies are now on the verge of being introduced commercially, revolutionizing the way we presently produce power. Fuel cell types are generally classified according to the nature of the electrolyte they use.

Each type requires particular materials and fuels and is suitable for different applications. All fuel cells are based around a central design using two electrodes separated by a solid or liquid electrolyte that carries electrically charged particles between them. A catalyst is often used to speed up the reactions at the electrodes. A fuel cell is like a battery that generates electricity from an electrochemical reaction (Garg and Garg, 2012). Both batteries and fuel cells convert chemical energy into electrical energy and also, as a by-product of this process, into heat. However, a battery holds a closed store of energy within it and once this is depleted the battery must be discarded, or recharged by using an external supply of electricity to drive the electrochemical reaction in the reverse direction (Khatib, 1998; Sing *et al.,* 1999).

A fuel cell, on the other hand, uses an external supply of chemical energy and can run indefinitely, as long as it is supplied with a source of hydrogen and a source of oxygen (usually air). The source of hydrogen is generally referred to as the fuel and this gives the fuel cell its name, although there is no combustion involved. Oxidation of the hydrogen instead takes place electrochemically in a very efficient way. During oxidation, hydrogen atoms react with oxygen atoms to form water; in the process electrons are released and flow through an external circuit as an electric current. Unlike storage cells, fuel cell can be continuously fed with a fuel so that the electrical power output is sustained indefinitely (Oh and Logan, 2005). They convert hydrogen, or hydrogen-containing fuels, directly into electrical energy plus heat through the electrochemical reaction of hydrogen and oxygen into water. The process is that of electrolysis in reverse (Eqn1).

Overall reaction: 2 H_2 (gas) + O_2 (gas)

2 H_2O + energy Equation 1

Fuel cells have the capacity to power almost any portable devices that normally use batteries and can also power transportation such as vehicles, trucks, buses, and marine vessels, as well as provide auxiliary power to traditional transportation technologies (Melis and Happe, 2005; Thomas and Zalbowitz, 2001). It does not involve any form of pollution and it runs continuously as long as it gets input fuels (hydrogen and oxygen). Unlike a battery, a fuel cell draws its input (hydrogen and oxygen) from outside, and it does not need any charging as is required by a battery (Barbir, 2005). Finally, there is no toxic output, when a fuel cell is discarded, as happens on discarding of a battery.

The two principle reactions in the burning of any hydrocarbon fuel are the formation of water and carbon dioxide (Solomon *et al.,* 2018a; b). As the hydrogen content in a fuel increases, the formation of water becomes more significant, resulting in proportionally lower emissions of carbon dioxide. As fuel use has developed through time, the percentage of hydrogen content in the fuels has increased. It seems a natural progression that the fuel of the future will be 100% hydrogen (Figure 1).

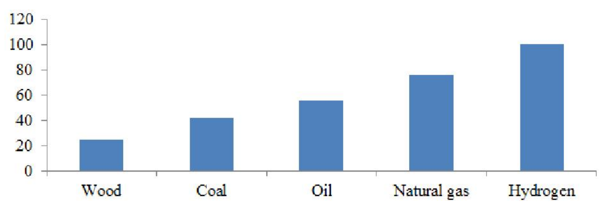

Figure 1. *Trends in the use of fuels.*

1.1. Hydrogen Fuel Cell

Fuel cell today is the leading authority on information relating to the fuel cell and hydrogen industries. Hydrogen can play a particularly important role in the future by replacing the imported petroleum we currently use in our cars and trucks (Sing *et al.,* 1999; Bond and Lovley, 2003). In the future, hydrogen will join electricity as an important energy carrier, since it can be made safely from renewable energy sources (Solomon, 2015) and is virtually non-polluting.

It will also be used as a fuel for 'zero-emissions' vehicles, to heat homes and offices, to produce electricity, and to fuel aircraft. Hydrogen, in fact, produces a lot of energy on burning, and the burning process is non-polluting, since hydrogen on burning uses oxygen, producing water vapour, electricity and heat (Solomon, 2015). Hydrogen fuel cells (HFC) directly convert the chemical energy in hydrogen to electricity, with pure water and heat as the only byproducts (Figure 2).

