

INVESTIGATION IN FUEL CELLS USING 'HYDRO-GENIUS TEACH'

MUZAMIR BIN ISA



Laporan projek ini dikemukakan sebagai memenuhi sebahagian daripada syarat penganugerahan Ijazah Sarjana Kejuruteraan Elektrik

اونيورسيتي مليسيا قهغ السلطان عبد الله
UNIVERSITI MALAYSIA PAHANG
AL-SULTAN ABDULLAH



Fakulti Kejuruteraan Elektrik
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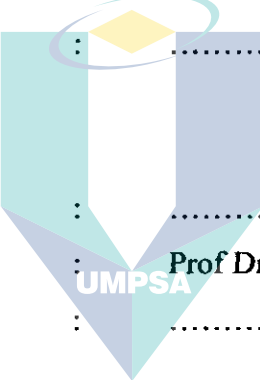
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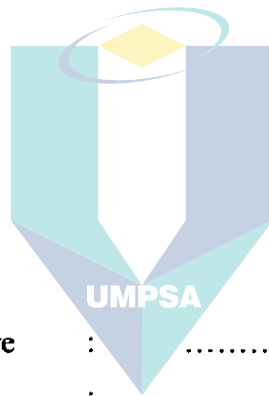
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Supervisor I : Prof Dr Klaus Heinen
Date :
Signature :
Supervisor II : Prof Dr Hashim Bin Saim
Date :


اونيورسيتي مليسيا قهغ السلطان عبد الله
Signature :
Supervisor III : Assoc. Prof Dr Ismail Bin Daut
Date :


“I declare that this report is the result of my own except for the notes and writings
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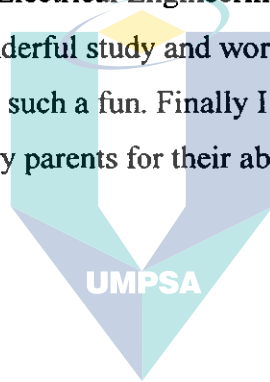
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ABSTRACT

The aim of this report is to deliver information's about features of fuel cells. Along with it, this report gives details about activities of renewable energy. It covers analysis of theories and doing experiments using a set of tool called Hydro Genius Teach. The experiments are about advantages of fuel cells compared to other methods that have been used to produce electrical energy from the process of renewable energy. Furthermore, methods on how fuel cells operate are also given. The main objective of this project is to analyses usage of renewable energy in the world nowadays. The main focus is to do analysis on features of fuel cells as one of ways in renewable energy.

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ABSTRAK

Laporan ini bertujuan untuk memberikan seberapa maklumat tentang ciri-ciri *fuel cells* secara khususnya dan tentang aktiviti pembaharuan tenaga secara umumnya. Ianya meliputi kajian dalam teori-teori dan menjalankan eksperimen menggunakan *Hydro Genius Teach* yang berkaitan dengan kelebihan dan kekurangan *fuel cells* berbanding dengan kaedah lain yang digunakan dalam menghasilkan tenaga elektrik daripada pembaharuan tenaga. Selain itu, kaedah-kaedah bagaimana *fuel cells* beroperasi juga diketengahkan. Objektif utama projek ini dijalankan adalah untuk mengkaji tentang kegunaan pembaharuan tenaga di dunia pada masa kini dan lebih khususnya bagi menjalankan kajian tentang ciri-ciri *fuel cells* sebagai satu kaedah pembaharuan tenaga.

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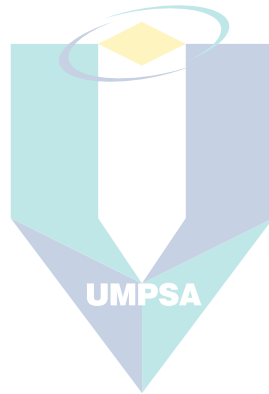
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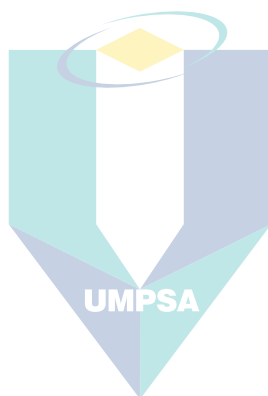
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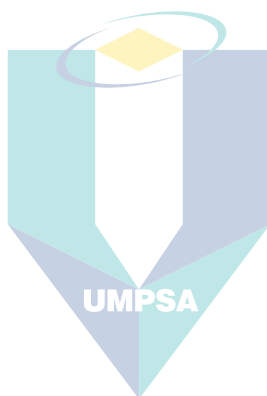
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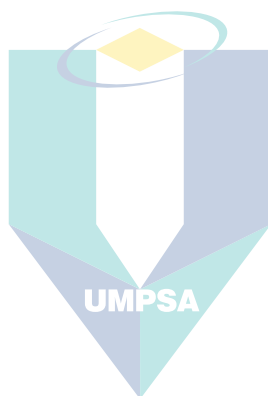
LIST OF SYMBOL

°C	Degree Celsius
PV	Photovoltaic
H ₂	Hydrogen Gases
OH ⁻	Hydro Oxide
H ₂ O	Water
O ₂	Oxygen Gases
CO ₂	Carbon dioxide
e ⁻	Electron
US	United State of America
kWh/litre	Kilowatt Hour per Litre
DC	Direct Current
AC	Alternate Current
V	Volt
KOH	Potassium Hydroxide
A/m ²	Ampere per Metre Square
K	Kelvin
atm	Atmosphere
kg/m ³	Kilogram per Metre Cube
kJ/g	Kilo joule per Gram
ΔG	Gibbs function change
ΔH	Enthalpy change



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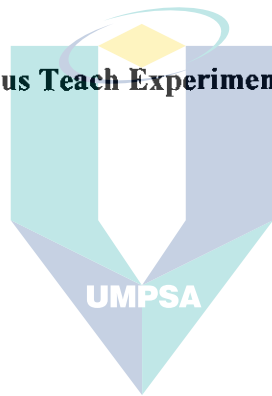
$T\Delta S$	Entropy of the gases
C	Coulomb
F	Faradays constant
kPa	Kilo Pascal
J	Joule
η	Efficiency
PEM	Polymer Electrolyte Membrane
mA	mili Ampere
Ω	Ohm
∞	Infinite
mW	mili Watt
MPP	Maximum Power Point
ml	mili litre
U	Voltage
I	Current
P	Power



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CHAPTER I

INTRODUCTION

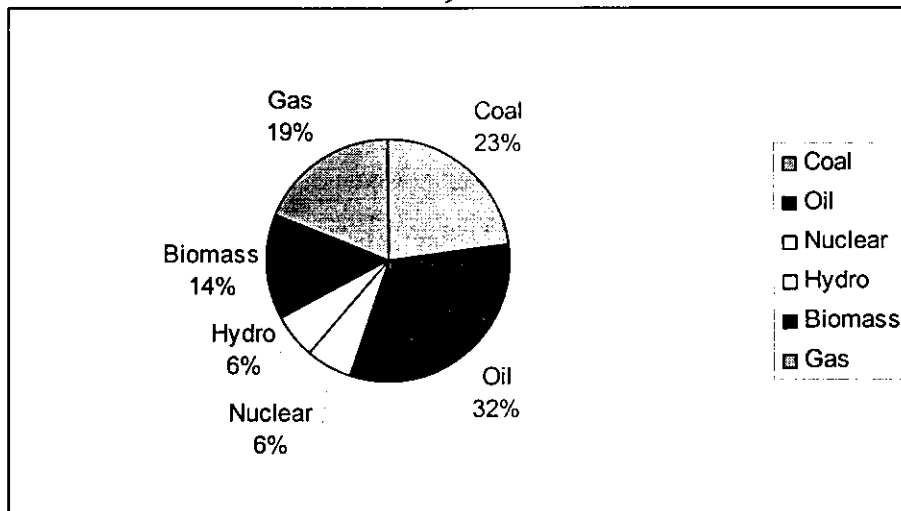
1.1 Project Background

At present, the large-scale use of fossil fuels is a dominant feature of industrial societies. It is regarded as essential for the growing, distribution and preparation of foods, for construction, manufacturing, communication and organisation, and many other activities.

As we have seen, modern societies, and particularly industrial societies, are now totally dependent upon the use of large quantities of energy, most of it in the form of fossil fuels, for virtually all aspects of life. In 1992, the estimated total world consumption of primary energy, in all forms, was approximately 400 Energy Joule (EJ) per year, equivalent to some 9500 million tones of oil per year.

Assuming a world population of about 5300 million in that year, this gives an annual average fuel use for energy man, woman and child in the world equivalent to about 1.8 tones of oil. A breakdown of world primary energy consumption by source in 1992 is shown in Figure 1.1.

Figure 1.1: World Primary Energy Breakdowns



Oil is the dominant fuel, contributing some 32%, followed by coal at 23%. Coal was once the dominant world fuel, but is now losing ground rapidly to oil and gas, which has a 19% share. Hydroelectricity and nuclear are used much less, at around 6% each. The estimated share of traditional non-commercial fuels such as biomass is around 14%.

To understand how best to make use of renewable sources and also to understand fully the problems caused by the present use of fuels, we must take a closer look at the way energy is currently used in industrial societies.

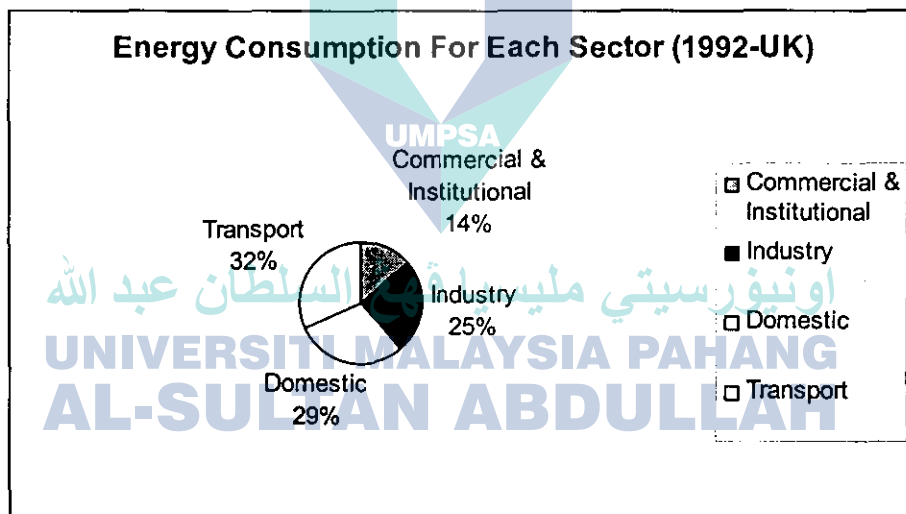
To make some sense of the great variety of energy use, it is necessary to categorise it. In most official statistics human activity is divided into four main sectors:

- The transport sector (which includes road, rail, air and water transport, both public and private, and both goods and passengers)
- The domestic sector (private households)

- The commercial and institutional sector (which includes government buildings, commercial offices, education, health, shops, restaurants, commercial warehouses, plus pubs, clubs, entertainment, religious buildings, and miscellaneous other energy users)
- The industrial sector (which includes manufacturing, iron and steel, food and drink, chemicals, buildings, agriculture)

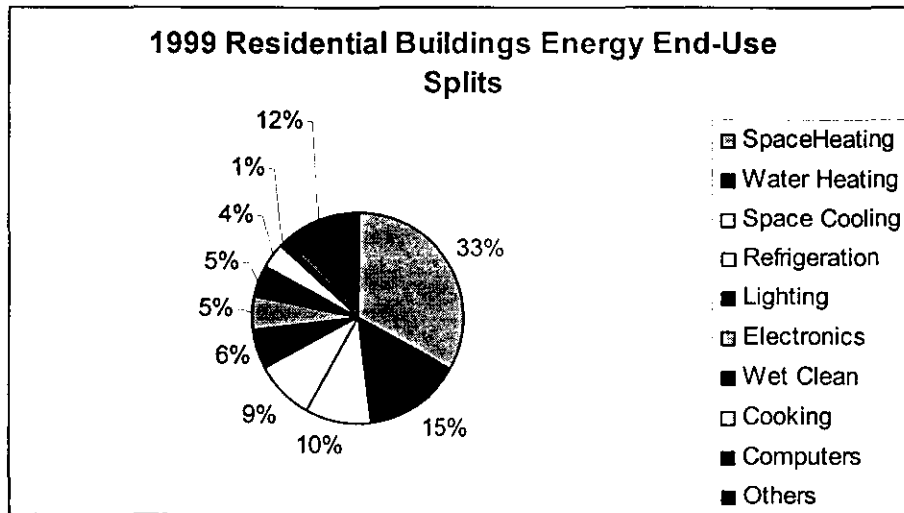
The first question to consider is how much energy is used by each sector. The domestic sector comprises the second most important energy consumer as we can see from the Figure 1.2.

Figure 1.2: Energy Consumption by Sector



The principal uses of energy in the domestic sector are for space heating, water heating, cooking, lighting and electrical appliances. Most of the energy used, around 70%, is for low-grade heat for space and water heating. This is generally provided directly by high-grade sources such as the electricity from thermal power plants. Figure 1.3 gives an overall picture of energy use in the domestic sector.

Figure 1.3: Energy Breakdowns in Houses



Today the energy related problems that hit the headlines most often are environmental ones. Various environmental problems look large in the public consciousness at present. Many of these are largely a result of large-scale fuel use. One of the most significant problems appears to be that of global warming, a gradual increases in the global average air temperature at the earth's surface. The majority of scientists believe that global warming is probably taking place, at a rate of around 0.3 °C per decade, and that it is caused by increases in the concentration of so called 'greenhouse gases' in the atmosphere.

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The most significant single component of these greenhouse gas emissions is carbon dioxide (CO₂) released by the burning of fossil fuels. Another side effect of the burning fuels is acid rain. Some of the gases which are given off when fuels are burned, in particular sulphur dioxide and nitrogen oxides, combine with water in the atmosphere to form sulphuric acid and nitric acid respectively. The result is that any rain, which follows is slightly acidic. This acid rain can cause damage to plant life, in some cases seriously affecting the growth of forests, and can erode buildings and corrode metal oxides.

After considered the ways in which energy is used and the scale of its use and have looked at the various problems associated with the current use of fossil and nuclear fuels such as the environmental impact we are now in a position to look more closely at renewable sources, to see whether and to what extent they offer solutions to these problems.

The term 'renewable energy' can be defined in several ways, for example Twidell and Weir (1986) define renewable energy as '*energy obtained from the continuous or repetitive currents of energy recurring in the natural environment.*' Sorensen (1979) defines renewable energy as '*energy flows which are replenished at the same rate as they are "used"*', adding that the term renewable energy may be taken to include 'the usage of any energy storage reservoir which is being "refilled" at rates comparable to that of extraction'.

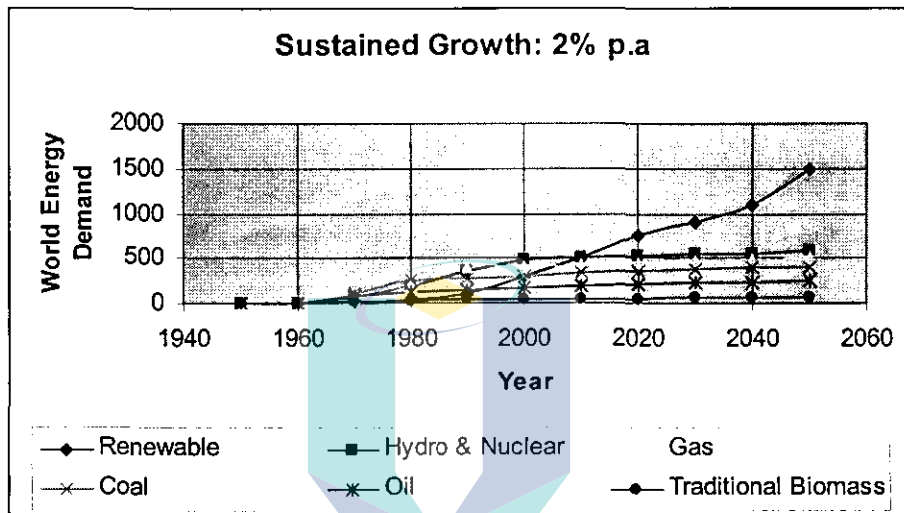
Most renewable energy sources are derived from solar radiation, including the direct use of solar energy for heating or electricity generation, and indirect forms such as energy from the wind, waves and running water, and from plants and animals. Tidal sources of energy result from the gravitational pull of the moon and sun, and geothermal energy comes from the heat generated within the earth. Energy from wastes of all kinds is also often included under the heading of renewable.

The use of renewable on a more significant scale than at present would at the very least replace a further significant proportion of fossil and nuclear fuel use, thereby reducing the associated environmental impacts. Most of the renewable sources enable the forms to be avoided, but all have some form of local environmental impact of their own, ranging from very minor to major in the case of the larger tidal and hydroelectric schemes.

As clearly shown on the following Figure 1.4, renewable sources are likely to make up more than 50% of the total energy supply after 2050. While, the use of oil

will start to decline after the year 2020, the message someone can get from the diagram is quite simple. The power plant for the domestic sector will need to use a fuel that can be derived from a variety of sources. This means that major structural changes are needed in the infrastructure of fuel supply and the domestic sector itself.

Figure 1.4: World Energy Generations



Summarizing all of the above it can be said that renewable energy sources seem to be a promising new way of producing energy, better and cleaner from the energy produced from the burnt of oil. With the passage of time, and as the fossil fuel reserves are getting smaller, renewable source of energy will eventually bring changes worldwide in the energy sector as they may offer a solution to the matter above.

1.2 Project Aim / Objective

The aim of this project is to investigate the use of renewable energy in the world today and more specifically, to do investigation in fuel cells characteristic as the renewable energy using 'Hydro-Genius Teach' experiment set.

1.3 Scope of Project

Upon completion of this project, the author will understand the:

- i. Advantages of fuel cells over conventional means of power production.
- ii. Principles upon which fuel cells work.
- iii. Operating principles and chemical reaction of fuel cells.
- iv. Comparative advantages and disadvantages of different kinds of fuel cells.

Roughly, the goal of this project is to become familiar with the principles and characteristics of fuel cells and to learn how to operate a fuel cell.

1.4 Research Methodology

Figure 1.5: Flow of obtaining electrical power from various sources of renewable energy.

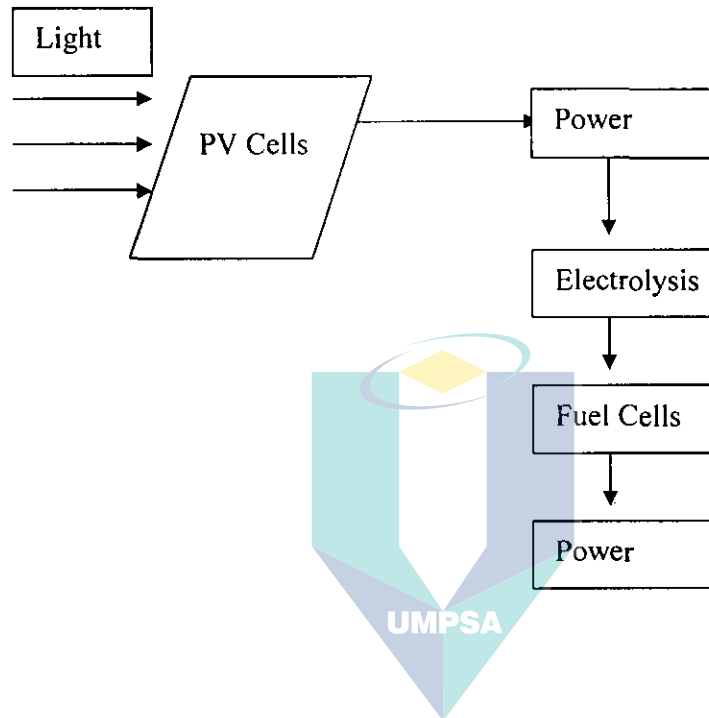


Figure 1.5 shows the process flow to obtain electrical power from several of renewable energy. Light is the main source to obtain electrical power by using this method. In this project, light from a lamp is used rather than the sun light. It will be shine directly to the solar module that is used as photovoltaic cells that will generate electrical power. The generated electrical power will then be used to perform the electrolysis process. Hydrogen and oxygen are gases that are produced by the process. These gases are then distributed or flamed the fuel cells to generate electrical power.

This project is started with analysis about features and behaviours of current and voltage that is generated by solar module (photovoltaic cells). Then, the characteristic of electrolysis is monitored. Differences between current and voltage that has been generated from solar module and electrolysis are being compared and

analyzed. Furthermore, this project tells about the relation between Faradays Law and electrolysis process. For the conclusion, the characteristic and efficiency of fuel cells are also explained.

1.5 Organisation of the thesis

This thesis is divided into 6 chapters.

Chapter 1: Introduction

This chapter describes about project background, objectives and scope of the project and research methodology.

Chapter 2: Basic Information of Fuel Cells

This chapter discuss basic information of fuel cells including history of fuel cells, types of fuel cells, applications of fuel cells, benefits of fuel cells in term of engineering and its advantages over battery. Basic information about battery is also explained.

