1. INTRODUCTION

Fuel cells have received considerable attention lately for their potential as clean and reliable electricity generating devices. Fuel cells cannot yet compete economically with more traditional energy technologies because of lack of reliable hydrogen source supply, but rapid technical advances are being made.

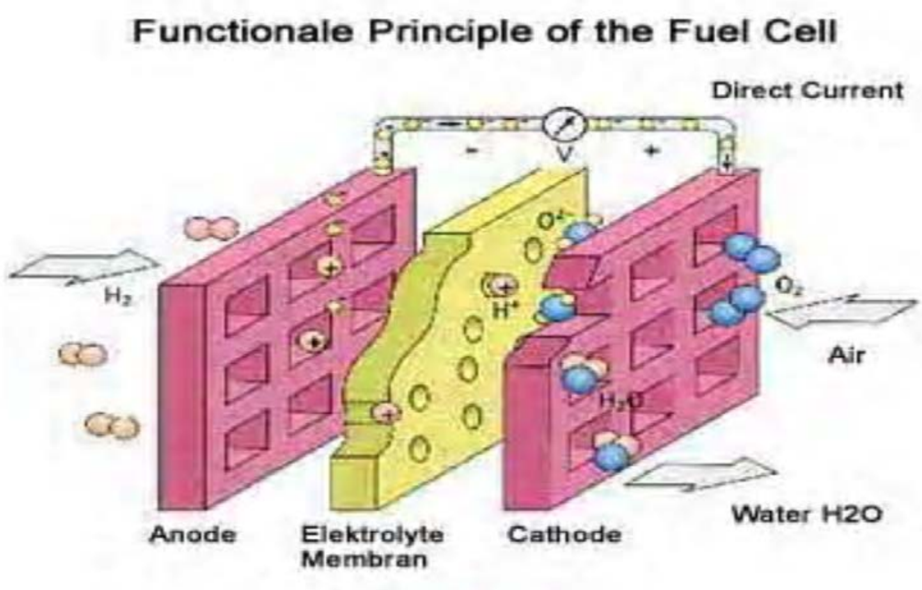
1.1 What are fuel cells?

A fuel cell is an electrochemical device used to create electricity. Much like the batteries that are found under the hoods of automobiles and in CD players and flashlights, it converts chemical energy to electrical energy. But unlike a typical battery, which holds a limited fuel supply in a sealed container, a fuel cell requires an ongoing supply of fuel to create a continuous flow of electricity. The fuels, hydrogen and oxygen, are fed to the two terminals of the fuel cell and a chemical reaction occurs which produces electricity along with the heat and water. Fuel cells have great potential for a variety of applications, including transportation as well as stationary and portable power uses.

1.2 Fuel cell parts and applications

A typical fuel cell system for stationary power applications has three main parts: a fuel cell stack, a fuel processor, and the power electronics. The fuel cell stack combines streams of hydrogen and oxygen, which react and create electricity. The fuel processor produces a supply of hydrogen fuel, separating it from other elements, such as carbon in fossil fuels, to send pure hydrogen gas to the fuel cell stack. The power electronics convert direct current (DC) electricity to alternating current (AC) electricity. A fuel cell system may also have a heat recovery system to harness excess energy for producing electricity. Fuel cells have many potential shapes and sizes suited for diverse applications. The three main applications of fuel cells are: transportation (as in personal or commercial vehicles), portable uses (for backup generation and small electronics), and stationary installations (in large buildings and military bases).

An illustration and explanation of a fuel cell functional principles:



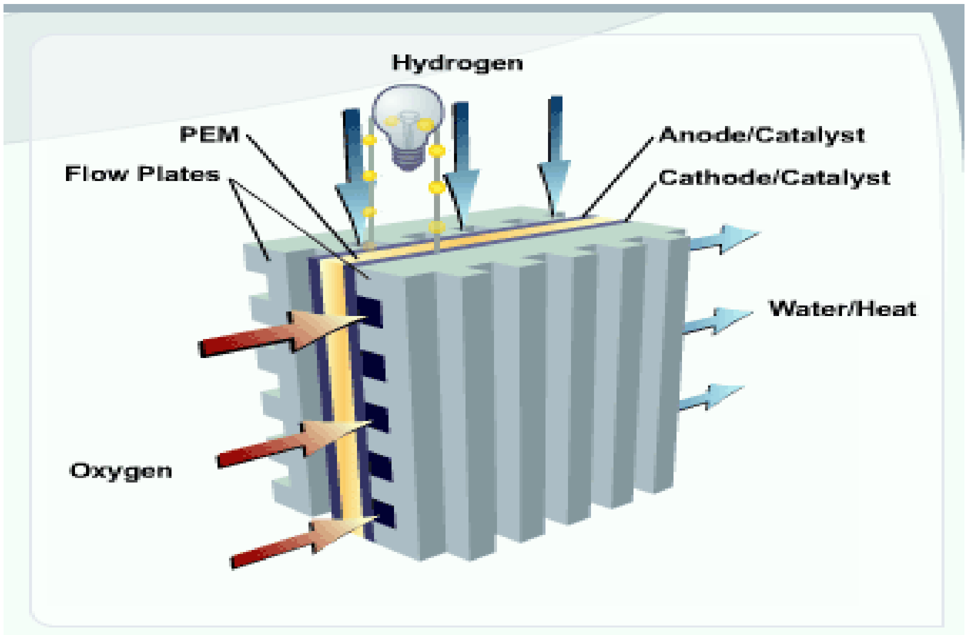
Hydrogen and oxygen react in the fuel cell and bond into water over a thin, permeable membrane. Energy is freed, through this process, in the form of electricity. The fuel cell, therefore, transforms the chemical energy of the oxidation process, the so-called "cold combustion", directly into electric energy. The only by-product is steam. If the needed hydrogen could be obtained through solar energy, this secondary energy source would become an important alternative for the power supply of the future: environmentally friendly and pollutant free. Hydrogen is, however, not a source of energy; it just carries and stores energy. And the fuel cell is not a Perpetuum Mobile (an object that continually moves without energy input), but technology through which electricity can be produced-nevertheless with remarkable efficiency: the heat obtained through electricity production can be used to heat, just as with a block-type thermal power station.

1.3 Fuel cell benefits and barriers

Fuel cells have a number of environmental, social, and other benefits. While they currently face market barriers due to their early stage of development, fuel cells have the potential to be more economically viable in the near future. Because a fuel cell only consumes fossil fuels within its system, it does not release many gases into the environment. Gases that are released, such as carbon dioxide (CO2), are emitted in very low quantities. This environmental benefit may be enhanced if fuel cells can eventually use hydrogen produced by electrolysis from renewable energy sources. Fuel cells may also be more reliable than current fossil fuel energy production, and have the added benefit of reducing dependence on foreign fossil fuel imports.

1.4 Types of fuel cells

a. Proton exchange membrane fuel cell (PEFMC): an illustration



PEM fuel cells work with a polymer electrolyte in the form of a thin, permeable sheet. Efficiency is about 40 to 50 percent, and operating temperature is about 80 degrees C. Cell outputs generally range from 50 to 250 kW. The solid, flexible electrolyte will not leak or crack, and these cells operate at a low enough temperature to make them suitable for homes and cars. But their fuels must be purified, and a platinum catalyst is used on both sides of the membrane, raising costs.
To function, the membrane must conduct hydrogen ions (protons) but not electrons as this would in effect "short circuit" the fuel cell. The membrane must also not allow either gas to pass to the other side of the cell, a problem known as "gas crossover". Finally, the membrane must be resistant to the reducing environment at the cathode as well as the harsh oxidative environment at the anode.

Unfortunately, while the splitting of the hydrogen [molecule] is relatively easy by using a [platinum] catalyst, splitting the stronger oxygen molecule is more difficult, and this causes significant electric losses. An appropriate catalyst material for this process has not been discovered, and platinum is the best option. Another significant source of losses is the resistance of the membrane to proton flow, which is minimized by making it as thin as possible.

The PEMFC is a prime candidate for vehicle and other mobile applications of all sizes down to [mobile phones], because of its compactness. However, the water management is crucial to performance: too much water will flood the membrane, too little will dry it; in both cases, power output will drop. Water management is a very difficult subject in PEM systems. Furthermore, the platinum catalyst on the membrane is easily [catalyst poisoning| poisoned] by [carbon monoxide], no more than one [part per million] is usually acceptable and the membrane is sensitive to things like metal ions, which can be introduced by corrosion of metallic [bipolar] plates, metallic components in the fuel cell system or from contaminants in the fuel / oxidant.