Hydrogen has the potential to be a very attractive alternative energy carrier. It can be clean, efficient, and derived from diverse domestic resources, such as fossil, nuclear, and renewable (biomass, hydro, wind, solar, geothermal) energy resources (Bullen *et al.,* 2006). There are three primary technology barriers that must be overcome to enable an industry commercialization decision on hydrogen fuel cell vehicles Khatib, 1998; Sing *et al.,* 1999); Barbir, 2005). These primary technology barriers include:

On-board hydrogen storage systems must be developed that allow a vehicle range of greater than 300 miles while meeting packaging, cost, and performance requirements,

i. Fuel cell system costs must be lowered while meeting performance and durability requirements and,

ii. The cost of safe and efficient hydrogen production and delivery must be lowered to be competitive with gasoline without adverse environmental impacts.

The biggest problem in using hydrogen as a fuel is the fact that hydrogen is not available in a free state. It is locked in water and in compounds like petrol, natural gas, and methanol. We need to use energy and an effective method to split these compounds to obtain hydrogen. Since water is available in abundance in nature, there may be a good potential for splitting it to produce hydrogen (Khatib, 1998). This splitting will, however, require either heat, or electricity to split it, through a process called "electrolysis".

The second problem that arises is in its storage, which is not easy, since hydrogen when stored as compressed gas is highly explosive, and needs tanks which have to be large, heavy, and costly. Only large trucks could, hold such tanks for carrying them from one place to another. When stored in the liquid form, the hydrogen needs a lot of energy for maintaining the very low temperatures that will be needed to keep it in liquid form.

Another method suggested is to store it as solid metal hybride (Thomas and Zalbowitz, 2001). Here again, energy is needed to release the hydrogen, when we want to use it. Usually, hydrogen is stored in under-ground tanks, and is transmitted through pipelines, which is a highly specialized job, needing its conversion into compressed gas, or in liquid or solid metal form. Hydrogen fuel cell is shown in Figure 2.

1.2. Fuel Cells for NASA

Currently, hydrogen is mainly used as a fuel in the NASA space program. For space applications, fuel cells have the advantage over conventional batteries, in that they produce several times as much energy per equivalent unit of weight. In the1960s, International Fuel Cells in Windsor Connecticut developed a fuel cell power plant for the Apollo spacecraft. The plant, located in the service module of the spacecraft, provided both electricity as well as drinking water for the astronauts on their journey to the moon. It could supply 1.5 kilowatts of continuous electrical power. Fuel cell performance during the Apollo missions was exemplary.

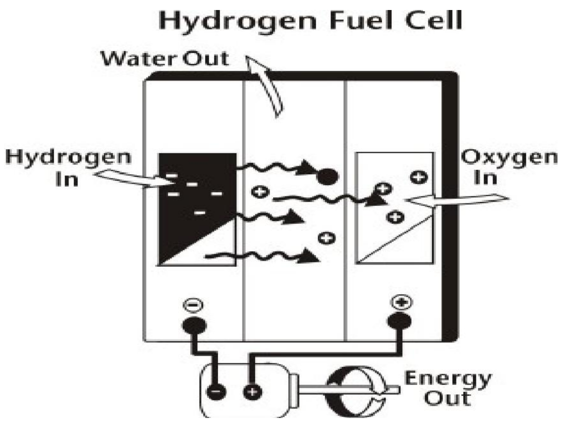

Figure 2. *Hydrogen fuel cell.*
Source: US-DOE (2013).

Over 10,000 hours of operation were accumulated in 18 missions, without a single in-flight incident. In the 1970s, International Fuel Cells developed a more powerful alkaline fuel cell for NASA's Space Shuttle Orbiter (Figure 3). The Orbiter uses three fuel cell power plants to supply all of the electrical needs during flight. There are no backup batteries on the space shuttle, and as such, the fuel cell power plants must be highly reliable. The power plants are fuelled by hydrogen and oxygen from cryogenic tanks and provide both electrical power and drinking water (Oh and Logan, 2005). Each fuel cell is capable of supplying 12 kilowatts continuously and up to 16 kilowatts for short periods. The Orbiter units represent a significant technology advance over Apollo, producing about ten times the power from a similar sized package.