Chapter 3: Introduction to Hydrogen

This chapter give us information about hydrogen. It includes on how hydrogen can be produced, properties of hydrogen physically and chemically, and how hydrogen can be transported and stored.

Chapter 4: Principle of Fuel Cells Operation

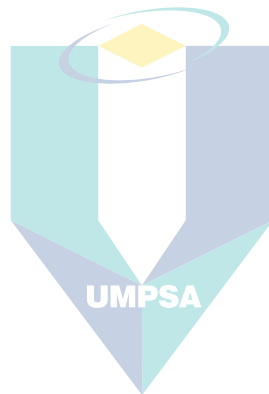
This chapter discuss about general characteristic of fuel cell operation, its chemical reactions, major component in fuel cells, source of fuel and oxidant, and fuel cells efficiency.

Chapter 5: Experiments, Results and Analysis

All result of experiments and analysis conducted in this project are discussed in this chapter.

Chapter 6: Discussion and Conclusion

This last chapter deliver a brief discussion and conclusion about fuel cells and the project conducted.



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CHAPTER II

BASIC INFORMATION OF FUEL CELLS

Hydrogen fuel cells are one of the most promising up and coming clean power sources today. Fuel cells have been used for decades on NASA spacecraft and other types of fuel cells are currently in use for power generation at a variety of commercial and industrial sites. Use of fuel cells in small system / home power applications has so far been limited by cost considerations, but prices are falling and fuel cells should emerge as a viable home power source within the next years.

UMPSA

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2.1 What Is Fuel Cell?

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In principle, a fuel cell operates like a battery. Unlike a battery, a fuel cell does not run down or require recharging. It will produce energy in the form of electricity and heat as long as fuel is supplied. A fuel cell consists of two electrodes sandwiched around an electrolyte. Oxygen passes over one electrode and hydrogen over the other, generating electricity, water and heat.

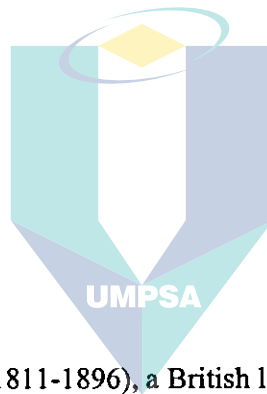
Hydrogen fuel is fed into the anode of the fuel cell. Oxygen (or air) enters the fuel cell through the cathode. Encouraged by a catalyst, the hydrogen atom splits into a proton and an electron, which take different paths to the cathode. The proton passes through the electrolyte. The electrons create a separate current that can be utilized

utilized before they return to the cathode, to be reunited with the hydrogen and oxygen in a molecule of water.

A fuel cell system that includes a “fuel reformer” can utilize the hydrogen from any hydrocarbon fuel from natural gas to methanol and even gasoline. Since the fuel cell relies on chemistry and not combustion, emissions from this type of a system would still be much smaller than emissions from the cleanest fuel combustion processes.

2.2 History of fuel cells

2.2.1 The “Gas Battery”



Sir William Grove (1811-1896), a British lawyer and amateur scientist developed the first fuel cell in 1839. The principle was discovered by accident during an electrolysis experiment. When Sir William disconnected the battery from the electrolyser and connected the two electrodes together, he observed a current flowing in the opposite direction, consuming the gases of hydrogen and oxygen (Figure 2.1). He called this device a ‘gas battery’. His gas battery consisted of platinum electrodes placed in test tubes of hydrogen and oxygen, immersed in a bath of dilute sulphuric acid.

It generated voltages of about one volt. In 1842 Grove connected a number of gas batteries together in series to form a ‘gas chain’. He used the electricity produced from the gas chain to power an electrolyser, splitting water into hydrogen and oxygen (Figure 2.2). However, due to problems of corrosion of the electrodes and

instability of the materials, Grove's fuel cell was not practical. As a result, there was little research and further development of fuel cells for many years to follow.

Figure 2.1: The principle of an electrolyser, shown left; of a fuel cell, shown right.

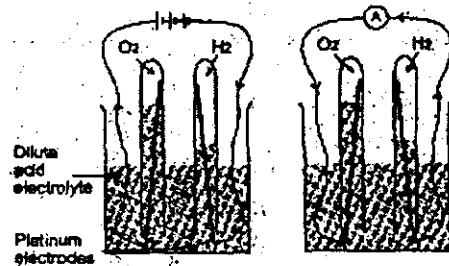
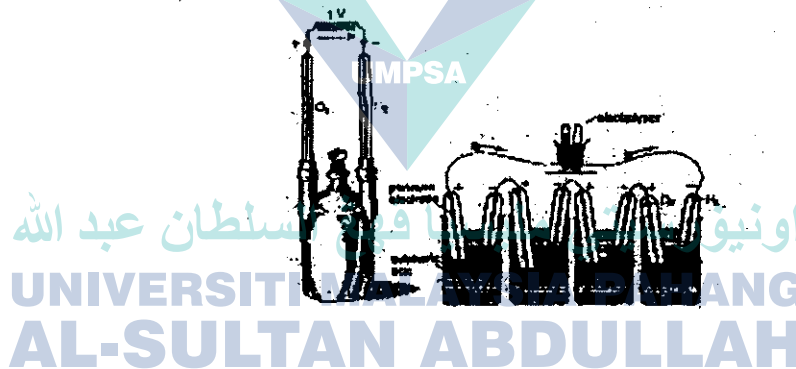


Figure 2.2: Groves gas battery (1839) produced a voltage of about 1 Volt, shown left. Groves 'gas chain' powering an electrolyser (1842), shown right.

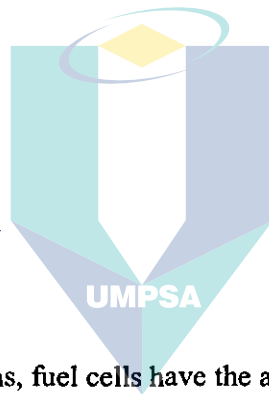
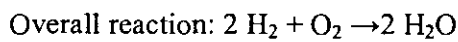
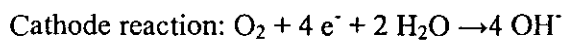
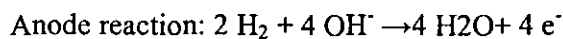


2.2.2 The "Bacon fuel cell"

Significant work on fuel cells began again in the 1930s, by Francis Bacon, a chemical engineer at Cambridge University, England. In the 1950s Bacon successfully produced the first practical fuel cell, which was an alkaline version. It used an alkaline electrolyte (molten KOH) instead of dilute sulphuric acid. The

electrodes were constructed of porous sintered nickel powder so that the gases could diffuse through the electrodes to be in contact with the aqueous electrolyte on the other side of the electrode.

This greatly increased the contact area contact between the electrodes, the gases and the electrolyte, thus increasing the power density of the fuel cell. In addition, the use of nickel was much less expensive than that of platinum. Alkaline fuel cell reaction is as below:



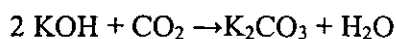
2.2.3 Fuel cells for NASA

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 the 1960s, 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. Over 10,000 hours of operation were accumulated in 18 missions, without a single in-flight incident (IFC). In the 1970s, International Fuel Cells developed a more powerful alkaline fuel cell for NASA's Space Shuttle Orbiter. 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. 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. 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).

2.2.4 Alkaline fuel cells for terrestrial applications

Compared with other types of fuel cells, the alkaline variety offered the advantage of a high power to weight ratio. This was primarily due to intrinsically faster kinetics for oxygen reduction to the hydroxyl anion in an alkaline environment. Therefore alkaline fuel cells were ideal for space applications. However, for terrestrial use, the primary disadvantage of these cells is that of carbon dioxide poisoning of the electrolyte. Carbon dioxide is not only present in the air but also present in reformat gas, the hydrogen rich gas produced from the reformation of hydrocarbon fuels. In the poisoning of an alkaline fuel cell, the carbon dioxide reacts with the hydroxide ion in the electrolyte to form a carbonate, thereby reducing the hydroxide ion concentration in the electrolyte. This reduces the overall efficiency of the fuel cell. The equation of carbon dioxide reacting with a potassium hydroxide electrolyte is shown below:



Because of the complexity of isolating carbon dioxide from the alkaline electrolyte in fuel cells for terrestrial applications, most fuel cell developers have focused their attention on developing new types using electrolytes which are non alkaline. These fuel cells include: solid oxide fuel cells (SOFC), phosphoric acid fuel

cells (PAFC), molten carbonate fuel cells (MCFC) and polymer electrolyte membrane (PEM) fuel cells.

2.2.5 The PEM fuel cell

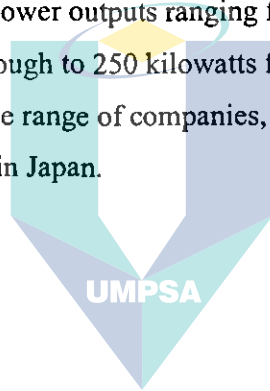
In the early 1960s, General Electric (GE) also made a significant breakthrough in fuel cell technology. Through the work of Thomas Grubb and Leonard Niedrach, they invented and developed the first polymer electrolyte membrane (PEM) fuel cell. It was initially developed under a program with the US Navy's Bureau of Ships and U.S. Army Signal Corps to supply portable power for personnel in the field. Attracted by the possibility of using GE's PEM fuel cell on the Apollo missions, NASA tested its potential to provide auxiliary power onboard its Gemini spacecraft. The Gemini space program consisted of 12 flights in preparation for the Apollo missions to the moon. For lunar flights, a longer power source was required than could be provided by batteries, which had been used on previous space flights. Unfortunately, the GE fuel cell, model PB2, encountered technical difficulties prior to launch, including the leakage of oxygen through the membrane. As a result the Gemini missions 1 to 4 flew on batteries instead. The GE fuel cell was redesigned and a new model, the P3, successfully operated on the Gemini flights 6 to 12. The Gemini fuel cell power plant consisted of two fuel cell battery sections, each capable of producing a maximum power of about 1000 watts (NASA).

2.2.5.1 Ballard Power

A further limitation of the GE PEM fuel cell at that time was the large quantity of platinum required as a catalyst on the electrodes. The cost of PEM fuel cells was prohibitively high, restricting its use to space applications. In 1983,

Geoffrey Ballard a Canadian geophysicist, chemist Keith Prater and engineer Paul Howard established the company, Ballard Power. Ballard took the abandoned GE fuel cell, whose patents were running out and searched for ways to improve its power and build it out of cheaper materials (Koppel, 1999).

Working on a contract from the Canadian Department of National Defence, Ballard developed fuel cells with a significant increase in power density while reducing the amount of platinum required. From these developments it was recognized that fuel cells could be made smaller, more powerful and cheaply enough to eventually replace conventional power technologies. Ballard Power has since grown to become recognized as a world leader in PEM fuel cell technology, developing fuel cells with power outputs ranging from 1 kilowatt, for portable and residential applications, through to 250 kilowatts for distributed power. Ballard has formed alliances with a wide range of companies, including Daimler Chrysler, Ford, Coleman and Ebara Power in Japan.



2.2.5.2 Los Alamos National Laboratory

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In the late 1980s and early 1990s Los Alamos National Laboratory and Texas A&M University also made significant developments to the PEM fuel cell. They also found ways to significantly reduce the amount of platinum required and developed a method to limit catalyst poisoning due to the presence of trace impurities in the hydrogen fuel (Los Alamos National Laboratory).

2.3 Types of Fuel Cells

Proton Exchange Membrane (PEM) fuel cells are currently being considered for development of fuel cell powered cars, home power generators and other small applications. Instead of using a liquid electrolyte, they use a thin polymer membrane. They operate in the range of 200° Fahrenheit and can quickly vary power output depending on current demand. Many companies are currently working to develop commercially available, mass-produced PEM fuel cells.

Alkaline fuel cells have been used by NASA to provide power to spacecraft since the 1960s. They use alkaline potassium chloride as their electrolyte. Alkaline fuel cells can reach power generating efficiency of 70%, although their production costs have long rendered them out of range for mass production. A few companies are currently working on mass production techniques for these cells that would reduce their price within range of commercial use.

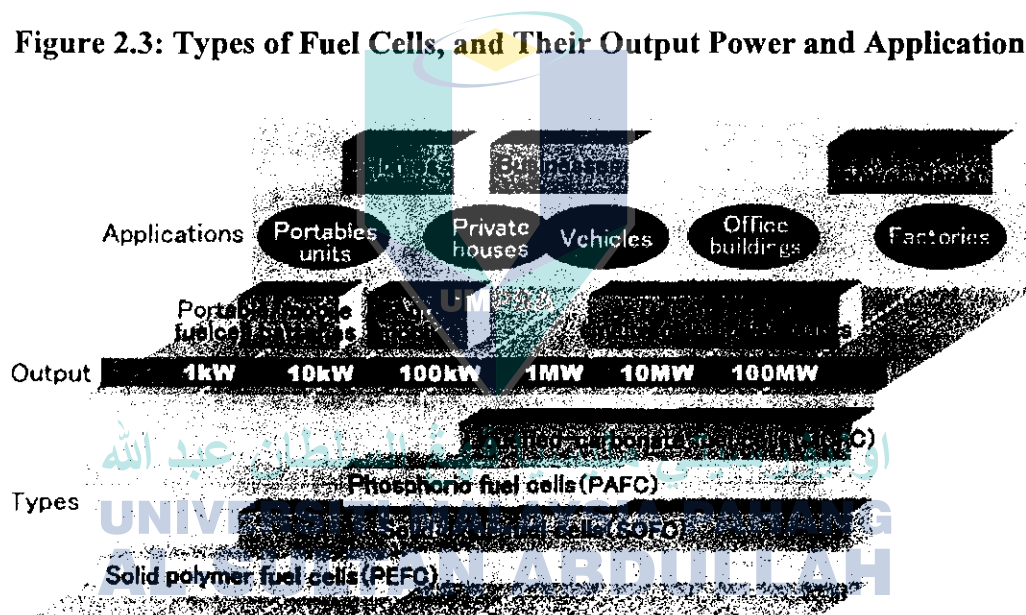
Phosphoric Acid fuel cells are by far the most widely used type of fuel cell today. They are primarily used for large back up and remote power applications in hospitals, schools and other locations where an engine generator would traditionally be used. They operate in the 400° Fahrenheit range, and can reach 40% power generation efficiency (much higher if by product heat and steam are used for other purposes). Phosphoric acid cells can also be used in large vehicles, such as buses and train engines.

Solid Oxide fuel cells are currently being refined for optimum operation in high-power industrial and utility applications. Operating efficiency could reach 60%, and the use of a hard ceramic electrolyte allows operating temperatures to run as high as 1800° Fahrenheit.

Molten Carbonate fuel cells operate in the range of 1200° Fahrenheit, and show promise for high power generation efficiency. They have the ability to use coal-based fuels, making them easy to integrate into the existing fuel supply system.

Direct Methanol fuel cells are a newer sub type of the PEM cells. Rather than using a fuel reformer to extract hydrogen from an external fuel source or an electrolyser to break down water molecules, the anode catalyst extracts hydrogen directly from liquid methanol. These cells are expected to reach operating efficiencies around 40%.

Figure 2.3: Types of Fuel Cells, and Their Output Power and Applications



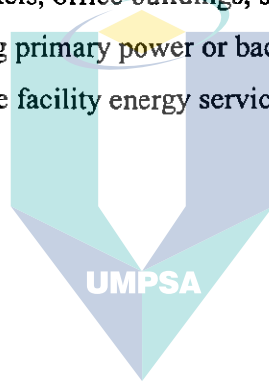
2.4 Applications for Fuel Cells

There are many uses for fuel cells right now, all of the major automakers are working to commercialise a fuel cell car. Fuel cells are powering buses, boats, trains, planes and scooters, even bicycles. There are fuel cell powered vending machines, vacuum cleaners and highway road signs. Miniature fuel cells for cellular phones,

laptop computers and portable electronics are on their way to market. Hospitals, credit card centres, police stations and banks are all using fuel cells to provide power to their facilities. Wastewater treatment plants and landfills are using fuel cells to convert the methane gas they produce into electricity. The possibilities are endless.

2.4.1 Stationary.

More than 200 fuel cell systems have been installed all over the world in hospitals, nursing homes, hotels, office buildings, schools, utility power plants and an airport terminal, providing primary power or backup. In large-scale building systems, fuel cells can reduce facility energy service costs by 20% to 40% over conventional energy service.



2.4.2 Residential.

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Fuel cells are ideal for power generation, either connected to the electric grid to provide supplemental power and backup assurance for critical areas, or installed as a grid independent generator for on site service in areas that are inaccessible by power lines. Since fuel cells operate silently, they reduce noise pollution as well as air pollution and the waste heat from a fuel cell can be used to provide hot water or space heating for a home. Many of the prototypes being tested and demonstrated for residential use extract hydrogen from propane or natural gas.

2.4.3 Transportation.

All the major automotive manufacturers have a fuel cell vehicle either in development or in testing right now as Honda, Toyota, Ford, Hyundai and Volkswagen.

2.4.4 Portable Power.

Miniature fuel cells, once available to the commercial market, will help consumers talk for up to a month on a cellular phone without recharging. Fuel cells will change the telecommuting world, powering laptops and palm pilots hours longer than batteries. Other applications for micro fuel cells include pagers, video recorders, portable power tools, and low power remote devices such as hearing aids, smoke detectors, burglar alarms, hotel locks and meter readers. These miniature fuel cells generally run on methanol, an inexpensive wood alcohol also used in windshield wiper fluid.

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2.4.5 Landfill / Wastewater Treatment.

Fuel cells currently operate at landfills and wastewater treatment plants across the country, proving themselves as a valid technology for reducing emissions and generating power from the methane gas they produce.

2.5 Fuel Cell Engineering Benefits

A fuel cell would be of most use in one of two ways. For individuals with an existing solar, wind or hydropower system, the fuel cell could be used for backup power in place of an engine generator. Given that an engine generator operates at approximately 30% efficiency and the least efficient fuel cell currently offers 40% efficiency (up to 80-90% if by product heat and/or steam are used for other heating needs), the advantage is clear. When you also consider that the fuel cell will operate silently, with no waste products in regenerative systems and minimal waste in others, the fuel cell comes out a clear winner. For individuals without an existing alternative energy system, a larger capacity fuel cell could comprise their primary power system. Since a fuel cell can produce power on demand, as long as hydrogen is available, there is no need for storage batteries if the fuel cell generator is large enough to support the electrical system in question. A wind turbine and/or solar panels could be added to power the water electrolyser or fuel reformer, and the entire power system would be virtually self-contained.

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2.5.1 Fuel Flexibility

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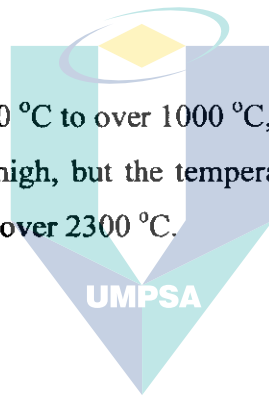
Fuel cells are capable of operating on hydrogen, or hydrogen reformed from any of the common fossil fuels available today.

2.5.2 High Power Densities

The amount of power a fuel cell can generate within a given volume is usually given in kWh/litre. These numbers continue to rise as manufacturers continue research and development on their respective products.

2.5.3 Low Operating Temperatures and Pressures

Fuel cells operate at 80 °C to over 1000 °C, depending on the type of fuel cell. These numbers might seem high, but the temperature inside your vehicle's internal combustion engine can reach over 2300 °C.



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2.5.4 Site Flexibility

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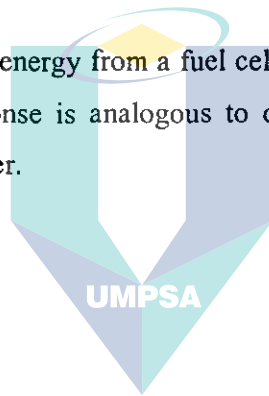
Fuel cells, with their inherently quiet operation, zero to minimal emissions and reduced permitting requirements, can be located in a variety of areas, both residential and commercial, inside and outside.

2.5.5 Cogeneration Capability

When the waste heat from the fuel cells electrochemical reaction is captured, it can be utilized for water, space heating and cooling. With cogeneration capabilities the efficiencies achieved by a fuel cell system approach 90%.

2.5.6 Quick Response to Load Variations

To receive additional energy from a fuel cell, more fuel is introduced into the system. Fuel cell load response is analogous to depressing the gas pedal in your vehicle, more fuel more power.



2.5.7 Engineering Simplicity

Fuel cells do not contain any moving parts. The lack of movement allows for a simpler design, higher reliability's, quite operation and a system that is less likely to fail.

2.5.8 Independence from the Power Grid

A residential fuel cell system allows people to become independent of the brown outs, power failures and voltage irregularities that are commonplace when connected to the utility grid. Any one of these common power disruptions can damage sensitive computer systems, electronic equipment and the quality of life people desire to have. Reliable energy in areas that are subjected to weather related power outages.