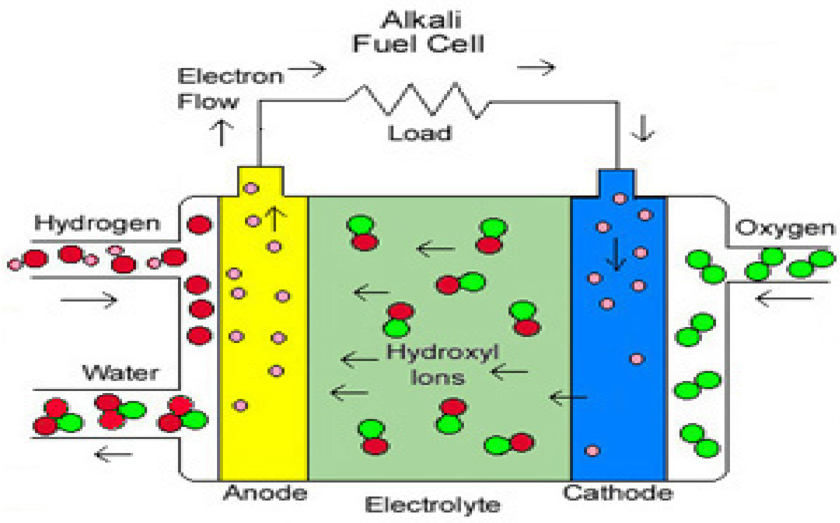
b. Phosphoric acid fuel cells (PAFC)

Phosphoric acid fuel cells (PAFC) operate at temperatures around 150 to 200 C. As the name suggests, PAFCs use phosphoric acid as the electrolyte. Positively charged hydrogen ions migrate through the electrolyte from the anode to the cathode. Electrons generated at the anode travel through an external circuit, providing electric power along the way, and return to the cathode. There the electrons, hydrogen ions and oxygen form water, which is expelled from the cell. A platinum catalyst at the electrodes speeds the reactions. The formation of carbon monoxide (CO) around electrodes can "poison" a fuel cell. One advantage of PAFC cells is that at 200 degrees C they tolerate a CO concentration of about 1.5 percent, which broadens the choice of fuels they can use. If gasoline is used, the sulfur must be removed. Platinum electrode-catalysts are needed, and internal parts must be able to withstand the corrosive acid. Another advantage is that concentrated phosphoric acid electrolyte can operate above the boiling point of water, a limitation on other acid electrolytes that require water for conductivity. The acid requires, however, that other components in the cell resist corrosion.

Hydrogen for the fuel cell is extracted from a hydrocarbon fuel in an external reformer. If the hydrocarbon fuel is gasoline, sulfur must be removed or it will damage the electrode catalyst. Efficiencies of PAFCs average 40 to 50 percent, but this can rise to about 80 percent if the waste heat is reused in a cogeneration system. PAFCs of up to 200 kw capacity are in commercial operation, and units of 11 MW capacity have been tested. Efficiency ranges from 40 to 80 percent. Existing phosphoric acid cells have outputs up to 200 kW, and 11 MW units have been tested.

c. Alkaline fuel cells.

An Illustration of an Alkali Fuel Cell:



Alkaline fuel cells (AFC) are one of the most developed technologies and have been used since the mid-1960s by NASA in the Apollo and Space Shuttle programs. The fuel cells on board these spacecraft provide electrical power for on-board systems, as well as drinking water. AFCs are among the most efficient in generating electricity at nearly 70%.

Alkaline fuel cells use an electrolyte that is an aqueous (water-based) solution of potassium hydroxide (KOH) retained in a porous stabilized matrix. The concentration of KOH can be varied with the fuel cell operating temperature, which ranges from 65°C to 220°C. The charge carrier for an AFC is the hydroxyl ion (OH-) that migrates from the cathode to the anode where they react with hydrogen to produce water and electrons. Water formed at the anode migrates back to the cathode to regenerate hydroxyl ions. Therefore, the chemical reactions at the anode and cathode in an AFC are shown below. This set of reactions in the fuel cell produces electricity and by-product heat.