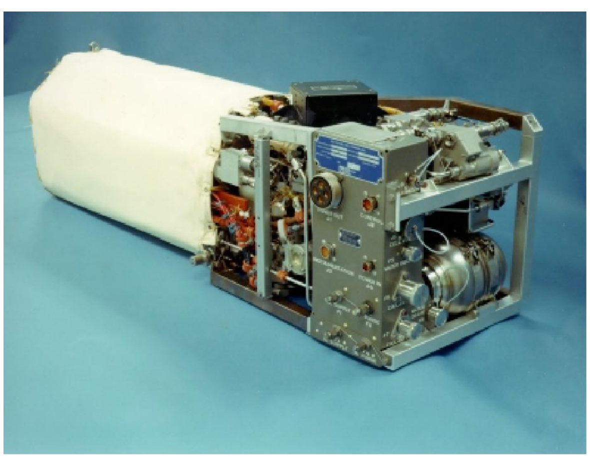

Figure 3. *NASA space shuttle orbiter fuel cell. US-DOE [15].*

Figure 4. *NASA uses hydrogen fuel to launch space shuttles. US-DOE [15].*

In the Shuttle program, the fuel cells have demonstrated outstanding reliability (over 99% availability). To date, they have flown on 106 missions and clocked up over 82,000 hours of operation (NASA). Liquid hydrogen is used to propel space shuttle and other rockets, while hydrogen fuel cells power the electrical systems of the shuttle. NASA uses hydrogen fuel to launch the space shuttles as shown in Figure 4. The hydrogen fuel cell is also used to produce pure water for the shuttle crew (Solomon, 2016; US-DOE, 2013).

1.3. Microbial Fuel Cell

There is an emergent interest to use clean energy sources that are sustainable for wastewater treatment in order to effectively generate power using microbial fuel cell (MFC) other than fossil fuel. Ogugbue*et al.* (2015) has reported significant electricity generation from swine wastewater using microbial fuel cell.

The MFC is a bio-electrochemical system which utilize microbial communities to degrade organic materials found within wastewater and convert stored chemical energy to electrical energy in a single step in which microbes are used to catalyze the conversion of organic material into electricity (Barbir, 2005; Emily *et al.,* 2012; Logan and Regan, 2006; Lovley, 2006).

A MFC has a great potential to offer solution to this problem by generating direct electricity during oxidation of organic matter. Previous studies have shown that the performance of microbial fuel cell is determined by several factors (Gil *et al.,* 2003; Allen and Bennetto, 1993; Choi *et al.,* 2000). These factors include the following:

i. Microbial activities oxidizing fuels in the anode,

ii. Electron transfer from microbial cells to the anode and,

iii. Proton transfer from the anode to cathode.

The microbial fuel cell (Figure 5) is made of four parts: the anode, the cathode, the proton-exchange membrane (PEM) and the external circuit. The anode holds the bacteria and organic material in an anaerobic environment (Logan and egan, 2006; Lovley, 2006). The cathode holds a conductive saltwater solution. As part of the digestive process, the bacteria create protons (H^+) and electrons (H^-).

The electrons are pulled out of the solution onto an electrode and are conducted through an external circuit (Choi *et al.,* 2000; Ghangrekar and Shinde, 2008). The electrons move through the circuit into the cathode (via cathode's electrode). The protons travel through the proton-exchange membrane or a salt bridge to meet with the electrons at the cathode.

The salt bridge is a mesh of proteins that separate the anode and cathode chambers, allows the protons to move from the anode to the cathode, but keeps the solutions in the anode and cathode separate. At the cathode, the protons and electrons combine with oxygen to create water (Ghangrekar and Shinde, 2008; Li *et al.,* 2009).

Microbial fuel cells can use a wide range of materials (Chris *et al.,* 2008; Larminie and Dick, 2000). Organic materials can offer the intriguing capability of purifying waste and producing fresh water while also creating electricity. Microbial fuel cells have recently received increased attention as a means to produce 'green' energy from organic wastewater or synthetically prepared carbohydrate substrates (Ghangrekar and Shinde, 2008).

The advantages of using MFC in this situation as opposed to a normal battery is that it uses a renewable form of energy and need not to be recharged like a standard battery would (Ghangrekar and Shinde, 2008; Li *et al.,* 2009). The microbial fuel cells still need a significant breakthrough to become economically competitive. Figure 5 is a schematic diagram of a dual chambered microbial fuel cell.

1.3.1. Applications Fuel Cell Technology

i. Transportation. Major companies associated with this project are Daimler-Chrysler, Royal Dutch Shell, and Norsk Hydro. Royal Dutch Shell will operate hydrogen filling stations. The project may take 20-25 years, but is likely to become a model for other countries to follow (Bossel, 2000). Other automobile companies like Honda, and General Motors have made prototype fuel cell cars.