2.6 Fuel Cells versus Traditional Batteries

Fuel cells offer a reduction in weight and come in a compact package for the same amount of available energy when compared to batteries. To increase the power in a fuel cell, more fuel is introduced into the system. To increase the power of a battery, more batteries have to be added increasing the cost, weight and complexity of the system.

A fuel cell never "runs down", it continues to produce electricity as long as fuel is present. When a battery "runs down" it has to undergo a lengthy, inconvenient recharge time to replace the spent electricity. Depending on where the electricity originates, pollution, costs and efficiency problems are transferred from the batteries location to the central generating plant.

Table 2.1: Advantages of fuel cells Vs Batteries

Energy Source Comparison		
	Fuel Cell	Battery
Efficiency	40 - 60%	35 - 85%
Emissions	Water	None
Fuel	H ₂ or Hydrocarbons	Electricity
Energy Output Duration	Unlimited based on Fuel Availability	Limited based on Size of Battery
Hazardous disposables	None	Acids and Corrosives
Noise	Low	Low
Life Expectancy	5 - 10 Years	3 - 4 Years
Maintenance Requirements	Low	Moderate

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2.7 Basic Battery Information اونيورسيتي مليسيا قهغ السلطان عبدالله

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Batteries are devices that translate chemical energy into electricity. But that simple definition greatly understates the pervasive role of batteries in our life. Batteries are an efficient way to make electricity portable. In addition, batteries provide power to replace electricity from the utility electrical grid for a variety of critical functions. As the world becomes increasingly addicted to electricity and mobility batteries play an ever-greater role in all aspects of our life.

Batteries are an integral part of any automotive, marine or home power electrical system. Since most people are fairly familiar with automotive batteries, we will concentrate on deep cycle power storage batteries used in home power and

marine applications, with brief comparisons between deep cycle and automotive batteries.

2.7.1 Battery Capacity

Battery capacity is a primary concern in home power systems. The storage battery bank must have enough storage capacity to meet power needs between charging cycles. Making sure the battery storage capacity is about double the power that would be used in a normal use day is a good minimum.

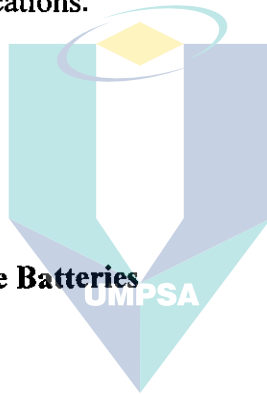
Home power (deep cycle) batteries are generally measured in "amp hour" capacity. One amp hour is equal to one amp of power drawn for one hour of time. Amp hour capacity is generally given as the "20 hour rate" of the battery. Therefore, the number given as the amp hour capacity for a deep cycle battery will be the number of amp hours the battery can deliver over a 20 hour period at a constant draw. A 105 amp hour battery can deliver 5.25 amps constantly over a 20 hour period before its voltage drops below 10.5 volts, at which point the battery is discharged.

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2.7.2 Types of Batteries

2.7.2.1 Lead Acid Automotive Batteries

Automotive batteries are designed to deliver a relatively high amount of current in a short period of time, but should never be heavily discharged. An automotive battery plate is very porous (like a slice of Swiss cheese), to maximize surface area and enable the sudden high current output. Because home power systems require repeated deep discharges of stored power, automotive batteries are largely useless for these applications.



2.7.2.2 Lead Acid Deep Cycle Batteries

Deep cycle batteries are designed to have a large amount of their stored current discharged between charging sessions, with very heavy non porous battery plates to withstand repeated major discharging and charging cycles (deep cycles). They are generally useless for delivering the sudden surges of power needed from automotive batteries.

1. **Marine Batteries** are usually 12 volt, and available in a variety of capacities up to 100 amp-hours. They can be found in "sealed" or standard serviceable types and are commonly used in small home power or portable power applications. Marine batteries are generally small, compact and easy to handle and install. They are relatively inexpensive, and the sealed type batteries are non spill able and safer for indoor applications.

However these batteries are not designed for very heavy cycling (as is found in a home power system), so their life spans are often shorter than other types of deep cycle batteries. Sealed batteries are also very sensitive to overcharging, which may further shorten their useful lifespan. Also, in order to obtain more than 100 amp hours of storage capacity, multiple batteries must be attached in parallel, which is less efficient than using a single, higher capacity battery

2. **Golf Cart Batteries** have capacities in the 220 – 300 amp hour range, and are generally 6 volt. They are well suited to small to medium home power systems. They are designed for deep discharge cycles, so they will tend to have longer lifespan and better performance in a residential alternative energy system. They are still relatively lightweight, but are generally cheaper per amp hour than marine type batteries. They are also less sensitive to mild overcharging.

However since most home power systems are 12 volt, two 6 volt batteries must be connected in series, which is a bit more complicated than connecting a single battery. Since golf cart batteries are unsealed, they need to be stored in a well-ventilated area and will require periodic water replacement. Their amp hour capacity is also too limited to be of use in a large power system.

3. **Industrial/Stationary Batteries** are normally manufactured as individual 2 volt units, which are then combined to create the necessary voltage for the power system. (Six for 12 volt systems, twelve for 24 volt systems) They are available in a wide variety of capacities, up to 3000 amp hours. A very high amp hour capacity can be obtained with a single six-cell set, so charging characteristics are very stable. Industrial batteries will have the longest average lifespan under deep cycling home power conditions.

However due to their extremely high amp hour capacities, industrial battery sets will have a significantly higher initial cost. These batteries can also weight up to

350 lbs. per two volt cell, so they will need to be stored in a well supported area, contained in a rigid external box and will likely require special transporting assistance.

2.7.2.3 Nickel Alloy Batteries

Nickel Cadmium (NiCad) and Nickel Iron batteries, rather than consisting of lead plates submerged in a sulphuric acid solution, feature nickel alloy plates in an alkaline solution. They are also well suited for home power use, but are much less common and much more expensive than lead acid types.

A nickel alloy battery can have up to 50 years of useful life, compared to 20 years with a well maintained lead acid battery. They can also sit for extended periods of time partially or fully discharged without suffering damage, unlike lead acid types. They are lower maintenance and can be completely discharged repeatedly without suffering damage. A lead acid battery should never be completely discharged, meaning they need to be more closely monitored. Nickel alloy batteries operate better at lower temperatures, and can discharge more of their total amp hour capacity as useful current.

Despite all these advantages, the higher initial cost of the batteries is prohibitive. Also, nickel alloy batteries are harder to dispose of when they finally become unchangeable. Their unique charging voltage range can also create compatibility problems with battery management and charging equipment.

2.7.3 How Batteries are used in Home Power

A storage battery bank is what enables a home power system to deliver a constant level of power to the electrical system. Without storage batteries, the entire electrical system would be limited by the immediate output of the alternative energy generators. At night, a solar run house would have no electrical power available to turn on interior lights. A wind powered system would be subject to constant power fluctuations as the wind speed increased, dropped or disappeared entirely.

By running the output of renewable power generators through charge controllers and into a battery bank, power can be available 24 hours a day, regardless of weather. Solar panels or wind generators can deliver power to the battery bank regardless of current power usage, so excess power can be stored during low use times (generally the middle of the day and middle of the night) and be available during high use times (usually morning and evening).

Batteries supply DC power, so if power is needed for an AC power system or a mixed AC/DC system, the battery power will need to be run through an inverter to change 12VDC or 24VDC power into 120VAC household current.

2.7.4 Basic Lead Acid Battery Function

Lead acid batteries are by far the most common type of power storage battery in use today. A fully charged lead acid battery undergoes a chemical reaction when attached to an electrical load, which releases stored energy from the battery. All lead acid batteries consist of the following components:

- A positive plate, composed of lead dioxide (PbO_2)

- A negative plate, composed of "sponge" lead (Pb)
- An electrolyte solution of sulphuric acid (H₂SO₄) and distilled water (H₂O)

When the battery discharges current, the sulphate (SO₄) in the electrolyte combines with lead from the plates to form lead sulphate deposits (PbSO₄). After repeated or extended discharge, the sulphate content of the electrolyte becomes increasingly "bound" in the lead sulphate deposits and can no longer be used to create electric current. The battery becomes discharged when too much of the electrolyte sulphate is depleted.

Over time, in a non-sealed battery, the water content of the electrolyte solution will drop due to evaporation during discharge. This leads to excessive acid concentration, which raises the resistance of the battery. Periodic checking and refilling of the fluid level in an unsealed battery is essential to its proper functioning.

When a discharged battery is recharged, the majority of the lead sulphate is broken down and the sulphate returns to the electrolyte where it is once again available to create electricity. However, over time a sulphate residue builds up on the battery plates and begins to crystallize. As more of the sulphate becomes locked in the crystallized residue, the battery capacity and ability to be recharged declines until the battery finally "dies."

With deep cycle batteries, the sulphate crystals simply "insulate" the battery plates from the remaining weakened electrolyte, preventing the chemical reactions needed to produce current. In automotive batteries, with their thin, porous plates, crystallization will actually cause the plates to break apart, permanently destroying the battery.

2.7.5 Battery Charging & Maintenance

In an alternative energy system, battery charging is usually accomplished through charge controllers attached to the various power generators. A good quality charge controller will use a three stage, pulse width modulated charging system. This allows the battery to receive the highest charging current during the bulk stage of charging, with a second lower absorption level to bring the charge to maximum voltage, and a third "float" charging current to maintain the battery charge. A good quality charge controller will maximize charging efficiency and minimize lead sulphate build up, increasing the battery's useable lifespan.

Lead acid batteries will lose their charge if they are left unused for an extended period of time. If an automotive or deep cycle battery goes unused for a month or longer, it should be outfitted with a charge maintainer or "trickle charger" (if the deep cycle battery is not attached to a three stage charge controller). Solar panels are available for this purpose, and will deliver a low level of current to the battery while exposed to sunlight. For batteries or vehicles stored indoors, plug in charge maintainers are also available.

Sulphate crystallization in batteries can be slowed or reversed by the use of battery pulse conditioners. Lead sulphate can be more effectively removed, and negative battery plates better maintained if battery voltage periodically reaches 2.5 volts per cell. (15V for a 12V battery, 30V for a 24V, etc.) A pulse conditioner will deliver periodic brief pulses of higher current to the battery, causing the sulphate residue to be released back into the electrolyte and maximizing the lifespan and performance of the battery.

CHAPTER III

INTRODUCTION TO HYDROGEN

3.1 Hydrogen Production

The fundamental question underlying the use of hydrogen as a fuel is, where do we get it from? Despite its abundance in the universe, hydrogen does not occur freely on earth, as it reacts very readily with other elements. For this reason, the vast majority of hydrogen is bound into molecule compounds. To obtain hydrogen means to remove it from these other molecules. With respect to the energy required, it is easy to remove hydrogen from compounds that are at a higher energy state, such as fossil fuels. This process releases energy, reducing the amount of process energy required. It takes more energy to extract hydrogen from compounds that are at a lower energy state, such as water, as energy has to be added to the process.

The process of extracting hydrogen from fossil fuels is called reforming. Today, this is the principal and least expensive method of producing hydrogen. Unfortunately, reforming emits pollutants and consumes non-renewable fuels. The process of extracting hydrogen from water is called electrolysis. In principal, electrolysis can be entirely non polluting and renewable, but it requires the input of large amounts of electrical energy. Consequently, the total environmental impact of acquiring hydrogen through electrolysis is largely dependent on the impacts of the source power. One way to assess the comparative environmental impact of electrolysis and the reforming of various fuels is by comparing the total amount of carbon dioxide emitted.

Alternative methods of hydrogen production include thermo chemical water decomposition, photo conversions, photo biological processes, production from biomass and industrial processes. Although some of these methods show promise for the future, they are still largely experimental and capable of supplying only small amounts of hydrogen. Hydrogen can be produced on a large scale at dedicated hydrogen production plants, or on a small scale at local production facilities. Large-scale production benefits from economies of scale and plants can be located near power and water, but suffers from the difficulties of hydrogen transportation. Some methods of hydrogen production, such as from coal or biomass can only be undertaken on a large scale. Small scale production can reduce the problems of hydrogen transportation by using energy that is easily brought to the facility, such as electricity, natural gas or solar.

On the downside, the amount of equipment required for the amount of hydrogen produced is significantly higher than for large-scale facilities, due to the economy of scale. At the extreme small scale, fossil fuels could be reformed to hydrogen on board a fuel cell vehicle, but the systems are complex and costly. Currently, the vast majority of all hydrogen manufactured worldwide originates from fossil fuels, as a by-product in chemical industries, or crude oil refining processes. Hydrogen production from renewable energy is not yet feasible on a large scale. Production of hydrogen currently costs from 3 to 15 times more than natural gas, and from 1.5 to 9 times more than gasoline, depending on the method used. When extracted from fossil fuels, the initial production and refining of the fuel further increases the total cost.

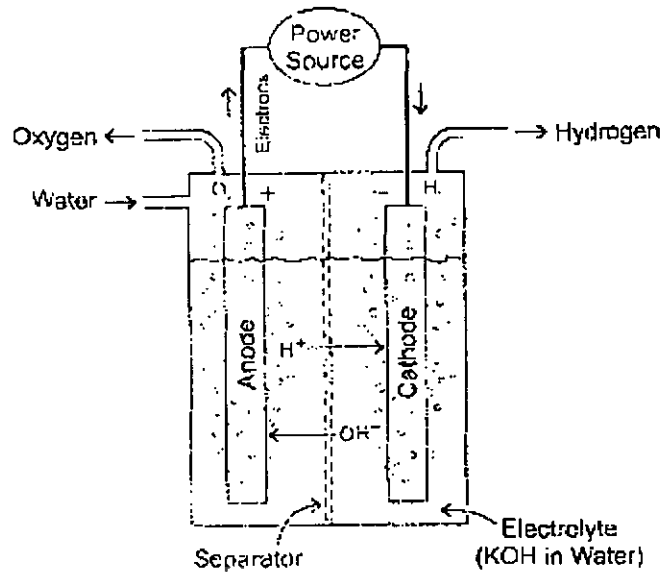
3.1.1 Electrolysis

In electrolysis, electricity is used to decompose water into its elemental components, hydrogen and oxygen. Electrolysis is often touted as the preferred method of hydrogen production as it is the only process that need not rely on fossil fuels. It also has high product purity and is feasible on small and large scales. Electrolysis can operate over a wide range of electrical energy capacities, for example, taking advantages of more abundant electricity at night. At the heart of electrolysis is an electrolyser. An electrolyser is a series of cells each with a positive and negative electrode. The electrodes are immersed in water that has been made electrically conductive, achieved by adding hydrogen or hydroxyl ions, usually in the form of alkaline potassium hydroxide (KOH).

The anode (positive electrode) is typically made of nickel and copper and is coated with oxides of metals such as manganese, tungsten and ruthenium. The anode metals allow quick pairing of atomic oxygen into oxygen pairs at the electrode surface.

The cathode (negative electrode) is typically made of nickel, coated with small quantities of platinum as a catalyst. The catalyst allows quick pairing of atomic hydrogen into pairs at the electrode surface and thereby increases the rate of hydrogen production. Without the catalyst, atomic hydrogen would build up on the electrode and block current flow. A gas separator, or diaphragm, is used to prevent intermixing of the hydrogen and oxygen although it allows free passage of ions. It is usually made of an asbestos based material and tends to break apart above 80 °C.

Figure 3.1: Typical electrolysis cells.



The reactions at the cathode are:

1. $K^+ + e^- \rightarrow K$ - a positively charged potassium ion is reduced.
2. $K + H_2O \rightarrow K^+ + H + OH^-$ - the ion reacts with water to form a hydrogen atom and a hydroxyl ion.
3. $H + H \rightarrow H_2$ - the highly reactive hydrogen atom then bonds to the metal of the cathode and combines with another bound hydrogen atom to form a hydrogen molecule that leaves the cathode as a gas.

The reactions at the anode are:

1. $OH^- \rightarrow OH + e^-$ - a negatively charged hydroxyl ion is oxidized.
2. $OH \rightarrow \frac{1}{2} H_2O + \frac{1}{2} O$ - the ion reacts to form water and an oxygen atom.
3. $O + O \rightarrow O_2$ - the highly reactive oxygen atom then bonds to the metal of the anode and combines with another bound oxygen atom to form an oxygen molecule that leaves the anode as a gas.

The rate of hydrogen generation is related to the current density (the amount of current divided by the electrode area measured in amps per area). In general, the higher the current density, the higher the source voltage required and the higher the power cost per unit of hydrogen. However, higher voltages decrease the overall size of the electrolyser and therefore result in a lower capital cost. State of the art electrolysers are reliable, have energy efficiencies of 65 to 80% and operate at current densities of about 2000 A/m².

A fuel cell reverses the process of electrolysis. Electrolysis adds electrical energy to low energy water to release two high-energy gases. A fuel cell allows the gases to react and combine to form water, releasing electrical power. Both processes release heat, which represents an energy loss.

For electrolysis, the amount of electrical energy required can be somewhat offset by adding heat energy to the reaction. The minimum amount of voltage required to decompose water is 1.23 V at 25 °C. At this voltage, the reaction requires heat energy from the outside to proceed. At 1.47 V (and same temperature) no input heat is required. At greater voltages (and same temperature), heat is released into the surroundings during water decomposition.

Operating the electrolyser at lower voltages with added heat is advantageous, as heat energy is usually cheaper than electricity and can be re circulated within the process. Furthermore, the efficiency of the electrolysis increases with increased operating temperature.

When viewed together with fuel cells, hydrogen produced through electrolysis can be seen as a way of storing electrical energy as a gas until it is needed. Hydrogen produced by electrolysis is therefore the energy carrier, not the energy source. The energy source derives from an external power generating plant.

In this sense, the process of electrolysis is not very different from charging a battery, which also stores electrical energy. Viewed as electricity storage medium, hydrogen is competitive with batteries in terms of weight and cost.

To be truly clean, the electrical power stored during electrolysis must derive from non-polluting, renewable sources. If the power is derived from natural gas or coal, the pollution has not been eliminated, only pushed upstream. In addition, every energy transformation has an associated energy loss. Consequently, fossil fuels may be used with greater efficiency by means other than by driving the electrolysis of hydrogen. Furthermore, the cost of burning fossil fuels to generate electricity for electrolysis is three to five times that of reforming the hydrogen directly from the fossil fuel.

Non-polluting renewable energy sources include hydroelectric, solar photovoltaic, solar thermal and wind. These methods of power generation are applicable only in specific geographic or climatic conditions. Furthermore, with the exception of hydroelectric, each of these power sources is intermittent. Despite growth in the use of these energy sources, they currently provide a very small amount of the power consumed today.

Hydroelectric power generation uses the energy of moving water to turn turbines that in turn rotate generators. Hydroelectric power is only feasible in areas with major rivers that undergo significant changes in height. Most suitable locations worldwide have already been developed. Hydroelectric power is a cheap source of clean power especially when utilizing excess, off-peak power. The efficiency of hydroelectric power generation can top 80%. This is probably the optimum form of renewable energy although the environmental and ecological cost of dams is high. Solar electric power generation uses banks of solar cells to convert the energy of the sun directly into electrical power. Solar power is only feasible in areas with significant amounts of intense sunlight and requires large tracts of land to generate

sufficient levels of power. The efficiency of solar cells currently ranges from 3 to 17%.

3.1.2 Reforming

Reforming is a chemical process that reacts hydrogen containing fuels in the presence of steam, oxygen, or both into a hydrogen rich gas stream. When applied to solid fuels the reforming process is called gasification. The resulting hydrogen rich gas mixture is called reformates. The equipment used to produce reformat is known as a reformer or fuel processor.

The specific composition of the reformat depends on the source fuel and the process used, but it always contains other compounds such as nitrogen, carbon dioxide, carbon monoxide and some of the unreacted source fuel. When hydrogen is removed from reformat, the remaining gas mixture is called raffinate. In essence, reforming a fossil fuel consists of the following steps:

1. Feedstock purification (including sulphur removal).
2. Steam reforming or oxidation of feedstock to form hydrogen and carbon oxides.
3. Primary purification - conversion of carbon monoxide to carbon dioxide.
4. Secondary purification - further reduction of carbon monoxide.

The reforming reactions require the input of water and heat. Overall reformer thermal efficiency is calculated as the lower heating value (LHV) of the product hydrogen divided by the lower heating value (LHV) of the total input fuel. This thermal efficiency depends on the efficiencies of the individual processes, the effectiveness to which heat can be transferred from one process to another, and the amount of energy that can be recovered through means such as turbochargers. In the

end, high temperature reformer efficiencies are approximately 65% and low temperature methanol reformers can achieve 70 to 75%.

The advantages of reforming fossil fuels are that they:

- uses existing fuel infrastructures
- reduces the need to transport and store hydrogen
- does not need the input of large amounts of energy as in electrolysis
- is less expensive than other hydrogen production methods

The disadvantages of reformers are that they:

- can have relatively long warm up times
- are difficult to apply to vehicle engines because of irregular demands for power (transient response)
- are complex, large and expensive
- introduce additional losses into the energy conversion process, especially those that have small thermal mass
- use non renewable fossil fuels
- generate pollution

The pollution generated by reformers take three forms:

- carbon dioxide emissions
- incomplete reactions, leaving carbon monoxide and some of the source fuel in the reformat
- production of pollutants through combustion, such as nitrous oxides

Reforming fossil fuels only makes sense if the hydrogen is needed directly, as in a fuel cell engine. For internal combustion engines, it is always more efficient to use the fossil fuel directly without passing it through a reformer first.