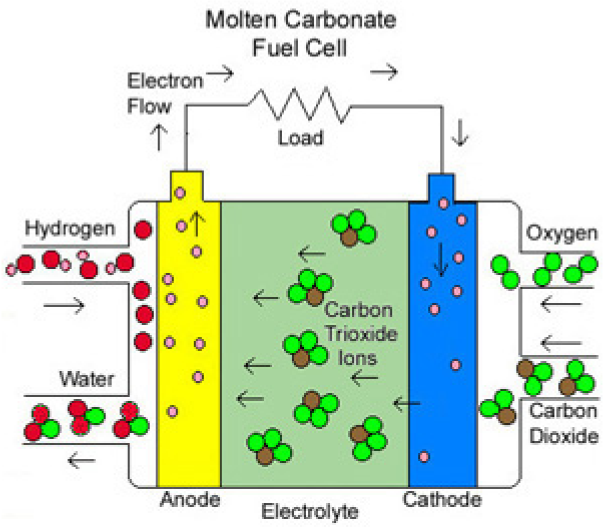
One characteristic of AFCs is that they are very sensitive to CO2 that may be present in the fuel or air. The CO2 reacts with the electrolyte, poisoning it rapidly, and severely degrading the fuel cell performance. Therefore, AFCs are limited to closed environments, such as space and undersea vehicles, and must be run on pure hydrogen and oxygen. Furthermore, molecules such as CO, H2O and CH4, which are harmless or even work as fuels to other fuel cells, are poisons to an AFC.

On the positive side, AFCs are the cheapest fuel cells to manufacture. This is because the catalyst that is required on the electrodes can be any of a number of different materials that are relatively inexpensive compared to the catalysts required for other types of fuel cells.

AFCs are not being considered for automobile applications. Their sensitivity to poisoning, which requires use of pure or cleansed hydrogen and oxygen, is an insurmountable obstacle at the present time. Conversely, AFCs operate at relatively low temperatures and are among the most efficient fuel cells, characteristics that would enable a quick starting power source and high fuel efficiency, respectively.

d. Molten Carbonate Fuel Cell (MCFC)

An Illustration of MCFC



Molten-carbonate fuel cells (MCFCs) are high-temperature fuel cells, which operate at temperatures of 600°C and above. They have the highest efficiencies of any type fuel cell, including solid oxide fuel cells, proton exchange membrane fuel cells and phosphoric acid fuel cell and are not subject to the high-temperature material issues that affect solid-oxide technology.

Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications. MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic matrix of beta-alumina solid electrolyte (BASE). Since they operate at extremely high temperatures of 650°C (roughly 1,200°F) and above, non-precious metals can be used as catalysts at the anode and cathode, reducing costs.

Improved efficiency is another reason MCFCs offer significant cost reductions over phosphoric acid fuel cells (PAFCs). Molten carbonate fuel cells can reach efficiencies approaching 60 percent, considerably higher than the 37-42 percent efficiencies of a phosphoric acid fuel cell plant. When the waste heat is captured and used, overall fuel efficiencies can be as high as 85 percent.

Unlike alkaline, phosphoric acid, and polymer electrolyte membrane fuel cells, MCFCs don't require an external reformer to convert more energy-dense fuels to hydrogen. Due to the high temperatures at which MCFCs operate, these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming, which also reduces cost.

Molten carbonate fuel cells are not prone to carbon monoxide or carbon dioxide "poisoning" —they can even use carbon oxides as fuel—making them more attractive for fueling with gases made from coal. Because they are more resistant to impurities than other fuel cell types, scientists believe that they could even be capable of internal reforming of coal, assuming they can be made resistant to impurities such as sulfur and particulates that result from converting coal, a dirtier fossil fuel source than many others, into hydrogen.

Units with output up to 2 megawatts (MW) have been constructed, and designs exist for units up to 100 MW. The high temperature limits damage from carbon monoxide "poisoning" of the cell and waste heat can be recycled to make additional electricity. Their nickel electrode-catalysts are inexpensive compared to the platinum used in other cells. But the high temperature also limits the materials and safe uses of MCFCs—they would probably be too hot for home use. Also, carbonate ions from the electrolyte are used up in the reactions, making it necessary to inject carbon dioxide to compensate.