These major automobile manufacturing companies are conducting research to introduce hybrid vehicles that use a combination of fossil fuel and electric motors. They are, in fact, focused on producing a vehicle that can reform gasoline or methanol into hydrogen, so that the car powered by fuel cells can still refuel at traditional filling stations.

The California Low Emission Vehicle Program, administered by the California Air Resources Board (CARB), has been a large incentive for automobile manufacturers to actively pursue fuel cell development.

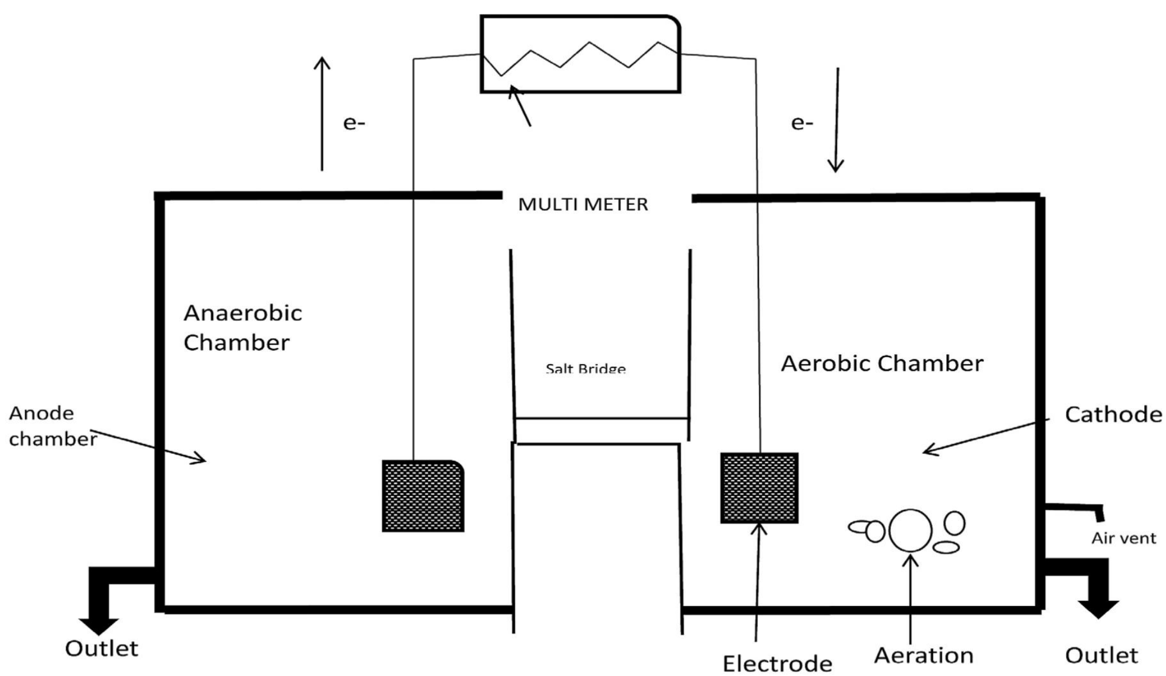

Figure 5. *A schematic diagram of a dual chambered microbial fuel cell.*
Source: Ogugbue*et al.* (2015).

This program requires that beginning in 2003, 10% of passenger cars delivered for sale in California from medium or large sized manufacturers must be Zero Emission Vehicles, called ZEVs. Automobiles powered by fuel cells meet these requirements, as the only output of a hydrogen fuel cell is pure water. The NECAR 5 (Figure 6) is the latest prototype fuel cell automobile by Daimler Chrysler. This automobile is fuelled with liquid methanol which is converted into hydrogen and carbon dioxide through use of an onboard fuel processor.

Figure 6. *Prototype automobiles, the NECAR 5 and JEEP Commander.*
Source**:** US-DOE [15].

The vehicle has virtually no pollutant emissions of sulphur dioxide, oxides of nitrogen, carbon monoxide or particulates, the primary pollutants of the internal combustion engine. The efficiency of a fuel cell engine is about a factor of two higher than that of an internal combustion engine and the output of carbon dioxide is considerably lower.