Medium or large size reformers can be installed at fuel cell vehicle fuelling stations. At these scales, the equipment complexity, warm up time and transient response are not issues, pollutants can be controlled more effectively and existing

power infrastructures can be used. The facility must store only small amounts of hydrogen and hydrogen transportation is avoided.

Small size reformers can be installed in fuel cell vehicles to entirely eliminate the problems associated with fuelling, storing and handling hydrogen directly. In fact, many fuel cell experts think that the true challenge in fuel cell engine design now lies in the development of an efficient, compact, reliable and highly integrated fuel processor. Other experts think that the use of on board reformers will never pose a realistic solution due to their size, complexity and cost.

3.1.3 Thermo chemical Water Decomposition

In thermo chemical water decomposition, heat alone is used to decompose water. This process is similar to electrolysis, with the difference that all the energy is added as heat and none as electricity. The maximum theoretical efficiency for this process is about 50%.

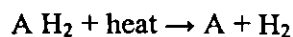
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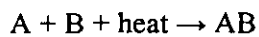
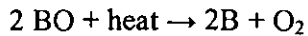
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Water decomposes directly at very high temperatures (> 2500 °C) which are too high to be practical. Instead, chemical reagents are used to decompose water in multi step chemical reactions in the following sequence:

1. Oxygen production
2. Hydrogen production
3. Materials regeneration

These reactions take the generic form of:





This is essentially an oxidation-reduction reaction where A and B are chemical compounds that commonly include iron, oxygen or chlorine. This process can take place at about 700 °C.

Selection of the specific chemical compounds for the reaction series depends on such factors as the:

- amount of energy needed for each step
- stability of the reactants for each step
- ability for the products of one step to be easily reacted in the next
- reaction time
- reaction yield
- individual reaction temperature
- pressure and flow requirements
- number of steps
- amount of cleanup required
- composition of waste products

In addition, as with any other chemical process, heat recovery, mass transfer and materials issues affect the overall system design.

Thermo chemical water decomposition, like electrolysis is only as renewable and environmentally clean as its energy source. If waste heat is used from other processes, the resulting hydrogen increases the overall efficiency of the heat generating parent process. If heat is obtained by burning fossil fuels, the resulting hydrogen will likely have generated more pollution than would have been by using the source fuel directly.

3.1.4 Photo Conversion

Photo conversion is an electrolysis process by which the electricity needed to decompose water into hydrogen and oxygen is generated directly using solar energy.

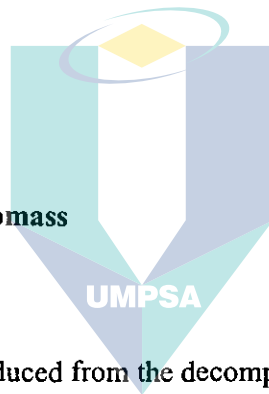
Water cannot absorb solar energy directly since it is transparent to the required wavelengths. The most common process uses a series of cells, each with a pair of semiconductor photo electrodes immersed in a watery electrolyte and separated by a membrane that allows ion transfer but prevents gas mixing. The cathode is made of a “p-type” semiconductor material (that has an excess of positive “holes”). The anode is made of a “n-type” semiconductor material (that has an excess of electrons). This is similar to a solar cell.

When the anode is illuminated by sunlight, electrons absorb the light energy and pass through an external circuit to the cathode. This creates an “electron hole” pair. The positive hole subsequently reacts with the water to create positive hydrogen ions and gaseous oxygen. The hydrogen ions pass through the membrane to recombine with the electrons at the cathode, resulting in hydrogen gas. Thus, the overall process results in photo electrolysis of the water.

A related method uses photochemical catalysts, suspended in alkaline or acidic solutions, as opposed to semiconductors. These catalysts absorb photon energy upon illumination, which creates an electric charge that drives a water splitting reaction.

Like any solar energy power generation process, photo conversion can only work in areas of prolonged, concentrated sunlight. Furthermore, this type of system has maximum efficiencies of between 8 and 12%.

Light energy can also produce hydrogen through photo biological processes, using biological systems such as cyanobacteria (blue-green) algae, photosynthetic algae or eukaryotic (green) algae. In principle, these algae contain hydrogen metabolizing enzymes that feed off base compounds in an anaerobic environment and release hydrogen gas in the process. These algae use compounds such as water, whey, starches, sugar refinery waste and distillery waste as electron donors. Unfortunately, the efficiency of these processes is very low, typically less than 1%.



3.1.5 Production from Biomass

Hydrogen can be produced from the decomposition of biomass. Biomass comprises all manner of plant and animal material that can be converted into energy. Biomass is organic in nature and can be derived from a variety of sources including residues, wastes and crops. Residues include the materials left over after the harvest of crops or trees. Wastes include those from food processing plants, sewage and municipal solid waste. Crops include those that can be grown specifically for their energy content, such as soybeans, trees and woody plants, among many others.

The appeal of hydrogen production from biomass is the obvious abundance of waste materials and its subsequent potential to supply large amounts of hydrogen. The primary problems are that the process is land and water intensive, and is hampered by the difficulties associated with handling solids. Furthermore, the associated technology is not well developed with the result that it is currently the most expensive means of obtaining hydrogen.

3.2 Hydrogen properties

3.2.1 Physical properties

3.2.1.1 State

All substances exist on earth as a gas, liquid or solid. Most substances will change from one of these states to another depending on the temperature and pressure of their surroundings. In general, a gas can be changed into a liquid by reducing its temperature and a liquid to a solid by reducing its temperature further. To some extent, an increase in pressure will cause a substance to liquefy and solidify at higher temperature than would otherwise be required.

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The transition from liquid to gas is known as boiling and the transition from liquid to solid as freezing. Accordingly, each substance has a characteristic boiling temperature and freezing temperature (at a given pressure). The opposite transitions, from gas to liquid and solid to liquid, are known as condensation and melting respectively. The condensation temperature is the same as the boiling temperature and the melting temperature is the same as the freezing temperature. The process of condensation is also known as liquefaction and the process of freezing is also known as solidification.

Boiling and freezing temperatures are most meaningfully compared relative to “absolute zero”. Absolute zero (0 K; -459.69°F ; -273.15°C) is the lowest temperature in the universe at which all-molecular motion stops.

Hydrogen has the second lowest boiling point and melting points of all substances, second only to helium. Hydrogen is a liquid below its boiling point of 20 K ($-253\text{ }^{\circ}\text{C}$) and a solid below its melting point of 14 K ($-259\text{ }^{\circ}\text{C}$) and atmospheric pressure.

Obviously, these temperatures are extremely low. Temperatures below 200 K ($-73\text{ }^{\circ}\text{C}$) are collectively known as cryogenic temperatures and liquids at these temperatures are known as cryogenic liquids.

The boiling point of a fuel is a critical parameter since it defines the temperature to which it must be cooled in order to store and use it as a liquid. Liquid fuels take up less storage space than gaseous fuels and are generally easier to transport and handle. For this reason, fuels that are liquid at atmospheric conditions such as gasoline, diesel, methanol and ethanol are particularly convenient. Conversely, fuels that are gases at atmospheric conditions such as hydrogen and natural gas are less convenient as they must be stored as a pressurized gas or as a cryogenic liquid.

Hydrogen as a vehicle fuel can be stored either as a high-pressure gas or as a cryogenic liquid.

3.2.1.2 Odour, Colour and Taste

Pure hydrogen is odourless, colourless and tasteless. A stream of hydrogen from a leak is almost invisible in daylight. Compounds such as mercaptans and thiophanes that are used to scent natural gas may not be added to hydrogen for fuel

cell use as they contain sulphur that would poison the fuel cells. Nitrogen, carbon dioxide, carbon monoxide and other trace gases typically accompany hydrogen that derives from reforming other fossil fuels. In general, all of these gases are also odourless, colourless and tasteless.

3.2.1.3 Toxicity

Hydrogen is non-toxic but can act as a simple asphyxiant by displacing the oxygen in the air. Oxygen levels below 19.5% are biologically inactive for humans. Effects of oxygen deficiency may include rapid breathing, diminished mental alertness, impaired muscular coordination, faulty judgement, depression of all sensations, emotional instability and fatigue. As asphyxiation progresses, dizziness, nausea, vomiting, prostration and loss of consciousness may result, eventually leading to convulsions, coma and death. At concentrations below 12%, immediate unconsciousness may occur with no prior warning symptoms.

In an enclosed area, small leaks pose little danger of asphyxiation whereas large leaks can be a serious problem since the hydrogen diffuses quickly to fill the volume. The potential for asphyxiation in unconfined areas is almost negligible due to the high buoyancy and diffusivity of hydrogen.

Gases that accompany hydrogen when reforming other fossil fuels, such as nitrogen, carbon dioxide, carbon monoxide and other trace gases, can also act as asphyxiants by displacing oxygen. In addition, carbon monoxide is a poisonous gas that is a severe health hazard.

3.2.1.4 Density and Related Measures

Hydrogen has lowest atomic weight of any substance and therefore has very low density both as a gas and a liquid.

Density is measured as the amount of mass contained per unit volume. Density values only have meaning at a specified temperature and pressure since both of these parameters affect the compactness of the molecular arrangement, especially in a gas. The density of a gas is called its vapour density and the density of a liquid is called its liquid density.

Table 3.1: Vapour and liquid densities of comparative substances.

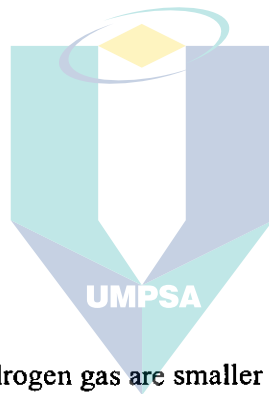
Substance	Vapour Density (at 68 °F; 20 °C, 1 atm)	Liquid Density (at normal boiling point, 1 atm)
Hydrogen	0.08376 kg/m ³	70.8 kg/m ³
Methane	0.65 kg/m ³	422.8 kg/m ³
Gasoline	4.4 kg/m ³	700 kg/m ³

The difference in volume between liquid and gaseous hydrogen can easily be appreciated by considering its expansion ratio. Expansion ratio is the ratio of the volume at which a gas or liquid is stored compared to the volume of the gas or liquid at atmospheric pressure and temperature.

When hydrogen is stored as a liquid, it vaporizes upon expansion to atmospheric conditions with a corresponding increase in volume. Hydrogen expansion ratio of 1:848 means that hydrogen in its gaseous state at atmospheric conditions occupies 848 times more volume than it does in its liquid state.

Even as a liquid, hydrogen is not very dense. Ironically, every cubic meter of water (made up of hydrogen and oxygen) contains 111 kg of hydrogen whereas a cubic meter of liquid hydrogen contains only 71 kg of hydrogen. Thus, water packs more mass of hydrogen per unit volume, because of its tight molecular structure, than hydrogen itself. This is true of most other liquid hydrogen containing compounds as well, a cubic meter of methanol contains 100 kg of hydrogen and a cubic meter of heptanes contains 113 kg. Hydrocarbons are compact hydrogen carriers with the added advantage of having higher energy density than pure hydrogen.

When used as vehicle fuel, the low density of hydrogen necessitates that a large volume of hydrogen be carried to provide an adequate driving range.



3.2.1.5 Leakage

The molecules of hydrogen gas are smaller than all other gases and it can diffuse through many materials considered airtight or impermeable to other gases. This property makes hydrogen more difficult to contain than other gases.

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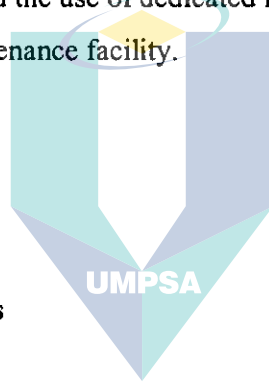
Leaks of liquid hydrogen evaporate very quickly since the boiling point of liquid hydrogen is so extremely low.

Hydrogen leaks are dangerous in that they pose a risk of fire where they mix with air. However, the small molecule size that increases the likelihood of a leak also results in very high buoyancy and diffusivity, so leaked hydrogen rises and becomes diluted quickly, especially outdoors. This results in a much localised region of flammability that disperses quickly. As the hydrogen dilutes with distance from the leakage site, the buoyancy declines and the tendency for the hydrogen to continue to

raise decreases. Very cold hydrogen, resulting from a liquid hydrogen leak, becomes buoyant soon after it evaporates.

For small hydrogen leaks, buoyancy and diffusion effects in air are often overshadowed by the presence of air currents from a slight ambient wind, very slow vehicle motion or the radiator fan. In general, these currents serve to disperse leaked hydrogen even more quickly with a further reduction of any associated fire hazard.

When used as vehicle fuel, the propensity for hydrogen to leak necessitates special care in the design of the fuel system to ensure that any leaks can disperse with minimum hindrance and the use of dedicated leak detection equipment on the vehicle and within the maintenance facility.



3.2.2 Chemical Properties

3.2.2.1 Reactivity

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High reactivity is characteristic of all chemical fuels. In each case, a chemical reaction occurs when the fuel molecules form bonds with oxygen (from air) so that the final, reacted molecules are at a lower energy state than the initial, unreacted molecules. As the molecules react, the change in chemical energy state is accompanied by a corresponding release of energy that we can exploit to do useful work. This is true in both a combustive reaction as in an internal combustion engine where the energy is released explosively as heat or in an electrochemical reaction as in a battery or fuel cell where the energy is released as an electrical potential and heat. This chemical energy release is analogous to that which occurs when water flows from a high level to a low level. The water at the high level has potential

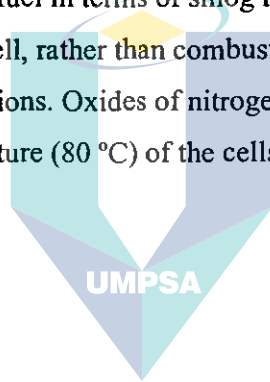
energy that is released as it falls to the low level. This energy can be harnessed to do useful work, such as turning a turbine. Once at the low level, the energy is spent and it cannot do further work at that level. In order to do further work, it must either fall to an even lower level, or be raised back to the high level through some external agency that inputs energy. The natural cycle of evaporation, condensation, and precipitation that returns water to a higher level is driven by solar and wind energy. Alternatively, a pump can return the water to a higher level, but the pump consumes a corresponding amount of energy.

Chemical reactions of this type often require a small amount of activation energy to get started, but then the energy released by the reaction feeds further reaction in a domino effect. Thus, when a small amount of activation energy in the form of a spark is provided to a mixture of hydrogen and oxygen, the molecules react vigorously, releasing a substantial amount of heat, with water as the final product. We experience this reaction as a fire or explosion and the resulting water vaporizes and is invisible to us since it is a superheated vapour. This water vapour can condense and become visible as it cools, this is the cloud we see when the space shuttle takes off. The water forming reaction of hydrogen and oxygen is reversible. Thus, it is possible to convert water, at a low energy state, to hydrogen and oxygen, at a higher energy state, by adding energy slightly greater than that which was previously released (the extra to cover losses). This is the principle behind hydrogen production through electrolysis.

All of the atoms present at the start of a reaction are present at the end of the reaction although they may be reorganised into different molecules. Hydrocarbon fuels, in addition to hydrogen and carbon, may contain other impurities such as sulphur. Air, in addition to being a ready source of oxygen, also consists of 78% nitrogen and 1% trace gases. The presence of carbon, nitrogen and sulphur as well as unreacted hydrocarbons result in chemical compounds during combustion that cause smog with serious health and environmental consequences.

The type of fuel and the use of post combustion catalytic converters affect the amount and type of smog pollution. Light hydrocarbons are relatively rich in hydrogen and therefore provide less carbon atoms for CO and CO₂ formation. Non sulphur containing fuels eliminate SO_x and soot. Hydrogen is a nearly ideal fuel in terms of smog reduction when combusted. Hydrogen contains no carbon or sulphur, so no CO, CO₂ or SO_x or soot is produced during combustion although the combustion of lubricating oil may result in trace amounts. Hydrogen allows for leaner combustion, resulting in lower combustion temperatures and very low NO_x emissions. Hydrogen is non toxic so uncombusted hydrogen does not pose a direct health risk.

Hydrogen is an ideal fuel in terms of smog reduction when used electrochemically in a fuel cell, rather than combusted. Hydrogen in a fuel cell produces zero harmful emissions. Oxides of nitrogen are completely eliminated due to the low operating temperature (80 °C) of the cells. Lubricating oil is not present and is therefore not reacted.



3.2.2.2 Energy

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Every fuel can liberate a fixed amount of energy when it reacts completely with oxygen to form water. This energy content is measured experimentally and is quantified by a fuels higher heating value (HHV) and lower heating value (LHV). The difference between the HHV and the LHV is the heat of vaporization and represents the amount of energy required to vaporize a liquid fuel into a gaseous fuel, as well as the energy used to convert water to steam. The higher and lower heating values of comparative fuels are indicated in Table 3.2. Although the terms HHV and LHV do not apply to batteries, the energy density of a lead acid battery is approximately 0.108 kJ/g.

Table 3.2: Heating values of comparative fuels.

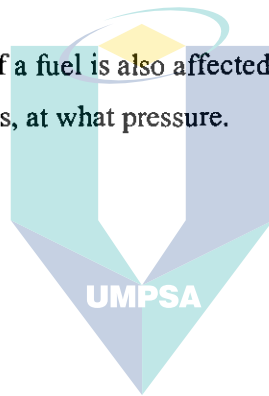
Fuel	Higher heating value (at 25 °C and 1 atm)	Lower heating value (at 25 °C and 1 atm)
Hydrogen	141.86 kJ/g	119.93 kJ/g
Methane	55.53 kJ/g	50.02 kJ/g
Propane	50.36 kJ/g	45.6 kJ/g
Gasoline	47.5 kJ/g	44.5 kJ/g
Diesel	44.8 kJ/g	42.5 kJ/g
Methanol	19.96 kJ/g	18.05 kJ/g

Gaseous fuels are already vaporised so no energy is required to convert them to a gas. The water that results from both a combustive reaction and the electrochemical reaction within a fuel cell occurs as steam, therefore the lower heating value represents the amount of energy available to do external work.

Both the higher and lower heating values denote the amount of energy (in Joules) for a given weight of fuel (in kilograms). Hydrogen has the highest energy to weight ratio of any fuel since hydrogen is the lightest element and has no heavy carbon atoms. It is for this reason that hydrogen has been used extensively in the space program where weight is crucial. Specifically, the amount of energy liberated during the reaction of hydrogen, on a mass basis, is about 2.5 times the heat of combustion of common hydrocarbon fuels (gasoline, diesel, methane, propane, etc.) Therefore, for a given load duty, the mass of hydrogen required is only about a third of the mass of hydrocarbon fuel needed. The high-energy content of hydrogen also implies that the energy of a hydrogen gas explosion is about 2.5 times that of common hydrocarbon fuels. Thus, on an equal mass basis, hydrogen gas explosions are more destructive and carry further. However, the duration of a conflagration tends to be inversely proportional to the combustive energy, so that hydrogen fires subside much more quickly than hydrocarbon fires.

Whereas the energy content denotes the amount of energy for a given weight of fuel, the energy density denotes the amount of energy (Joules) for a given volume (in m^3) of fuel. Thus, energy density is the product of the energy content (LHV in our case) and the density of a given fuel. The energy density is really a measure of how compactly hydrogen atoms are packed in a fuel. It follows that hydrocarbons of increasing complexity with more and more hydrogen atoms per molecule have increasing energy density. At the same time, hydrocarbons of increasing complexity have more and more carbon atoms in each molecule so that these fuels are heavier and heavier in absolute terms. On this basis, hydrogen energy density is poor since it has such low density although its energy to weight ratio is the best of all fuels because it is so light.

The energy density of a fuel is also affected by whether the fuel is stored as a liquid or as a gas, and if a gas, at what pressure.



3.2.2.3 Flammability

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Three things are needed for a fire or explosion to occur, a fuel, oxygen (mixed with the fuel in appropriate quantities) and a source of ignition. Hydrogen, as a flammable fuel, mixes with oxygen whenever air is allowed to enter a hydrogen vessel, or when hydrogen leaks from any vessel into the air. Ignition sources take the form of sparks, flames, or high heat.

All fuels burn only in a gaseous or vapour state. Fuels like hydrogen and methane are already gases at atmospheric conditions, whereas other fuels like gasoline or diesel that are liquids must convert to a vapour before they will burn. The characteristic that describes how easily these fuels can be converted to a vapour is the flashpoint. The flashpoint is defined as the temperature at which the fuel

produces enough vapours to form an ignitable mixture with air at its surface. If the temperature of the fuel is below its flashpoint, it cannot produce enough vapours to burn since its evaporation rate is too slow. Whenever a fuel is at or above its flashpoint, vapours are present. The flashpoint is not the temperature at which the fuel bursts into flames, that is the auto ignition temperature.