2. INTERNATIONAL TECHNOLOGICAL ADVANCES: including Germany.

2.1 The Technology: Fuel Cells for Cars and Heating.

Not only drivers and heating oil consumers are hoping for an alternative to ever more expensive fossil fuels. Large oil companies, such as Shell and BP, and power companies are drawing more strongly on regenerative energy and are looking for subsidiary solutions. The leading automobile producers, with DaimlerChrysler at the forefront, and the heating system company Vaillant want to deliver market-ready fuel cell products in the next few years. BMW wants to equip a number 7 sedan with an engine that burns hydrogen rather than gasoline. The researchers from the Volkswagen Corporation, along with Ford, General Motors, Honda and Toyota, are working on concepts where hydrogen will not be produced until during driving.

DaimlerChrysler wants to offer, production ready A-Class automobiles as well as "Citaro" city buses with this new technology. The Daimler Fuel Cell Project is cooperating with the Canadian manufacturer Ballard Power Systems. The worldwide market leader for proton exchange membranes (PEM) develops and delivers fuel cells for transportation, power supply, portable equipment and further uses.

Drive quick, clean and quiet- without a bad conscience? The dream of the environmentally conscious driver appears to be becoming a reality. DaimlerChrysler already presented the New Electric Car 4 (NECAR IV) in the USA in early 1999, a fuel cell automobile with a large range and good mileage in an A-Class Mercedes. The fuel cell, the tank and room for up to five people with luggage have found, for the first time, space in a compact car. Just a few years ago, the mobile fuel cell technology would have needed a large vehicle.

Illustration: DaimlerChrysler AG The "sandwich floor" in the A-Class is the platform where the fuel cell propulsion is installed.

The NECAR 4 runs on liquid hydrogen; the tank is located in the back of the vehicle. A proton-conducting fuel cell (Proton Exchange Membrane Fuel Cell- PEMFC) processes the fuel. A platinum plated membrane disperses the hydrogen into protons and electrons. Water is formed through contact with atmospheric oxygen. Positive and negative poles are formed by the surplus or shortage of electrons and protons; the electric motor, which powers the vehicle, is connected through this. One tank-up should last up to 450 kilometers.
"The fuel cell activities are no longer driven by technology or are influenced by environmentalism, but depict, in the meantime, a real competition factor," stated Prof. Panik at a press conference in Stuttgart. “We recognize the fuel cell as a business opportunity to secure high tech jobs and company success."

The "mobile power station" could stand in front of the house or in the garage and deliver about 75 kilowatts of energy, of which only 3-10 kilowatts would be used in the household. The rest would be fed into the electricity network.

2.2 Fuel Cells in the Cellar: Heating Systems from Vaillant

The Vaillant Group, one of the leading European producers for heating technology, wants to bring their new fuel cell heating unit onto the market as early as possible. The company has already been working for two years on the integration of the technology into the household heating system. The heating of residences should, in the future, deliver electricity and heat at the same time, reduce primary energy consumption and greenhouse gasses, and also contribute to the safeguarding of the power supply. Vaillant goes a step beyond the well-known block-type thermal power plant to the local energy supply and brings the technology to the final consumer.

Illustration: Vaillant-Gruppe

Electricity and heat can be produced in a linked process with fuel cell heating units in almost every building that has a gas supply. The pure CO2-free hydrogen for the PEM-fuel cell will be obtained from natural gas through a so-called reformer. The electrical efficiency of the heating unit will amount to approximately 35-40%; an entire efficiency of 80% will be reached through the power-heat coupling. The waste heat from the fuel cell will be used for heating and warming of domestic water. On especially cold days, an integrated conventional boiler will cover the remaining demand

The Vaillant heater can also be environmentally persuasive in comparison to the traditional low temperature boiler and electricity from the socket. The fuel cell heater uses low-carbon natural gas and the waste heat too, and thus reduces CO2 emissions by up to 50%. If the climate goals of the European Union are reached, the fuel cell can play an important role in this field. If mass production begins soon, then the hydrogen will still be obtained from natural gas. Solar hydrogen, produced via electrolysis with Photovoltaic electricity is, in and of itself, still the dream of the future for the engineers from Vaillant. It certainly sounds good, since there would always be an emission-free energy source available.