The NECAR 5 drives and feels like a "normal" car. It has a top speed of over 150 km/hr (90 mph), with a power output of 75 kW (100 horsepower). It is also believed that this vehicle will require less maintenance. It combines the low emission levels, the quietness and the smoothness associated with electric vehicles, while delivering a performance similar to that of an automobile with an internal combustion engine.

In April 1999 the California Fuel Cell Partnership was developed. Fuel cells operate best on pure hydrogen. But fuels like natural gas, methanol, or even gasoline can be reformed to produce the hydrogen required for fuel cells (Hart *et al.,* 2015). Some fuel cells even can be fueled directly with methanol, without using a reformer. In the future, hydrogen could also join electricity as an important energy carrier.

An energy carrier moves and delivers energy in a usable form to consumers. Renewable energy sources, like the sun and wind, can't produce energy all the time. But they could, for example, produce electric energy and hydrogen, which can be stored until it's needed. Hydrogen can also be transported to locations where it is needed. Figure 7 shows the future hydrogen energy infrastructure.

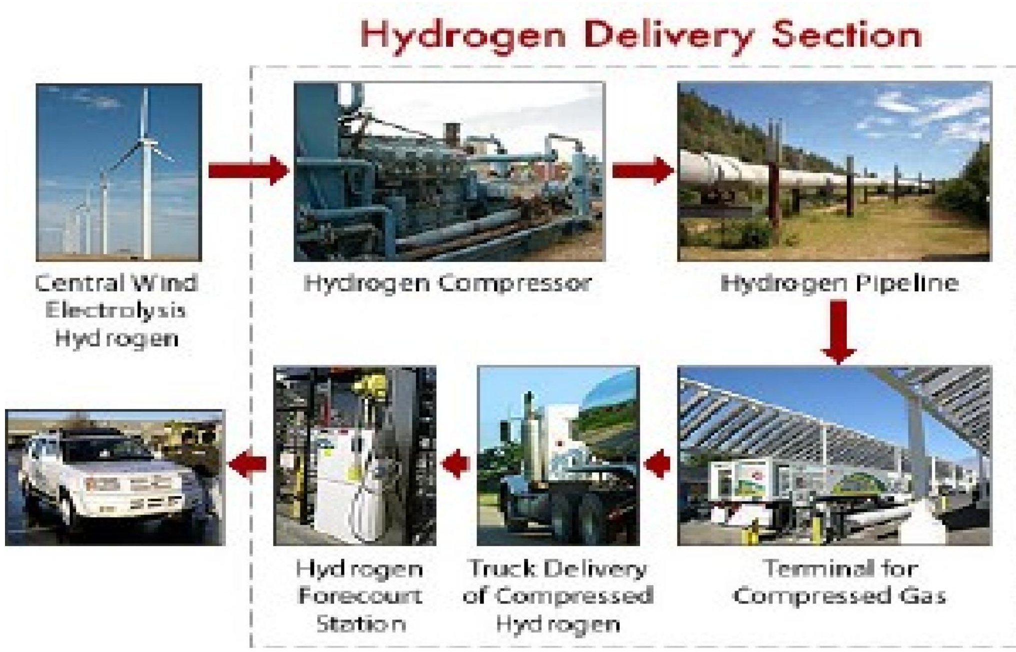

Figure 7. *Future hydrogen energy infrastructure [15].*

ii. Distributed power generation. Electrical energy demands throughout the world are continuing to increase. In Canada the demand is growing at an annual rate of approximately 2.6%. In America the rate is about 2.4%, and in developing countries it is approximately 6% [3]. How can these energy demands be met responsibly and safely? Distributed power plants using fuel cells can provide part of the solution.

Distributed or "decentralized" power plants, contrasted with centralized power plants, are plants located close to the consumer, with the capability of providing both heat and electrical power (a combination known as "cogeneration"). Heat, the by-product of electrical power generation, is transferred from the fuel cell to a heat exchanger. The exchanger transfers the heat to a water supply, providing hot water to local customers.

The overall efficiency of a cogeneration system can be in excess of 80%, comparatively high compared to a system producing electricity alone. An increase in efficiency naturally corresponds to a decrease in fuel consumption (Cho *et al.,* 2008). Distributed power plants have many additional advantages. For example, they can provide power to a remote location without the need of transporting electricity through transmission lines from a central plant (Beling, 2012; Feng *et al.,* 2009; Liu and Logan, 2005). There is also an efficiency benefit in that the cost of transporting fuel is more than offset by the elimination of the electrical losses of transmission. The ability to quickly build up a power infrastructure in developing nations is often cited. Using fuel cell power plants obviates the need for an electrical grid.