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The flashpoint is always lower than the boiling point. For fuels that are gases at atmospheric conditions (like hydrogen, methane and propane), the flashpoint is far below ambient temperature and has little relevance since the fuel is already fully vaporized. For fuels that are liquids at atmospheric conditions (such as gasoline or methanol), the flashpoint acts as a lower flammability temperature limit.

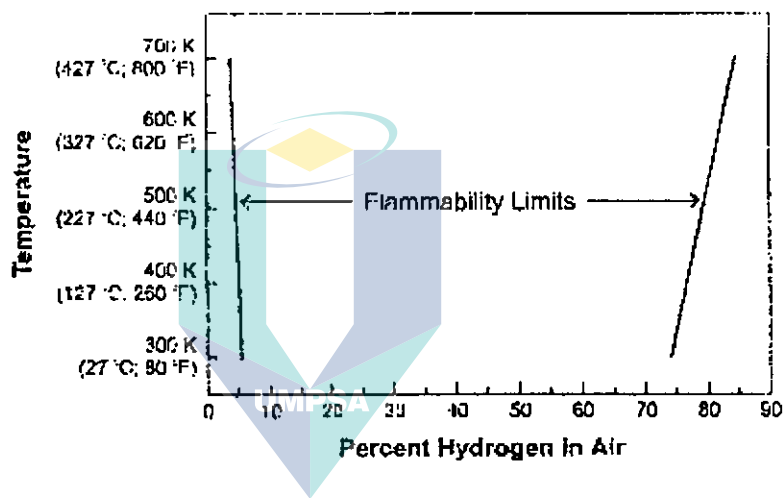
Table 3.3: Flashpoint of comparative fuels

Fuel	Flashpoint
Hydrogen	(< -253 °C; 20 K)
Methane	(-188 °C; 85 K)
Propane	(-104 °C; 169 K)
Gasoline	Approximately (-43 °C; 230 K)
Methanol	(11 °C; 284 K)

The flammability range of a gas is defined in terms of its lower flammability limit (LFL) and its upper flammability limit (UFL). The LFL of a gas is the lowest gas concentration that will support a self-propagating flame when mixed with air and ignited. Below the LFL, there is not enough fuel present to support combustion, the fuel / air mixture is too lean.

Hydrogen is flammable over a very wide range of concentrations in air (4 – 75%) and it is explosive over a wide range of concentrations (15 – 59%) at standard atmospheric temperature. The flammability limits increase with temperature as illustrated in Figure 3.2. As a result, even small leaks of hydrogen have the potential to burn or explode. Leaked hydrogen can concentrate in an enclosed environment, thereby increasing the risk of combustion and explosion.

Figure 3.2: Variation of hydrogen flammability limits with temperature.



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3.2.2.4 Hydrogen Embrittlement

Constant exposure to hydrogen causes a phenomenon known as hydrogen embrittlement in many materials. Hydrogen embrittlement can lead to leakage or catastrophic failures in metal and non-metallic components.

The mechanisms that cause hydrogen embrittlement effects are not well defined. Factors known to influence the rate and severity of hydrogen embrittlement include hydrogen concentration, hydrogen pressure, temperature, hydrogen purity,

type of impurity, stress level, stress rate, metal composition, metal tensile strength, grain size, microstructure and heat treatment history. Moisture content in the hydrogen gas may lead to metal embrittlement through the acceleration of the formation of fatigue cracks.

3.3 Hydrogen storage

If new sources of energy are to be fully exploited then an efficient energy storage system must be developed to meet variable demand. This is so because, in most cases, energy demands are periodic in nature whereas energy supply operates most efficiently on a constant output basis.

The supply and demand patterns of the electric utility industry illustrate the point well. Generating capacity must be sized for maximum demand, which can be more than twice minimum demand, since no economic storage method is currently available on a large scale basis. The result is that fixed charges contribute significantly to electricity costs and consumers must pay heavily for a guaranteed supply.

At present, the relative ease with which fossil fuels are stored is taken for granted. The energy associated with such fuels is in the form of latent chemical energy, which can be released on combustion. On the other hand, in the case of new energy sources the actual form of energy is different. It is usually kinetic (wind, tidal) or heat (nuclear, geothermal, solar) energy. Also it is not available uniformly, but rather on a cyclic basis.

In order to enable effective storage, these new energy sources need to be converted into a secondary energy form. Electricity and hydrogen are the two most promising candidates to fulfil this role. However, electricity suffers from the disadvantage that it is almost impossible to store efficiently. Storage of electricity by means of batteries is not practical.

In contrast to electricity, hydrogen closely resembles our present fuels, especially natural gas. It can be made fluid and hence can be moved and stored in the same manner as today's fuels.

Hydrogen can be stored in three forms: as a gas, as liquid, or as a solid combined chemically with a metal. The first two methods are applicable to natural gas storage but the third is unique to hydrogen.

Which of the above forms will serve best, as a form to store hydrogen will depend upon the gas's end use? In addition the economic criteria, safety aspects must also be carefully considered.

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3.3.1 Choice of storage

The choice of which method of hydrogen storage is best depends on:

- The application (Is liquid hydrogen required? What pressure is required?)
- The required energy density (What form of hydrogen delivery will be used? Is space an issue?)
- The quantity of hydrogen to be stored (Is the storage used as a buffer, or primary storage for a large amount of hydrogen?)

- The storage period (Will the storage be used to keep hydrogen for a few hours, or is it seasonal storage?)
- What forms of energy are readily available (Is there waste heat available? Is there high-pressure steam available for a turbine?)
- What is the geology of the area (Are there abandoned natural gas well available?)
- Any future expansion needs (Are there reasons to believe additional storage will be needed in the future?)
- Maintenance requirements (Is high reliability required? How often can the storage system be shut down for maintenance?)
- Capital costs (Are high capital costs prohibitive?)

3.3.2 Storage Period



The longer hydrogen is to be stored, the more favourable underground or liquid hydrogen storage becomes because of lower capital costs. If hydrogen is stored for a long time, the operating cost can be a small factor compared to the capital costs of storage. Underground storage is the cheapest for short-term storage, followed by aboveground compressed gas storage, which should be considered for storage times of several hours to several days. Liquid storage and underground storage should be considered for seasonal or long-term storage of hydrogen for periods longer than a couple of days or 5% annual turnover rates of gas. Metal hydride storage is not economical for large quantities of gas because of the high capital cost of the metal hydride.

3.3.3 Energy Availability

The available energy may be another consideration when choosing methods of storage. For compressed gas storage and hydrogen liquefaction, compressor power consumption can be quite high. If inexpensive electricity, gas turbine, or steam turbine power is available, the compression costs will be lower. A cheap source of thermal energy or waste heat would benefit metal hydride storage by reducing the energy costs for releasing the hydrogen from the hydride.

3.3.4 Maintenance and Reliability

Maintenance and reliability will depend on how simple the storage method is to operate and maintain. A liquefaction plant will be much more complicated and more costly to maintain than a metal hydride storage unit that has no rotating assemblies. Liquefaction will have the highest maintenance requirements, followed by compressed gas storage, and then metal hydrides.

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3.3.5 Safety

Safety is a concern with any option. When the main options for storage are examined, metal hydrides appear to be the safest storage option because the storage unit is at low pressure. If there is a leak in the container, very little hydrogen will leak out because a source of continuous heat is required to release the bond between the metal and the hydrogen. For compressed gas, there are two dangers. First, a high-pressure vessel always presents some level of risk, whether it is an inert gas or a

reactive gas such as hydrogen. Second, if a compressed gas tank develops a leak, it will result in the release of a large amount of hydrogen very quickly. Liquid hydrogen has the potential to release even more hydrogen than compressed gas if a storage container leaks because the liquid hydrogen will quickly vaporize. In open areas there is, however, little chance of detonation, because hydrogen diffuses into air quickly.

3.3.6 Summary of hydrogen storage

Based on current hydrogen storage technology, the following generalizations can be made:

- Underground Storage - For large quantities of gas or long-term storage.
- Liquid Hydrogen - For large quantities of gas, long term storage, low electricity costs or applications requiring liquid hydrogen.
- Compressed Gas - For small quantities of gas, high cycle times or short storage times.
- Metal Hydrides - For small quantities of gas.

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CHAPTER IV

PRINCIPLE OF FUEL CELL OPERATION

4.1 General characteristic

A fuel cell is a galvanic device or energy conversion device that continuously converts the chemical energy of a fuel and oxidant directly into electricity without any intermediate thermal or mechanical processes. Fuel cells convert this energy electrochemically and are not subject to the Carnot cycle limitation of thermal engines, thus offering the potential for highly efficient conversion.

In a fuel cell, the fuel and the oxidant are supplied continuously from an external source when power is desired. The fuel cell can produce electrical energy as long as the active materials are fed to the electrodes.

The electrode materials of the fuel cell are inert in that they are not consumed during the cell reaction, but have catalytic properties, which enhance the electro reduction or electro oxidation of the reactants (the active materials).

The anode active materials used in fuel cells are generally gaseous or liquids fuels such as hydrogen, methanol, hydrocarbons, natural gas, which are fed into the anode side of the fuel cell. Oxygen, most often air is the predominant oxidant and is fed into the cathode. Fuel cell technology can be classified into two categories:

1. Direct systems where fuels, such as hydrogen can react directly in the fuel cell.
2. Indirect system in which the fuel, such as natural gas or other fossil fuels is first converted by reforming to a hydrogen-rich gas which is then fed into the fuel cell.

Fuel cell systems can take a number of configurations depending on the combinations of fuel and oxidant, the type of electrolyte, temperature of operation, etc.

4.2 Reaction of mechanisms

A simple fuel cell is illustrated in Figure 4.1. Two catalysed electrodes are immersed in an electrolyte (acid in this illustration) and separated by a gas barrier. The fuel, in this case hydrogen, is bubbled across the surface of one electrode while the oxidant, in this case oxygen from ambient air is bubbled across the other electrode.

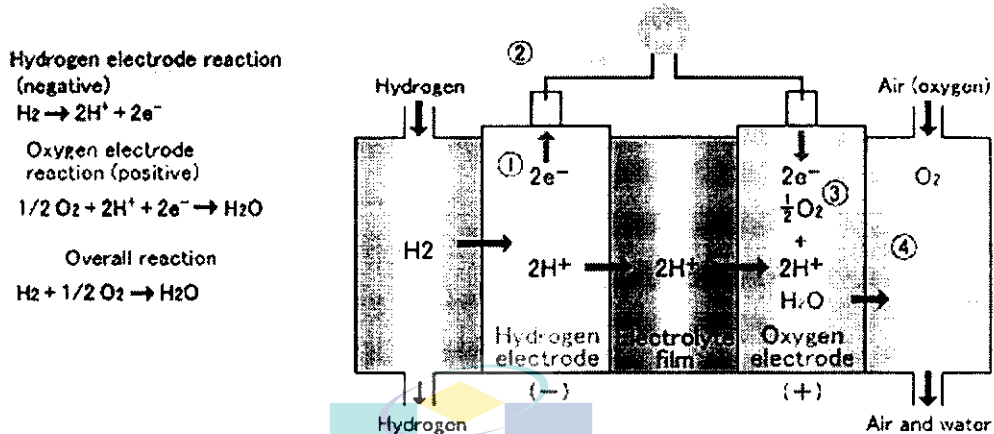
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When the electrodes are electrically connected through an external load, the following events occur (see Figure 4.1):

1. The hydrogen dissociates on the catalytic surface of the fuel electrode, forming hydrogen ions and electrons.
2. The hydrogen ions pass through the anode into the electrolyte, moving towards the cathode.
3. Simultaneously, the electrons move through the external circuit, performing useful work (this is the electric current generated) and eventually return to the cathode which is supplied with oxygen.

4. At this point the electrons, hydrogen ions and oxygen combine to form water (H₂O) and heat.

Figure 4.1: Schematic representation of the operation of a simple acid electrolyte fuel cell.



As long as the fuel cell is supplied with hydrogen and oxygen, this electrical production can continue indefinitely. The reaction mechanisms of this fuel cell in acid and alkaline electrolytes are shown in Table 4.1.

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In the acid electrolyte, water is produced at the cathode and in the alkaline electrolyte fuel cell, it is produced at the cathode. The net reaction is that of hydrogen and oxygen producing water and electrical energy.

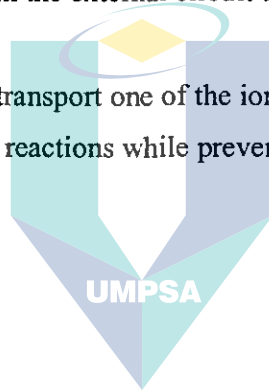
Table 4.1: Reaction mechanisms of the H₂ / O₂ fuel cell.

	Acid electrolyte	Alkaline electrolyte
Anode	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$
Cathode	$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$\frac{1}{2} O_2 + 2e^- + H_2O \rightarrow 2OH^-$
Overall	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$	$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$

4.3 Major components of the fuel cell

The important components of the individual fuel cell are:

1. The anode (fuel electrode) must provide a common interface for the fuel and electrolyte, catalyze the fuel oxidation reaction and conduct electrons from the reaction site to the external circuit.
2. The cathode (oxygen electrode) must provide a common interface for the oxygen and the electrolyte, catalyze the oxygen reduction reaction and conduct electrons from the external circuit to the oxygen electrode reaction site.
3. The electrolyte must transport one of the ionic species involved in the fuel and oxygen electrode reactions while preventing the conduction of electrons.



4.4 Sources of fuel and oxidant

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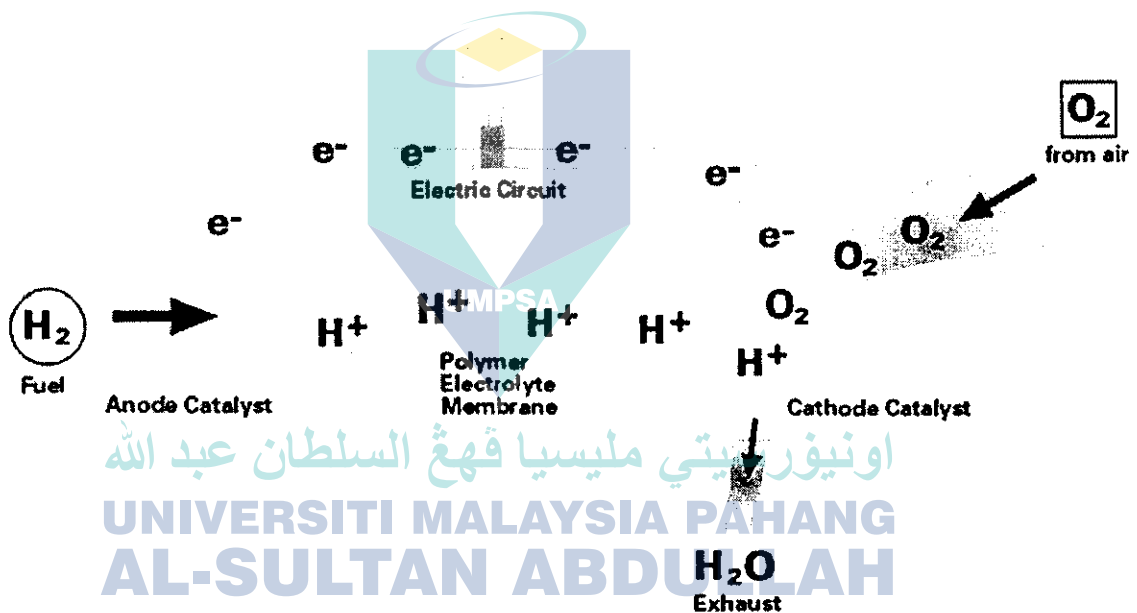
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Various methods are used to supply the fuel cell with the necessary hydrogen and oxygen. Some systems use a fuel reformer to extract hydrogen from another fuel source such as propane and can extract oxygen from the surrounding air. Some systems in laboratory or industrial settings are designed to be attached to tanks of pure hydrogen and oxygen.

The most interesting method of obtaining hydrogen is to use an "electrolyser" to separate water into hydrogen and oxygen, which is then stored in tanks and fed into either end of the fuel cell. The water produced at the end of the fuel cell process is then fed back into the initial water source.

Fuel cells operate at maximum efficiency when operating on pure hydrogen and pure oxygen. Pure oxygen is very expensive and thus air is used as the source of oxygen in most applications except where the extra cost can be justified. Pure hydrogen also is expensive and difficult to transport and store, therefore like pure oxygen it is only used in special cases. Gaseous mixtures of hydrogen (H_2) and carbon dioxide (CO_2), which can be created by the processing of fossil fuels or biomass, are used instead of pure hydrogen in most commercial uses of fuel cells.

Figure 4.2: How a fuel cell works



4.5 Fuel cell efficiency

The efficiency of a device may be viewed in several ways. But, the overall efficiency of any system:

$$\text{Efficiency} = (\text{What you get}) / (\text{What you pay for})$$

When work is the desired output, this becomes:

$$\text{Efficiency} = (\text{work output}) / (\text{energy input})$$

The fuel cell thermodynamic efficiency is given by the ratio of the Gibbs function change (ΔG) to the Enthalpy change (ΔH) in the overall cell reaction. The Gibbs function change (ΔG) measures the electrical work and the enthalpy change (ΔH) is a measure of the heating value of the fuel.

Fuel cell efficiency, $\eta = (\Delta G / \Delta H) * 100\%$, where $\Delta G = - n F E_0$. The relation between ΔG and ΔH is known to be: $\Delta G = \Delta H - T \Delta S$, hence, the efficiency of the fuel cell as follows:

$$\begin{aligned} \text{Fuel cell efficiency, } \eta &= ((\Delta H - T \Delta S) / \Delta H) * 100\% \\ &= (1 - (T \Delta S / \Delta H)) * 100\% \end{aligned}$$

Depending on the sign of the reaction entropy, ΔS , the efficiency may be smaller, equal to or even higher than 100%. The fuel cell directly supplies electric current of the theoretical dc voltage (E_{rev}).

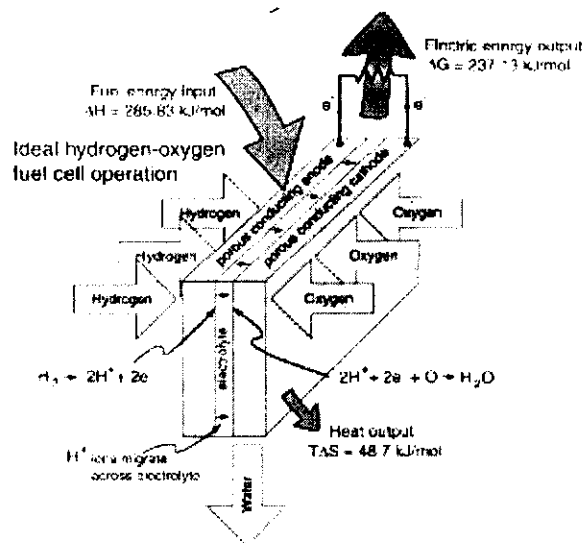
$$E_{rev} = - \Delta G / nF;$$

where $n = 1.602 * 10^{-19}$, no of electrons transferred per molecule reactant.

$$F = 96485 \text{ C / mol, Faradays constant}$$

The most important, the fuel cell reaction is the combustion reaction of hydrogen ($2H_2 + O_2 \rightarrow 2H_2O$). At a pressure of 1 bar (1013 kPa) and a temperature of 25 °C (298K), the corresponding dc voltage for this reaction is 1.23 V.

Figure 4.3: Energy distributed in fuel cell.



For the hydrogen – oxygen reaction (see Figure 4.3); $\text{H}_2(\text{g}) + \frac{1}{2} \text{O}_2(\text{g}) \rightarrow \text{H}_2\text{O}(\text{l})$. This process is presumed to be at 298K, 1 atmosphere pressure and the relevant values are taken from a table of thermodynamic properties.

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Table 4.2: Table of thermodynamic properties.

Quantity	H_2	0.5 O_2	H_2O	Change
Enthalpy	0	0	-285.83 kJ	$\Delta H = -285.83 \text{ kJ}$
Entropy	130.68 J/K	$0.5 \times 205.14 \text{ J/K}$	69.91 J/K	$T \Delta S = -48.7 \text{ kJ}$

Energy is provided by the combining of the atoms and from the decrease of the volume of the gases. Both of those are included in the change in enthalpy (ΔH) included in the table above. At temperature 298K and 1 atmosphere pressure, the system work is;

$$W = P\Delta V = (101.3 \times 10^3 \text{ Pa}) (1.5 \text{ moles}) (-22.4 \times 10^{-3} \text{ m}^3/\text{mol}) (298\text{K}/273\text{K}) = -3.715 \text{ kJ}.$$

Since the enthalpy $H = U + PV$, the change in internal energy U is then;
 $\Delta U = \Delta H - P\Delta V = -285.83 \text{ kJ} - 3.72 \text{ kJ} = -282.1 \text{ kJ}$.