2.3 The Future: Sun and Hydrogen in the Solar Global Economy

The new technology is awakening many hopes that still have to be fulfilled. Cars and heaters are not yet available; the final price for the product is at this time incalculable. How much the fuel cell powered A-Class will cost is still unanswerable, as well as the question on nationwide maintenance with fuel. That the technology is still, in some part, in an early stage of development, is especially exhibited with the cars: many manufacturers are competing here, and it is not yet settled, which standards will prevail. Even when the developers have mastered technological risks such as explosion hazards, there are still a few questions to clear up. The methods of storage, transportation and distribution of the initial substance have to be tested to see if they are environmentally harmful. Methanol, for example, one of the chemical bonds obtained from hydrogen, is corrosive, highly poisonous, and mixes easily with water. If the hydrogen is obtained from gasoline, OPEC will be all the more pleased.

If the electricity stems from coal-fired power stations, then the atmosphere will be burdened with more CO2. At this time, the production costs of solar hydrogen can only be roughly estimated: if it is obtained through large PV systems (300 MW electrolysis), a cubic meter will cost, in the least expensive case, about 2.90 DM (Deutsche Mark), which corresponds to a kilowatt price of about 85 pfennigs for electricity from fuel cells. Produced in small industrial systems, a kilowatt-hour will cost up to 1.70 DM. Only after mass production of PV modules has been expanded, and with it the associated lowering of prices, could Photovoltaic produced hydrogen be offered as an economical solution.

The scenarios of large-scale use, which were developed in the 80s, are firmly rejected by Professor Panik and others. Since then, gigantic solar farms in the Sahara are seen by many as the wrong method. The DaimlerChrysler project manager places more value on wind or water power. The latter produces not only electricity, but also hydrogen via electrolysis. Decentralized solutions, such as the Vaillant heater, fit better with solar energy. Herman Scheer, German Member of Parliament and 1999 winner of the Right Livelihood Award (the Alternative Nobel Prize), also votes for decentralization. He characterizes the global energy industry of the future through the phasing out of fossil sources: they should be replaced by small-, mini-, and micro-power stations.

Solar heat, photovoltaics, and fuel cells have something in common: they are best suited for direct consumer use. Transportation costs and losses will drop. Solar heating systems and domestic Photovoltaic systems are a first and, as of today, feasible step. Fuel cells and solar hydrogen are a consequential continuation-and an important chance for climate politics.

3. SOUTH AFRICA'S COMPARATIVE ADVANTAGE

The reasons for wanting to introduce fuel cells are clear. They can work more efficiently than internal combustion engines and therefore consume less fuel. They are cleaner than many alternative technologies, producing less local pollution and improving urban air quality. They can allow a country to control its energy use and improve its energy security. But are there other reasons why South Africa should be interested?

3.1 The materials

Unsurprisingly, the answer is that there are. Firstly, the most popular type of fuel cell, proton exchange membrane (PEM) technology employs platinum as the catalyst for the electricity-producing reaction. Other types are not so dependant on the precious metal but since PEM is the leading technology for use in vehicles, widespread adoption of fuel cells should be beneficial for the platinum industry.

Unlike the environmental benefits, this advantage will come regardless of whether a fuel cell is built or used in South Africa or elsewhere.

3.2 The fuel

Next, the question of which fuel these devices might use has not yet been decided. In the long run, the expectation is that they can be closely tied in with renewable energy sources (such as hydro-electric or solar power). But, in the meantime, it is likely that hydro-carbon fuels will be the original source for the hydrogen which a fuel cell drinks.

Although oil is the most prominent contender for this role, there are other options. In a meeting about the introduction of hydrogen and fuel cell technology into Europe, one proposal was to use newly-developed coal gasification technology to produce this hydrogen and use it in huge fuel cells. Using low-sulphur coal, such as that found in South Africa, allows the process to be cleaner and more efficient with centralised production of electricity and an unwanted by-product, carbon dioxide. In the longer term, it may even prove possible to store this gas, sequestering it and further reducing the environmental impact.