1.3.2. Advantages of Fuel Cells

About 175 years have passed since the invention of the fuel cell by Schoenbein und Grove, but up until now, only limited market penetration has occurred despite the potentially high energy conversion efficiency of fuel cell technology (Bossel, 2007). Its benefits are:

i. Fuel cells are efficient: They convert hydrogen and oxygen directly into electricity and water, with no combustion in the process. The resulting efficiency is between 50 and 60%, about double that of an internal combustion engine.

ii. Fuel cells are clean: If hydrogen is the fuel, there are no pollutant emissions from a fuel cell itself, only the production of pure water. In contrast to an internal combustion engine, a fuel cell produces no emissions of sulphur dioxide, which can lead to acid rain, nor nitrogen oxides which neither produce smog nor dust particulates.

iii. Fuel cells are quiet: A fuel cell itself has no moving parts, although a fuel cell system may have pumps and fans. As a result, electrical power is produced relatively silently. Many hotels and resorts in quiet locations, for example, could replace diesel engine generators with fuel cells for both main power supply or for backup power in the event of power outages.

iv. Fuel cells are modular: That is, fuel cells of varying sizes can be stacked together to meet a required power demand. Fuel cell systems can provide power over a large range, from a few watts to megawatts.

v. Fuel cells are environmentally safe: They produce no hazardous waste products, and their only by-product is water (or water and carbon dioxide in the case of methanol cells).

vi. Fuel cells may give us the opportunity to provide the world with sustainable electrical power.

1.3.3. Major Pitfalls of Fuel Cells

At present there are many uncertainties to the success of fuel cells and the development of a hydrogen economy. Some of its challenges include:

i. Fuel cells must obtain mass-market acceptance to succeed. This acceptance depends largely on price, reliability, longevity of fuel cells and the accessibility and cost of fuel. Compared to the price of present day alternatives e.g. diesel-engine generators and batteries, fuel cells are comparatively expensive. In order to be competitive, fuel cells need to be mass produced less expensive materials developed.

ii. An infrastructure for the mass-market availability of hydrogen, or methanol fuel initially, must also develop. At present there is no infrastructure in place for either of these fuels. As it is we must rely on the activities of the oil and gas companies to introduce them. Unless motorists are able to obtain fuel conveniently and affordably, a mass market for motive applications will not develop.

iii. At present a large portion of the investment in fuel cells and hydrogen technology has come from auto manufacturers. However, if fuel cells prove unsuitable for automobiles, new sources of investment for fuel cells and the hydrogen industry will be needed.

iv. Changes in government policy could also derail fuel cell and hydrogen technology development. At present stringent environmental laws and regulations, such as the California Low Emission Vehicle Program have been great encouragements to these fields. Deregulation laws in the utility industry have been a large impetus for the development of distributed stationary power generators. Should these laws change it could create adverse effects on further development.

v. At present platinum is a key component to fuel cells. Platinum is a scarce natural resource; the largest supplies to the world platinum market are from South Africa, Russia and Canada. Shortages of platinum are not anticipated; however changes in government policies could affect the supply.

2. Conclusion

As our demand for electrical power grows, it becomes increasingly urgent to find new ways of meeting it both responsibly and safely. Fuel cells are a promising technology for use as a source of heat and electricity for buildings, and as an electrical power source for electric motors propelling vehicles.

3. Recommendations

With the use of fuel cells, hydrogen and microbial powered technologies, electrical power from renewable energy sources can be delivered where and when required, cleanly, efficiently and sustainably.

Although the implementation of a hydrogen fuel cell technology as well as microbial-based economies would clearly take time, the key point is that research and development to address these viable ventures must occur now. Considering the fact that it is environmentally friendly, it will go a long way to ameliorate the incidence of pollution as a step towards sustaining the environment.

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Competing and Conflicting Interests

The authors declare that there is no competing and/or conflict of interest related to this research work.

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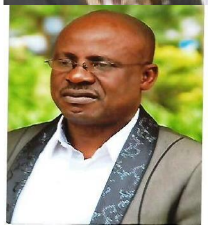

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