The entropy of the gases decreases by 48.7 kJ in the process of combination since the number of water molecules is less than the number of hydrogen and oxygen molecules combining. Since the total entropy will not decrease in the reaction, the excess entropy in the amount $T\Delta S$ must be expelled to the environment as heat at temperature T . The amount of energy per mole of hydrogen, which can be provided as electrical energy, is the change in the Gibbs free energy;
 $\Delta G = \Delta H - T\Delta S = -285.83 \text{ kJ} + 48.7 \text{ kJ} = -237.13 \text{ kJ}$.

Therefore, the efficiency of the ideal fuel cell is; Fuel cell efficiency, $\eta = (\Delta G / \Delta H) * 100\% = (237.13 / 285.83) * 100\% \approx 83\%$. Although real fuel cells do not approach that ideal efficiency, they are still much more efficient than any electrical power plant which burns a fuel.

Another measure of the fuel cell efficiency is known as the "Voltage Efficiency". The fuel cell voltage efficiency is given by the ratio of the actual voltage under operating conditions to the theoretical cell voltage.

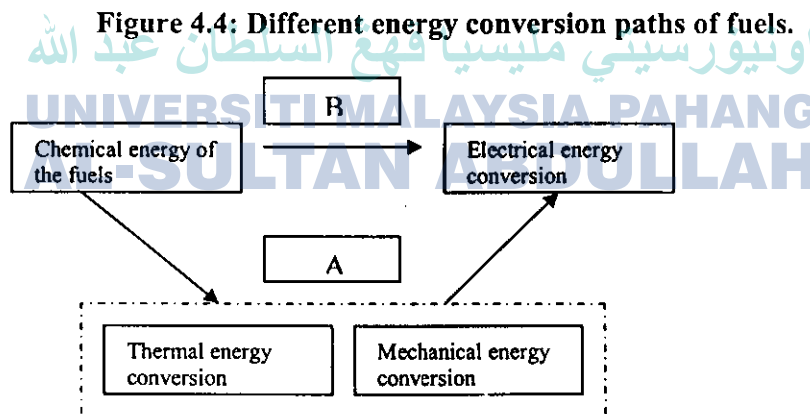
Fuel cell voltage efficiency, $\eta = (\text{Actual voltage} / \text{Theoretical voltage}) * 100\%$
 $= (-nFE_K / \Delta G) * 100\%$
 $= (E_K / E_O) * 100\%$
 $= (E_K / 1.23) * 100\%$

4.6 Fuel cell efficiency versus Carnot efficiency

The theoretical thermodynamic derivation of Carnot Cycle shows that under ideal conditions, a heat engine cannot convert all the heat energy supplied to it into mechanical energy, some of the heat energy is rejected. In an internal combustion engine, the engine accepts heat from a source at a high temperature (T_h), converts part of the energy into mechanical work and rejects the remainder into a heat sink at a low temperature (T_c). The greater the temperature differences between source and sink, the greater the efficiency.

Maximum efficiency (Carnot), $\eta_{\text{carnot}} = \frac{T_h - T_c}{T_h}$.

Because fuel cells convert chemical energy directly to electrical energy, this process does not involve conversion of heat to mechanical energy. Therefore, fuel cell efficiencies can exceed the Carnot limit even when operating at relatively low temperature, for example, 80°C. Figure 4.4 shows a graphical illustration of energy conversion processes from chemical energy in fuels to electrical energy.

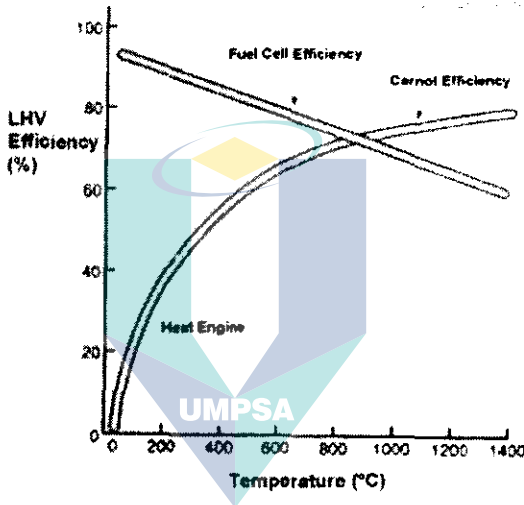


There are two ways in converting chemical energy to electrical energy, route A and route B. The route A is a general route for the combustion process plus electricity generation in vehicles and power stations that use fossil fuels. The route B

is for fuel cells. Fuel cell generates electricity by electrochemical reactions. It bypasses the thermal and mechanical energies conversion, hence are more efficient.

A comparison of efficiencies between the Carnot process and the hydrogen cell process is shown in figure below.

Figure 4.5: Thermodynamic efficiency for fuel cells and Carnot efficiency for heat engines.



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CHAPTER V

EXPERIMENTS, RESULTS & ANALYSIS

5.1 Introduction to 'Hydro-Genius Teach'

Figure 5.1 show the 'Hydro-Genius Teach' experiment set. The 'Hydro-Genius Teach' is a complete practice and instructional fuel cell kit. It can be used immediately without extensive preparation and is perfect for science classes on energy, electrical technology or in any subject dealing with renewable energy systems. The adjustable solar module can be tilted to vary the incident angle of the light source. A high-performance PEM fuel cell and electrolyser with 65 ml graduated cylinders for gas storage. Requires no chemicals for operation, only distilled water (a solid electrolyte is contained within the electrolyser membrane). 'Hydro-Genius Teach' load box contains electric motor with fan. Please refer appendix B to see a real 'Hydro-Genius Teach' tool set during an experiment in conduct.

Figure 5.1: Assemble of 'Hydro-Genius Teach' experiment set.



5.2 Experiments, results and analysis.

5.2.1 Determination of current-voltage behaviour over solar module.

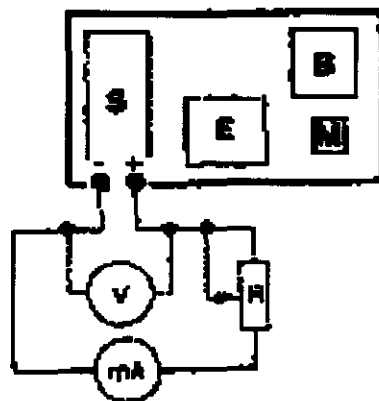
Objective: To study the current voltage behaviour over solar module.

Methods:

1. A circuit as Figure 5.2 is built up.
2. The solar module is lighted up with a lamp (the distance between the lamp and the solar module is about 5 cm and the current should be approximately 300 mA).
3. The module is warmed up for 5 minutes and the characteristic is taken relatively according to the temperature.
4. The Potentiometer is varied (starting with 0 Ω) and the respective voltage and current at various resistances are measured.

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Figure 5.2: Schematic connections for determination of current voltage behaviour over solar module.



S = solar module E = electrolyser
B = fuel cell M = load / motor

Measurements and analysis:

Table 5.1: Measurement of current, voltage and power in different resistance for distance of lamp = 5cm.

R	U(V)	I(mA)	P(mW)
0	0,06	298	17,28
4	0,36	296	105,67
10	2,38	282	671,16
15	2,74	242	663,08
20	2,91	178	517,98
30	3,01	110	331,1
40	3,05	80	244
50	3,07	62	190,34
150	3,11	22	68,42
250	3,12	13	40,56
350	3,12	9	28,08

Figure 5.3: Current voltage behaviour over solar module for distance of lamp = 5cm.

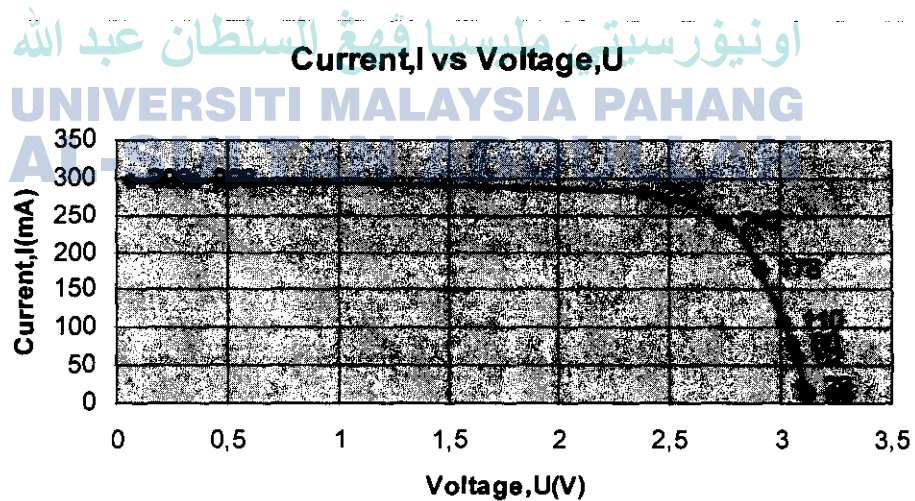
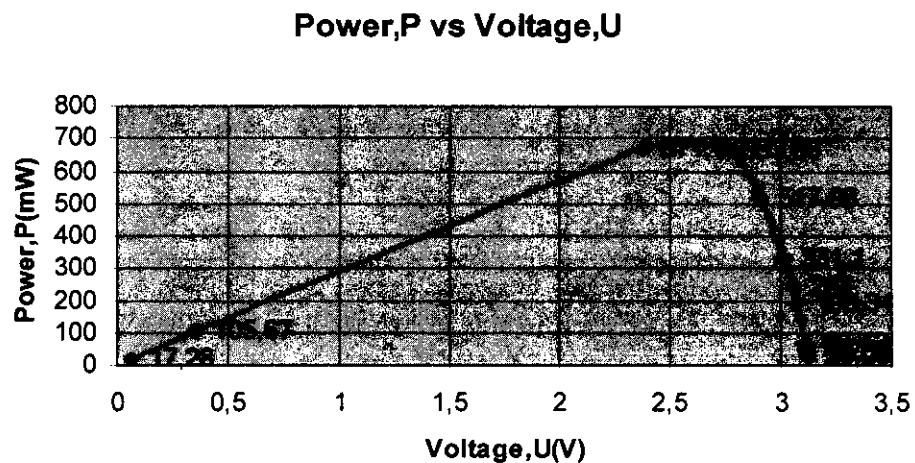


Figure 5.4: Maximum powers over solar module for distance of lamp = 5cm.



Observation:

Figure 5.3 and Figure 5.4 shows the form of the characteristic of solar modules corresponds to a single solar cell, since a solar module consists of series connection of single solar cells (six silicon solar cells in a row). The following details are important for a characteristic, the nominal voltage, the short circuit current and the point at the maximum power point (MPP). Without a current withdrawal, the solar modules have a nominal voltage of about 3 V ($R = \infty$). A single silicon solar cell has a typical nominal voltage of 0.5V – 0.6V.

The solar module is closed for a while ($R = 0\Omega$) then the maximum current (short circuit current) would flow. From the experiment, the value is about 298mA. The maximum power point (MPP) describes a point, where the solar module irradiates its maximum power given. The point lies in a break point of the current at voltage characteristic and can be determined by the maximum value of the power voltage characteristic.

For our measuring, the MPP is about 700mV. The adoption of a solar module to the respective used power plays a roll. The used power should be always approximately near to MPP.

5.2.2 Characteristic of Electrolysis.

Objective: To study the characteristic of electrolysis.

Methods:

1. The circuit as Figure 5.5 is set up.
2. The supply voltage is increased from 0V to 2.5V.

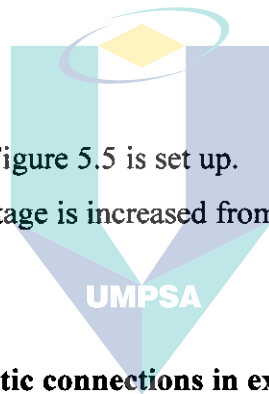
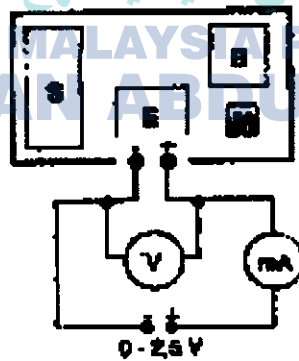


Figure 5.5: Schematic connections in experiment for investigating the characteristic of electrolysis.

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S = solar module

E = electrolyser

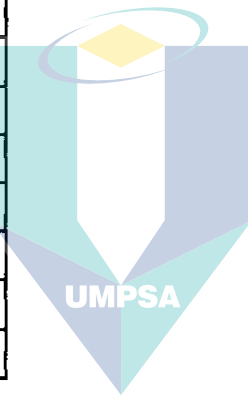
B = fuel cell

M = load / motor

Measurements and analysis:

Table 5.2: Measurement of current and power in different supply voltage through electrolysis.

U(V)	I(mA)	P(mW)
0.0	0.00	0.00
0.5	0.00	0.00
1.0	0.22	0.22
1.5	1.03	1.55
1.6	5.52	8.83
1.7	4.90	8.33
1.8	10.32	18.58
1.9	20.54	39.03
2.0	79.30	158.60
2.1	104.00	218.40
2.2	154.50	339.90
2.3	214.50	493.35
2.4	285.10	684.24
2.5	493.00	1232.50



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Figure 5.6: Characteristic of current voltage behaviour over electrolysis.

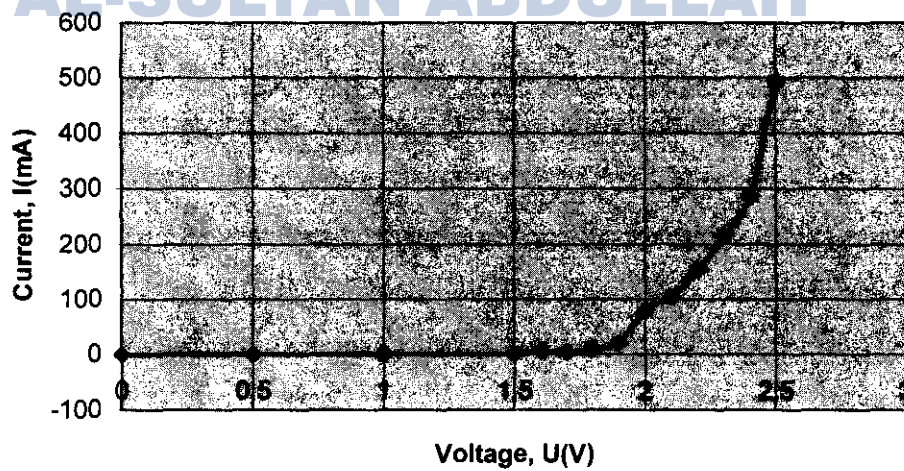
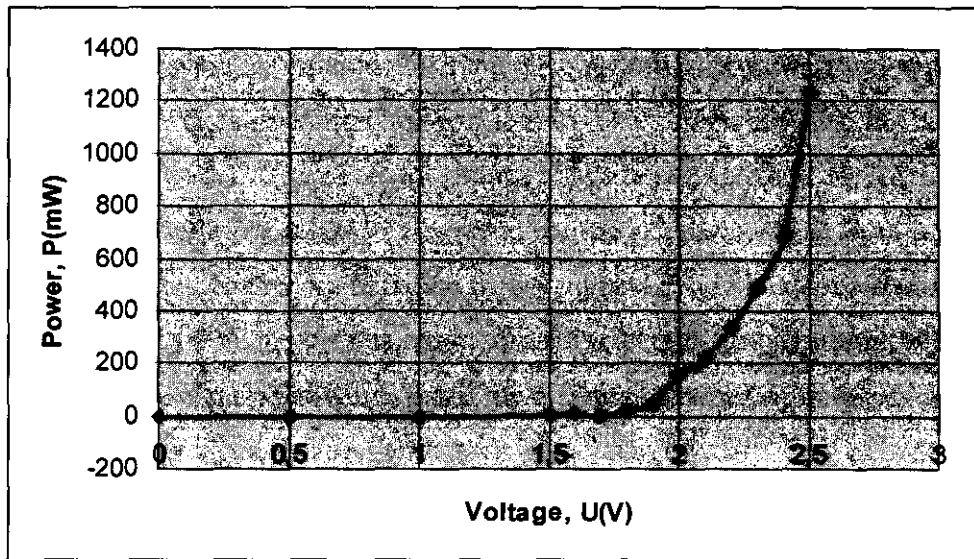


Figure 5.7: Characteristic of maximum power over electrolysis.



Observation:

From the current voltage curve in Figure 5.6, we can recognise that from the beginning it shows no reading at ammeter till a specific voltage, where the current flows increase continuously. At voltage 1.7V the current start to flow. Initially, low voltage causes no electrolysis where current lead the separation process. The hydrogen goes to cathode and the oxygen goes to anode.

At the beginning of the process, when the initial voltage remains low, it contains gas that is absorbed by both the electrode. The electrode contains or created from galvanic cell. These galvanic cells have special cell voltage (polarization voltage) that causes current. This internal current affects the electrolysis current towards. When we increase the outer voltage, more gas will be absorbed. From the specific point, the gas pressure at both electrodes will reach the value of outer air pressure and the gas start blowing increasingly from the electrodes.

The next increments of outer voltage lead to the gas development continuously with step exponential ascent of the electrolysis current (see Figure 5.6). The low voltage, which is used to make the decomposition process from water begin. It is also called as decomposition voltage. It is for electrolysis and also for the cell voltage of galvanic cell. The decomposition voltage needed for $H_2 / H_2O // OH^- / O_2$ under standard condition is 1.23V. However, the measurement value from decomposition voltage is more from the theory values. From the experiment the readings is about 1.7V. Means, the separation from oxygen and hydrogen at the electrodes will be clearly shown. We call the difference values from theory and experiment of specific separation voltage as power surge.

The power surge depends on the type of materials that are used as electrodes, the finishing of the electrodes, the types of electrolyte that is used, the current density (current per surface area of electrode) and temperature. The power surges are rarely low by electrodes reactions which lead to the separation metal. It is rather high when the gases are hydrogen, oxygen or chlorine (H_2, O_2, Cl_2).

In practical, we have to keep the power surge as small as possible. The most important thing is to use the best active materials for electrodes. The Hydro-Genius Teach is good for electrolysis because the electrode is made from nickel. Nickel is the best active fluid in alkaline process. In technical electrolysis, this nickel electrode that is used has improved the electrolysis process. The material and the finishing is changed, making the decomposition voltage lies between 1.4 till 1.5. Another advantage is electrical energy can be saved and the efficiency of electrolysis will increase.

5.2.3 Comparison of current voltage behaviour over solar module by different distance of lamp and over electrolysis.

Objective: To compare the characteristics of current voltage behaviour over solar module by different distance of lamp and over electrolysis.

Methods:

1. Longer distances of the solar module are recorded compared to experiment 5.2.1 (repeat the same experiment but in different distances).
2. The characteristic of the electrolysis is recorded using instruction in experiment 5.2.2.

Measurements and analysis:

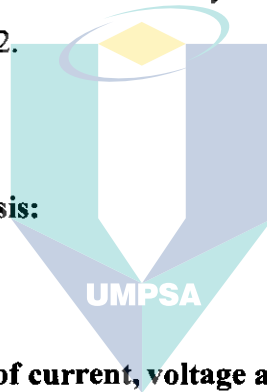


Table 5.3: Measurement of current, voltage and power in different resistance for distance of lamp = 20 cm.

R	U(V)	I(mA)	P(mW)
0	0.01	175	1.75
4	0.16	168	26.88
10	1.12	148	165.76
15	1.60	142	227.20
20	2.28	133	303.24
30	2.77	100	277.00
40	2.84	74	210.16
50	2.90	57	165.30
150	2.98	20	59.60
250	3.00	12	36.00
350	3.02	8	24.16

Table 5.4: Measurement of current, voltage and power in different resistance for distance of lamp = 15 cm.

R	U(V)	I(mA)	P(mW)
0	0.01	204	2.04
4	0.01	204	2.04
10	1.24	189	234.36
15	1.99	179	356.21
20	2.67	154	411.18
30	2.79	103	287.37
40	2.84	73	207.32
50	2.87	58	166.46
150	2.92	20	58.40
250	2.94	12	35.28
350	2.94	8	23.52

Table 5.5: Measurement of current, voltage and power in different resistance for distance of lamp = 10 cm.

R	U(V)	I(mA)	P(mW)
0	0.01	242	2.42
4	0.01	242	2.42
10	1.58	223	352.34
15	2.42	211	510.62
20	2.76	162	447.12
30	2.85	104	296.40
40	2.89	76	219.64
50	2.91	59	171.69
150	2.95	20	59.00
250	2.95	12	35.40
350	2.95	8	23.60

Figure 5.8: Comparison of current voltage behaviour over solar module by different distances.