3.3 The future

Apart from South Africa's mineral wealth, what other opportunities are there? The nature of fuel cell technology makes it hard to forecast all of the possibilities but two spring to mind immediately. The first is obvious: whenever the technology takes off,

manufacturing of components and the fuel cells themselves will be required. The country already has experience of attracting carmakers and may likewise be able to garner investment and build jobs in fuel cells. Perhaps fuel cells will also play a significant role in power generation, decentralising it rather than building large power stations and hundreds of miles more cables.
And in the far future? Just as no-one predicted the rise of the computer; we should expect fuel cells to surprise us there too.

4. SUPPLY CHAIN ANALYSIS: with Limpopo platinum mining output as an emphasis.

The world is growing increasingly convinced that fuel cells will be the widespread future providers of energy. Because these engines of the future use primarily platinum, one of the keenest observers of the development of fuel cells is Impala Platinum market research and business development division. Impala Platinum, as the world's second-largest platinum producer, is encouraged by the potential application of fuel cells over a broad spectrum. This multinational company also happens to have considerable fixed investment operations in the province

The use of fuel cells in mobile, stationary and micro applications, such as laptops, personal computers and digital cameras, is already in the pipeline or has arrived slightly. Fuel cells are already being in-stalled in areas of power instability and acute environmental awareness such as California, Japan and parts of Europe. Although this is encouraging and shows some progress, there are still major challenges – **the first being cost and the second hydrogen provision.**
A fuel cell for a vehicle initially required between 60 g and 80 g of PGMs (platinum group metals) compared to the current 5 g of PGMs used in an autocatalyst converter. Though loadings have declined, 10 g is considered competitive for a vehicle fuel cell and developers are confident that they can attain such thrifting – but they need time. As hydrogen is envisaged as the ideal fuel, its ready accessibility is crucial – and again it is time that is needed to remove what is regarded as the biggest stumbling block of all as far as fuel-cell powered cars are concerned. Some recommend that facilitation be provided for fuel-cell vehicles to be able to pull up at existing petrol stations and fill up with petrol in the normal way. These recommend that the petrol is then reformed into hydrogen on board the vehicle. Others see this as being too cumbersome and costly and would prefer motorists to be able to fill up with hydrogen immediately.

While this eliminates the need for on-board reformers, it places challenges on obtaining hydrogen from natural and synthetic gas sources. Still others would like solar power to be the original clean power source in the production of the hydrogen so that accusations of environmental pollution are kept totally out of the picture. Impala Platinum's Market Research and Business Development believes that the ideal fuel for fuel cells is hydrogen, but concurs that the creation of widespread hydrogen infrastructure is still the biggest challenge. Moreover, they point out that if petrol is reformed in a car using an on-board reformer, there is still emission in the production of the petrol, whereas with the direct input of solar-power-produced hydrogen there would be zero emission at all stages. There is a conviction that the next wave of platinum demand will come from fuel cells, just as the previous wave was generated by autocatalytic converters used to limit air pollution from vehicle exhaust systems. Therefore the province, as endowed with significant amount of platinum resources or PGMs (Platinum Group Metals), stands to benefit from the Germany's advanced technology in order to benefit fully from the value chain. Private Public Partnerships need to be forged in all areas of fuel cells technology for all stakeholders to benefit in some breakthroughs or environmentally efficient outcomes from hydrogen sources as fuel resource.

Schematic representation of the supply chain:

Solar Energy (Electrolysis)
Or photovoltaic process Fossil Fuel (gasoline)

↓ ↓

Hydrogen (energy carrier)

↓

Chemical reaction with oxygen
(With platinum as a catalyst) ← **Limpopo platinum reserves**

↓

Steam or water is a byproduct
When energy is released from
the chemical reaction. That steam can be reused in
cogeneration system of the fuel cell

Types of fuel cells:

Proton Exchange Membrane Fuel Cells
Phosphoric Acid Fuel Cells
Alkaline Fuel Cells
Molten Carbonate Fuel Cells

Technological uses:

Transportation (personal and commercial vehicles)
Portable uses (back up generation and small electronics)
Stationery installations (in large buildings and military bases)