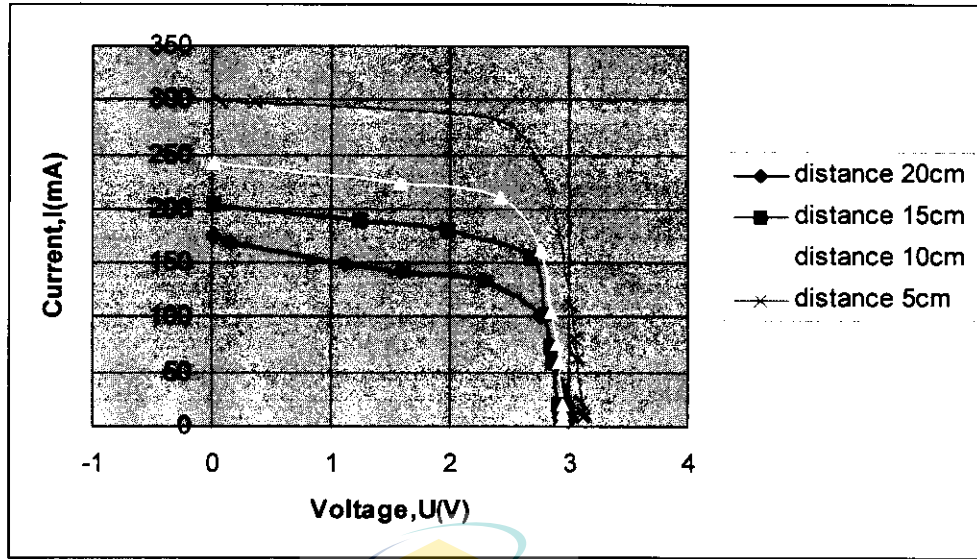


Figure 5.9: Comparison of maximum power over solar module by different distances.

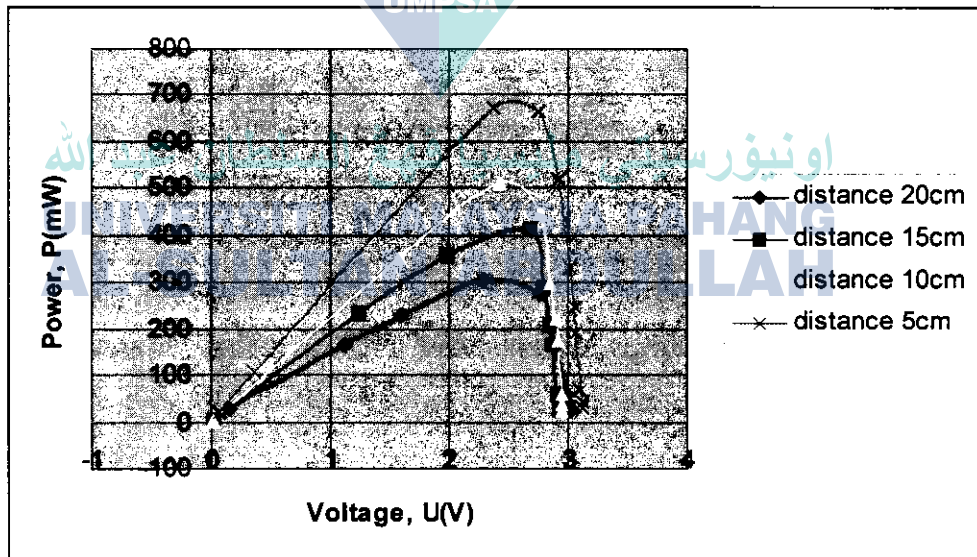
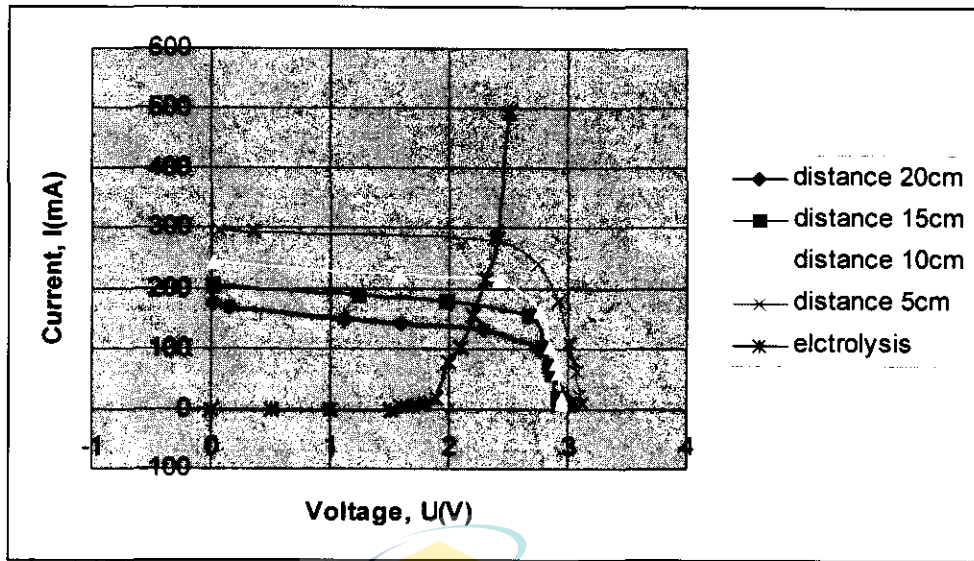


Figure 5.10: Comparison of current voltage behaviour in different distance over solar module and electrolysis.



Observation:

From the graphical representations in Figure 5.8, Figure 5.9 and Figure 5.10 can be recognised that the solar module does not match the consumer's needs, but it is different for electrolysis. The power reception of electrolysis lies before the point of maximum power of the solar module. However, this situation depends on different cases, in which the electrolysis lies before the MPP. Since the power reception of the electrolysis may lay before the MPP solar modules, the fluctuations in the electrolysis will occur. This may lead to a very bad customisation.

From the graphical representations, it is also recognised that the lamp distance has no influence on the optimal customisation on the solar model. Practically, different types of the sun beam or wave intensity has no influence on the adjustment or adoption of the electrolysis. But, the power reception of the consumer depends on the size and the number of the solar cells. An optimal solar module may have 5 silicon solar cells.

5.2.4 Faradays Law.

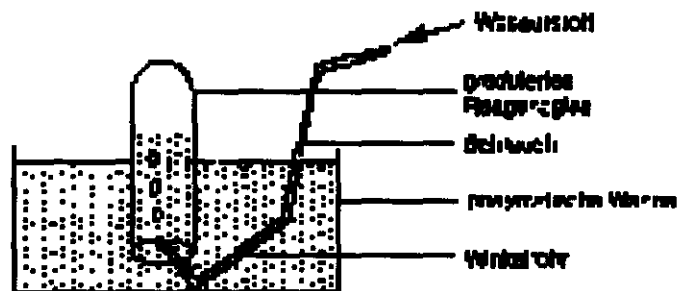
Objective: To study and prove the Faradays Law.

Methods:

1. The apparatus is set up according to Figure 5.11.
2. The hydrogen is allowed to flow carefully into the flexible tube.
 - The appropriate reading of hydrogen will be shown as a result of displacement current in reagent tube. (See figure 5.11).
3. The power supply is set to constant current (= 300mA) and the volume of the hydrogen is measured with different time (from 60s – 210s, 30s intervals).
4. The time is set to constant $t > 180s$. Measure the volume of the hydrogen is measured with different current. (From 100mA – 600mA, 100mA intervals).

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Figure 5.11: Schematic representations for Faradays Law experiment.



Measurements and analysis:

Table 5.6: Measurement volume of hydrogen in constant current and different time frame.

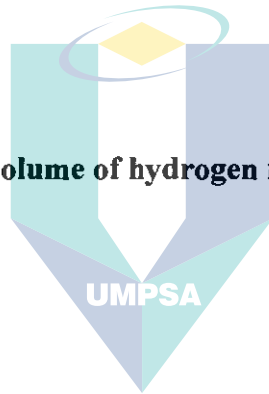
t(s)	VH ₂ (ml)
60	2.2
90	3.2
120	4.8
150	5.8
180	7.4
210	8.6

I = 320mA = constant

Table 5.7: Measurement volume of hydrogen in constant time and different current.

I(mA)	VH ₂ (ml)
400	9.00
450	10.00
500	11.50
550	12.75
600	14.50

t = 180s = constant



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Figure 5.12: The volume of hydrogen in specific time.

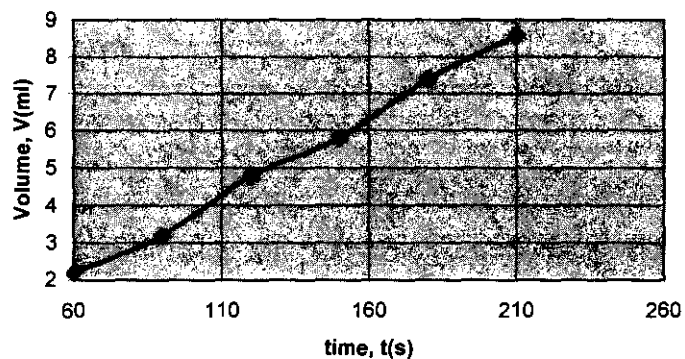
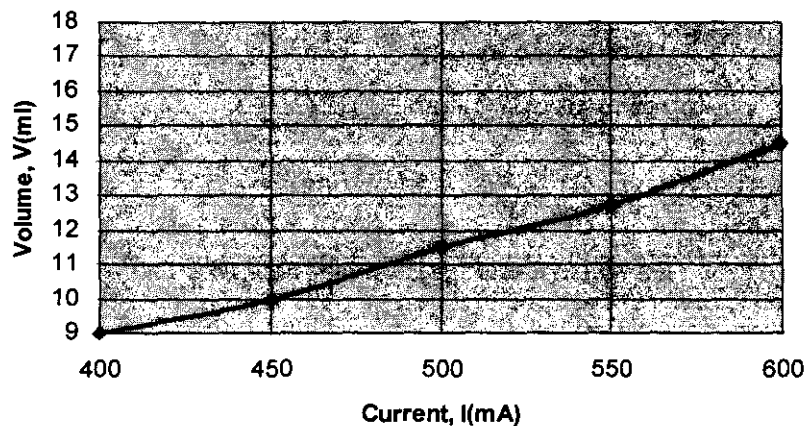


Figure 5.13: The volume of hydrogen in specific current.



The derivation of 1st Faradays Law.

From Figure 5.12, we could recognise that the volume of hydrogen is proportional to the time (when current is constant);

$$\text{Volume of hydrogen, } V_{H_2} \propto \text{time, } t$$

From Figure 5.13, we could see that the volume of hydrogen is proportional to current (when time is constant);

$$\text{Volume of hydrogen (} V_{H_2} \text{)} \propto \text{current (} I \text{)}$$

When volume of hydrogen, $(V_{H_2}) \propto$ time (t) and volume of hydrogen $(V_{H_2}) \propto$ current (I) , so;

volume of hydrogen $(V_{H_2}) \propto$ current $(I) \times$ time (t) and assume current $(I) \times$ time $(t) =$ electrical charge (Q)

Then we get;

$$\text{Volume of hydrogen (} V_{H_2} \text{)} \propto \text{electrical charge (} Q \text{)}$$

The relationship for molar volume, volume of hydrogen, $V_{H_2} = n \cdot V_{H_{2m}}$,

n = amount of material

$V_{H_{2m}}$ = molar volume of hydrogen

At the end we can conclude that the 1st Faradays law as;

Amount of material, $n \propto$ electrical charge, Q

In other words, we can state the first Faradays Law of electrolysis, as “The amount of any substance deposited, evolved or dissolved at an electrode is directly proportional to the amount of electrical charge passing through the circuit”.

The derivation of 2nd Faradays Law.

From this experiment we set the value of, current, $I = 320\text{mA} = 0.32 \text{ A}$, time, $t = 180\text{s}$ and the volume of hydrogen, $V_{H_2} = 7.4\text{ml}$. Let the separation charge, Q to be calculated and the relationship of separation amount of substances to be placed.

Electrical charge (Q) = current (I)*time (t)

$$Q = 0.32 \text{ A} \cdot 180\text{s}$$

$$Q = 57.6 \text{ As} = 57.6 \text{ C}$$

For 57.6 C of electric charge, Q , 7.4ml of hydrogen is separated. For separation from 1 mol hydrogen we need the molar charge, Q_m ;

$$Q_m = Q / n, \text{ where } n = V_{H_2}/V_{H_{2m}}$$

$$Q_m = Q \cdot (V_{H_{2m}}/V_{H_2}), \text{ where } V_{H_{2m}} = 24 \text{ l mol}^{-1} (20^\circ\text{C}; \text{ Normal pressure})$$

$$Q_m (H_2) = 57.6 \text{ C} \cdot 24 \text{ l mol}^{-1} / 7.4 \cdot 10^{-3} \text{ l}$$

$$Q_m (H_2) = 186 \text{ 810 C mol}^{-1} \text{ (from experiment)}$$

The theory has stated, to separate 1 mol hydrogen, 96484C charge is needed. The electrical charge $Q_m = 96484 \text{ C mol}^{-1}$ is called Faraday constant (F), where;

$$\text{Electrical charge, } Q = z \cdot F$$

The value of z is the number of electron that has changed due to separation of particle at the electrode. From that,

$$Q_m (\text{H}_2) = 2 \cdot F = 2 \cdot 96484 \text{ C mol}^{-1}$$

$$Q_m (\text{H}_2) = 192\,968 \text{ C mol}^{-1} \text{ (from theory)}$$

Comparing the value from theory and experiment, there is only a slight difference. The relationships of electrical charge, Q and amount of material, n proved the 2nd Faradays Law as;

$$Q = n \cdot z \cdot F \text{ or } I \cdot t = n \cdot z \cdot F$$

In other words, we can state that the second faradays law of electrolysis as “The mass of different substances produced by the same quantity of electricity are directly proportional to the molar masses of the substances concerned and inversely proportional to the number of electrons in the relevant half reaction.

5.2.5 Faradays and the energy efficiency of electrolysis

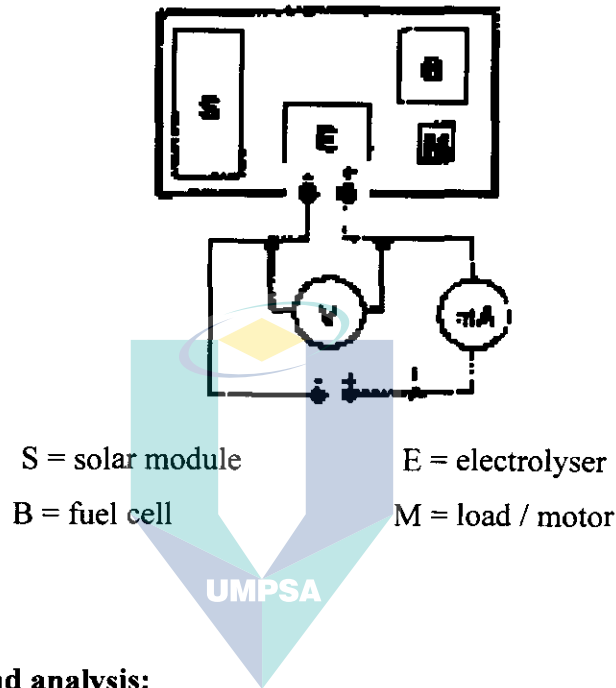
Objective: To study and calculate the efficiency of energy of electrolysis.

Methods:

1. The apparatus is set up according to Figure 5.14.
2. The hydrogen is allowed to flow carefully into the flexible tube.
 - the appropriate reading of hydrogen will be shown as a result of gas displacement in Reagent Tube (see Figure 5.11).
3. The power supply is set to constant current (between 300mA to 600mA) and the volume of the hydrogen is measured in particular time. Three

measurements are made with a same time ($t = 210s$). The values of hydrogen volumes are taken for calculation.

Figure 5.14: Schematic connections to investigate the Faradays law and the energy efficiency of electrolysis.



Measurements and analysis:

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Table 5.8: Measurement volume of hydrogen in specific time, current and voltage.

t(s)	210
U(V)	2.01
I(mA)	320
V ₁ (ml)	8.50
V ₂ (ml)	8.30
V ₃ (ml)	8.40
V _{average} (ml)	8.40

The calculation of faraday – Efficiency of electrolysis

The efficiency of electrolysis can be identified from particular experiment and theoretical values of hydrogen volume;

Efficiency of electrolysis, $\eta = (\text{Volume of hydrogen, } V_{H_2} \text{ from experiment}) / (\text{Volume of hydrogen, } V_{H_2} \text{ from theory})$.

From the 2nd faradays law, we can derive that:

$$I \cdot t = n \cdot z \cdot F; \quad n = V_{H_2} / V_{H_{2m}}$$

$$V_{H_2} \text{ (from theory)} = (I \cdot t) \cdot (V_{H_{2m}} / z \cdot F)$$

The efficiency should lay nearly 100%.

From experiment;

$$V_{H_{2m}} = 24 \text{ l mol}^{-1} \text{ (at normal pressure, } 20^\circ\text{C)}$$

$$t = 210\text{s}$$

$$U = 2.01\text{V}$$

$$I = 320\text{mA}$$

$$V_1 = 8.5\text{ml}$$

$$V_2 = 8.3\text{ml}$$

$$V_3 = 8.4\text{ml}$$

$$V_{H_2 \text{ average}} = 8.4\text{ml}$$

$$V_{H_2} \text{ theory} = (I \cdot t) \cdot (V_{H_{2m}} / z \cdot F)$$

$$V_{H_2} \text{ theory} = (320\text{mA} \cdot 210\text{s}) \cdot (24 \text{ l mol}^{-1} / 2 \cdot 96484 \text{ C mol}^{-1})$$

$$V_{H_2} \text{ theory} = 8.36\text{ml} \approx 8.4\text{ml}$$

$$\text{So, } \eta = (V_{H_2} \text{ experiment} / V_{H_2} \text{ theory}) \cdot 100\%$$

$$\eta = (8.4 \text{ ml} / 8.36 \text{ ml}) \cdot 100\%$$

$$\eta \approx 100\%$$

The faraday state that the efficiency of electrolysis can be expressed as how much current that has been used for the reaction. In technical electrolysis, the faraday efficiency must be 1 (100%). If the efficiency is smaller than 100%, the side reaction system would be expired. Corrosion is the one of the disadvantages, that causes the life duration of electrolysis become shorter and needs higher energy.

The calculation of energy efficiency of electrolysis

The energy efficiency of electrolysis is the result of behaviour from the amount energy from hydrogen and the electrical energy that is needed.

η = amount of energy of hydrogen / electrical energy

$$\eta = H_{\text{OH}_2} * V_{\text{H}_2 \text{ experiment}} / U * I * t$$

Under the calorific value we can understand, that the behaviour of the free burning warm energy for volume of the gas is in normal condition. The upper calorific value would be given out, when the burning water is in liquid condition. The upper calorific value of hydrogen stated 12770 kJm^{-3} at 0°C and 11920 kJm^{-3} at 20°C .

From the experiment, the efficiency of energy state;

$$\eta = 11970 \text{ kJm}^{-3} * 8.4 \text{ ml} / 2.01 \text{ V} * 320 \text{ mA} * 210 \text{ s}$$

$$\eta = 0.74$$

Unit:

$\text{kJ} * \text{ml}$	1 mA	10^3 J	1 VAs	1 m^3
$\text{m}^3 * \text{V} * \text{mA} * \text{s}$	1 A	1 kJ	1 J	10^6 ml

The energy efficiency is dependent from voltage. It technical means, the increment of the voltage to produce the hydrogen will cause the energy efficiency to decrease. So, in practical we must find the optimal point of the electrolysis process. The energy efficiency must be high, because the electrical energy is expensive nowadays. The technical system can reach till 90% of energy efficiency with high performance.

5.2.6 Characteristic and the efficiency of fuel cells.

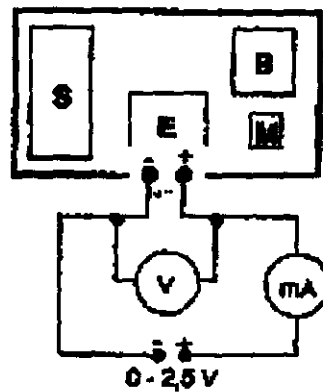
Objective: To study the characteristic of fuel cell and the efficiency.

Methods:

* The Hydro-Genius Teach hydrogen fuel cell should be in operation approx. 10 minutes for the characteristic of the photo to take place.

1. Apparatus is assembled as Figure 5.16.
2. The gas supply to tubes is checked to ensure it is attached correctly at the hydrogen fuel cell.
3. The power supply at the electrolyser is adjusted to get the constant current (between 300 and 350 mA).
4. The potentiometer is varied and the respective value for voltage and current intensity is measured at various resistances.
5. The potentiometer is changed with electromotor of Hydro-Genius Teach as a load. The voltage and current intensity is measured when the engine runs.

Figure 5.15: Schematic connection for determining fuel cell characteristic and efficiency.



S = solar module

E = electrolyser

B = fuel cell

M = load / motor

Measurements and analysis:

Table 5.9: Measurement of current, voltage and power in different resistance in fuel cells with electrolyser current = 520mA.

$I_{\text{electrolyser}} = 520\text{mA}$ (pure O_2)

R(ohm)	U(V)	I(mA)	P(mW)
600	0.98	0	0
300	0.91	20	18.2
100	0.89	40	35.6
70	0.87	60	52.2
40	0.86	80	68.8
10	0.85	100	85.0
8	0.84	120	100.8
6	0.83	140	116.2
4	0.80	230	184.0
motor	0.90	60	54.0

Table 5.10: Measurement of current, voltage and power in different resistance in fuel cells with electrolyser current = 320mA.

$I_{\text{electrolyser}} = 320\text{mA}$ (pure O_2)

R(ohm)	U(V)	I(mA)	P(mW)
600	0.96	0	0
300	0.87	20	17.4
100	0.84	40	33.6
70	0.82	60	49.2
40	0.81	80	64.8
10	0.80	100	80.0
8	0.79	120	94.8

6	0.78	140	109.2
4	0.75	230	172.5
motor	0.83	55	45.7

Table 5.11: Measurement of current, voltage and power in different resistance in fuel cells with electrolyser current = 320mA (O₂ from the air).

I, electrolyser = 320mA (O₂ from air)

R(ohm)	U(V)	I(mA)	P(mW)
600	0.94	0	0.0
300	0.80	15	12.0
100	0.78	25	19.5
70	0.77	28	21.6
40	0.75	30	22.5
10	0.64	83	53.1
4	0.31	250	77.5
Motor	0.58	48	27.8

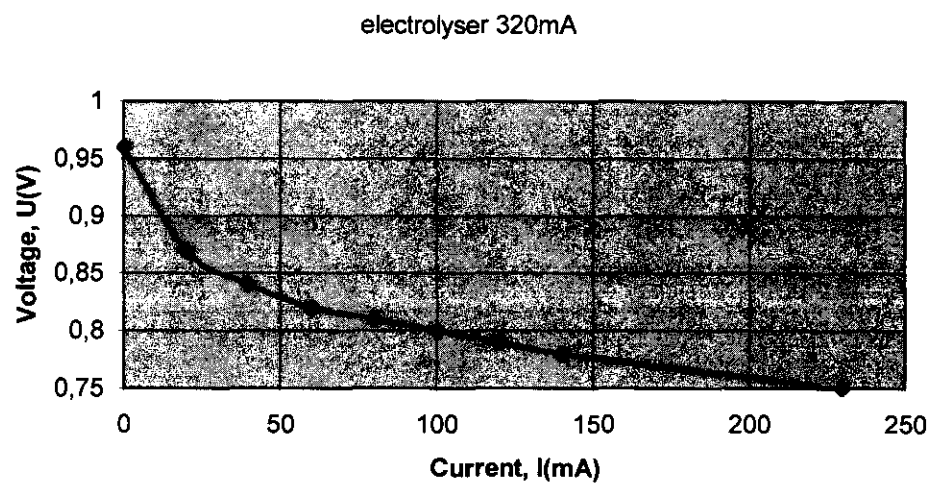
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Observation and Evaluation:

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During recording the characteristic, fluctuations may appear. It is important that the hydrogen fuel cell is operating at least 10 minutes before the beginning of the experiment. The measurements have to be done carefully to obtain exact values.

Figure 5.16: Current and voltage behaviour in fuel cell for electrolyser current 320mA.



Fuel cell voltage efficiency for electrolyser current = 320mA,

$$\begin{aligned}
 \eta &= (\text{Actual voltage} / \text{Theoretical voltage}) * 100\% \\
 &= (-nFE_K / \Delta G) * 100\% \\
 &= (E_K / E_O) * 100\% \\
 &= (0.96 / 1.23) * 100\%
 \end{aligned}$$

$$= 78.05\%$$

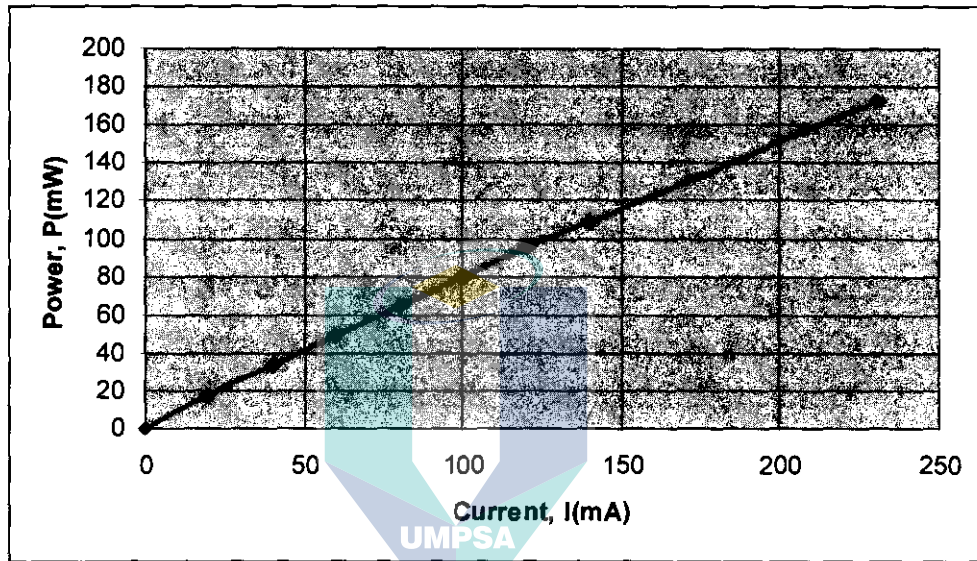
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To understand the characteristic of the hydrogen fuel cell one should have known the characteristic of the electrolysis (experiment 3). The process in the hydrogen fuel cell is the reversal to the electrolysis. During the electrolysis of water at least 1.23 volts must be applied. For the decomposition of water at the beginning and as a rule, the voltage is even higher (overload).

For the same reasons, lower voltage will be produced by a hydrogen fuel cell (same as galvanic cell). The characteristic of the electrodes material (catalysis), the internal resistance, the temperature and also the quantity of the hydrogen and oxygen will be influenced. For none or at very low current when the voltage of the hydrogen fuel cell is between 0.9 – 1.0 V, one describes this voltage as open circuit voltage (in

analogy to the battery). It is strongly dependent on the set and purity of the gasses brought in at the hydrogen fuel cell. The more one takes current from the hydrogen fuel cell, the smaller the voltage becomes. An exponential increase of the current arises in the context of reduction of the voltage.

Figure 5.17: Characteristic of power in fuel cell for electrolyser current 320mA.



If one writes down the operating point of the electromotor on the P - I diagram it can be then seen that the engine doesn't run in the optimal point i.e. hydrogen is lost here. Well, more performance can be taken from the hydrogen fuel cell.

In the practice one endeavours to operate the hydrogen fuel cell at higher current (that is high power). However, the degree of effectiveness of a hydrogen fuel cell relieves at high current. Simultaneously, so that also here the task is to find an optimal operating point (high degree of effectiveness, high performance).

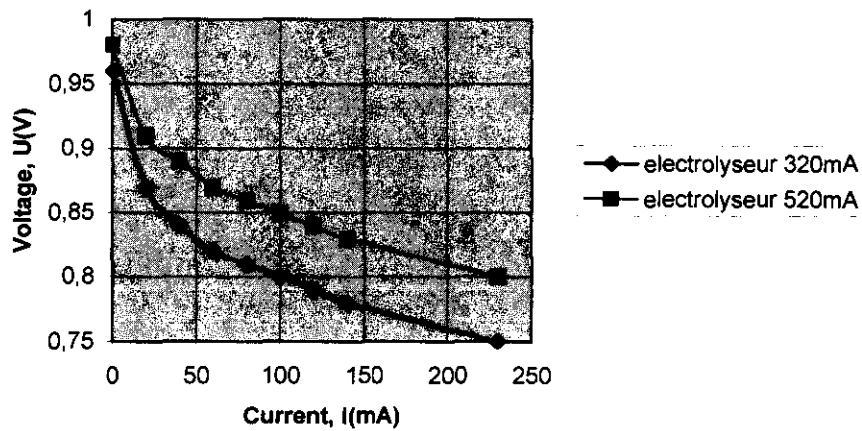
Experiment variations:

One plot the graphic of the characteristics of the hydrogen fuel cell, i.e. at various gas supplies and one gets the following picture for various electrolyzers current.

It can be recognised from the comparison of both characteristics that the hydrogen fuel cell delivers more current at the same voltage of more gas per time unit. It is possible furthermore to take a characteristic of the hydrogen fuel cell at which only the oxygen in the air is involved in the reaction in the hydrogen fuel cell. One carefully pulls the tube for the oxygen supply at the hydrogen fuel cell and takes the appropriate guidance. It has to be made sure that the oxygen, which still is in the hydrogen fuel cell, must be used up before recording the characteristic.

By small overloads (near the quiescent voltage / open circuit voltage) the current rises exponentially. Catalytic events have the decisive influence at the electrodes here. The antransport and the concentration of the gasses at great overloads are primarily decisive for the height of the current and can lead to great deviations in the height of the current.

Figure 5.18: Current voltage behaviour in fuel cell for electrolyser current 320mA and 520mA.

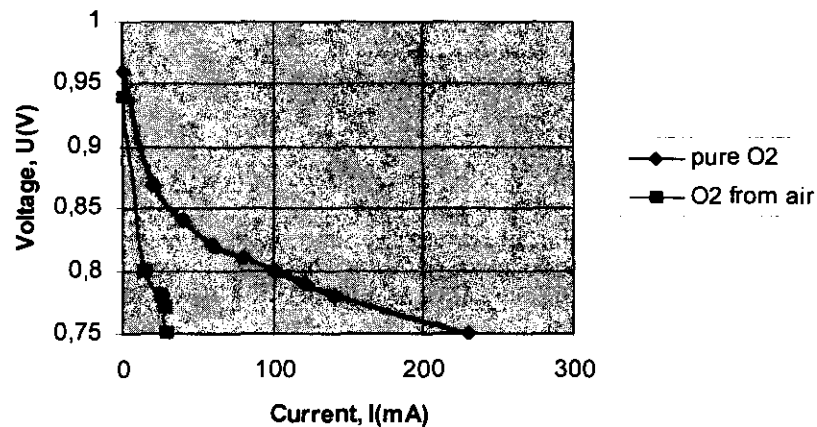


Fuel cell voltage efficiency for electrolyser current = 520mA,

$$\begin{aligned}
 \eta &= (\text{Actual voltage} / \text{Theoretical voltage}) * 100\% \\
 &= (-nFE_K / \Delta G) * 100\% \\
 &= (E_K / E_0) * 100\% \\
 &= (0.98 / 1.23) * 100\% \\
 &= 79.67\%
 \end{aligned}$$

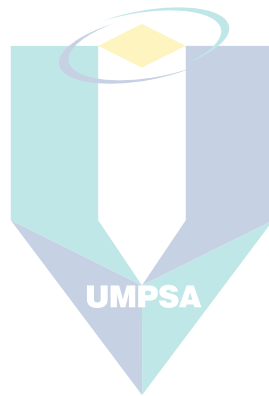
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Figure 5.19: Comparison of current voltage behaviour in fuel cell between in pure oxygen and oxygen form the air.



Fuel cell voltage efficiency for oxygen from the air,

$$\begin{aligned}\eta &= (\text{Actual voltage} / \text{Theoretical voltage}) * 100\% \\ &= (- nFE_K / \Delta G) * 100\% \\ &= (E_K / E_O) * 100\% \\ &= (0.94 / 1.23) * 100\% \\ &= 76.42 \%\end{aligned}$$



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CHAPTER VI

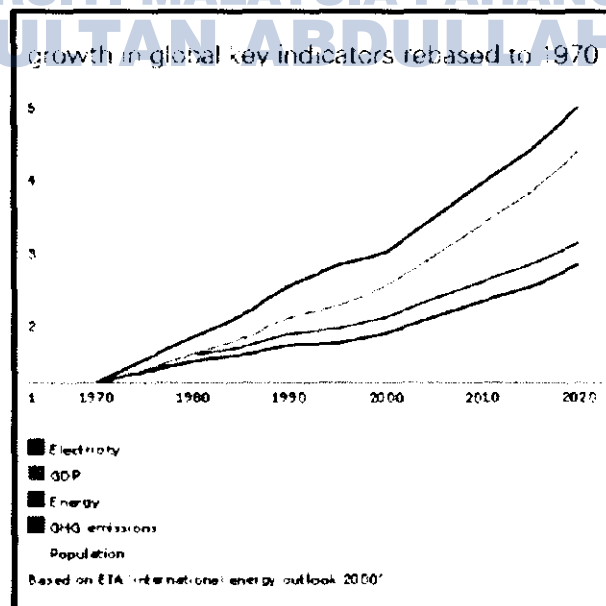
DISCUSSION AND CONCLUSION

6.1 Discussion

Energy fuelled the industrial revolution and has continued to drive economic development. The graph below shows the close link between economic prosperity and energy use especially electricity. The graph also shows how greenhouse gas emissions have followed the curve of energy use, and are expected to continue to rise even without stringent action to limit emissions.

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Figure 6.1: Growth in Global Key Indicators Rebased to 1970.



Fuelling social and economic development around the world without harming the environment is the challenge all face in the 21st century. Many believe that it is essential to stabilize the amount of greenhouse gases in the atmosphere while still providing the energy that is needed for development.

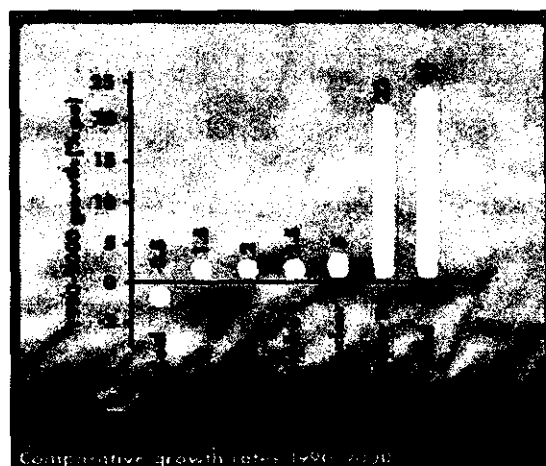
Clean, renewable energy is the ultimate goal. But this is a long way off as the graph below shows. Hydrocarbons are expected to remain as the dominant source of energy for several decades.

All the signs are that the world's demand for energy will continue to increase in the future. As populations increase and living standards improve around the globe, more and more energy will have to be generated unless substantial improvements in energy efficiency are achieved.

As we see in the figure below renewable energy had the biggest growth in the last decade. This means that the energy mix in the next decades may change to more environmental friendly sources of energy.

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Figure 6.2: Growth Rates of Energy Sources

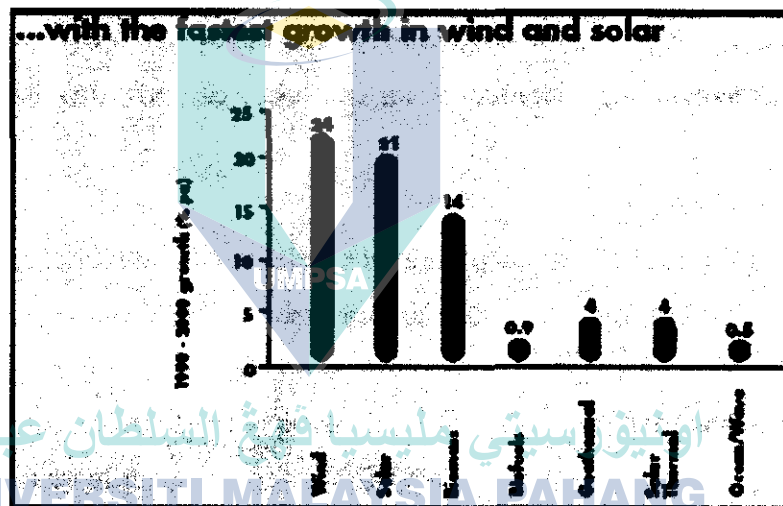


The greatest challenge will be to replace all conventional technologies and fossil fuels with renewable that could have the ability to meet energy needs of the entire world.

Exploring opportunities in renewable energy

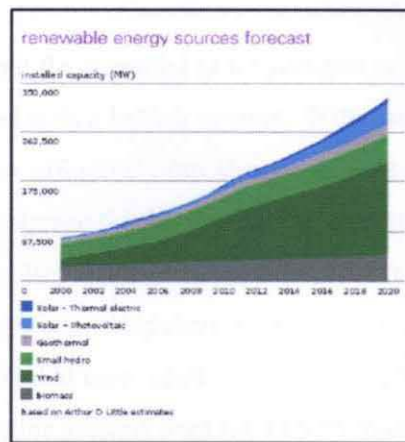
As mentioned before “Renewable energy markets are expanding rapidly, with an annual growth rate of more that 20%.”

Figure 6.3: Growth Rate of Renewable Energy Sources



It is always necessary to look in to the future. Therefore a major part of investment should go in to developing other forms of energy.

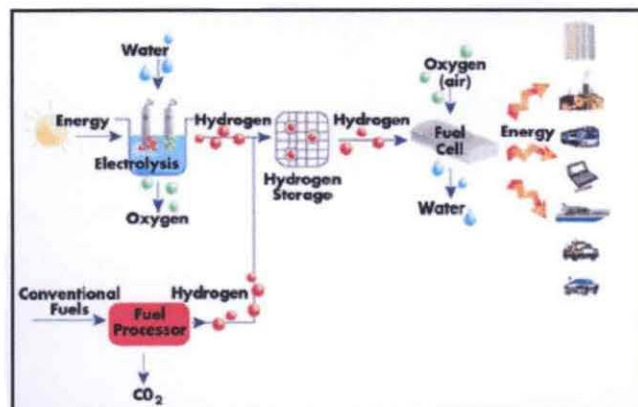
Figure 6.4: Renewable Energy Sources Forecast



Other forms of technology using new fuels have to be developed with considering the future in mind. Both the society and the companies must support projects to develop hydrogen systems and technological improvements in the storage of hydrogen, which could help to make it a more commercially attractive fuel.

In the long term, two potentially transforming energy technologies are: Solar photovoltaic, which offer the possibility of abundant direct and widely distributed energy, and Hydrogen fuel cells, which offer the possibility of high performance and clean energy from a variety of fuels.

Figure 6.5: Production and Use of Hydrogen



6.2 Conclusion

This paper has illustrated the potential of a hydrogen and fuel cell storage system for electricity compared with a battery system. With this analysis we saw that a system like this not only work effectively but also to provide in the whole world a more environmental friendly solution for the future. The difference between the battery and the fuel cell system laid in the environmental concerns of the two systems. We concluded that the fuel cell system is a more environmental system than the battery because the material that uses together with the high reliability and effective operation gives a greater lifetime than the battery system does.

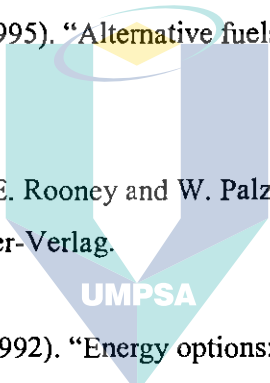
As our demand for electrical power grows, it becomes increasingly urgent to find new ways of meeting it both responsibly and safely.

In the past, the limiting factors of renewable energy have been the storage and transport of that energy. With the use of fuel cells and hydrogen technology, electrical power from renewable energy sources can be delivered where and when required, cleanly, efficiently and sustainably.

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CHAPTER VII

REFERENCES

1. Rozmeen Tambe and Hampton. (2003). "Renewable energy." Key Note Ltd.
2. Robert Hill, Phil O'Keefe and Colin Snape. (1995). "The future of energy use." London: Earthscan.
3. Frances S. Sterrett. (1995). "Alternative fuels and the environment." London: Boca Raton, Fla.
4. G. T. Wrixon, A.-M. E. Rooney and W. Palz. (1993). "Renewable energy-2000." Berlin: Springer-Verlag.
5. Drummond Hislop. (1992). "Energy options: an introduction to small-scale renewable energy technologies." London: Intermediate Technology Publications. 

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6. H.W.Pohl. (1995). "Hydrogen and other alternative fuels for air and ground transportation." Chichester: John Wiley & Sons.
7. Charles A. and McAuliffe. (1980). "Hydrogen and energy." London: Macmillan.
8. David Linden and Thomas B. Reddy. (2002). "Handbook of batteries." New York: Mc Graw-Hill.

www.fuelcells.com

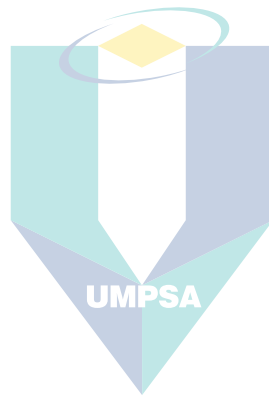
Appendix A

Thermodynamic Properties of Selected Substances For one mole at 298K and 1 atmosphere pressure

Substance (form)	Enthalpy $\Delta_f H$ (kJ)	Gibbs $\Delta_f G$ (kJ)	Entropy (J/ K)	Specific heat C_p (J/K)	Volume V (cm ³)
Al (s)	0	0	28.33	24.35	9.99
Al ₂ SiO ₅ (kyanite)	-2594.29	-2443.88	83.81	121.71	44.09
Al ₂ SiO ₅ (andalusite)	-2590.27	-2442.66	93.22	122.72	51.53
Al ₂ SiO ₅ (sillimanite)	-2587.76	-2440.99	96.11	124.52	49.90
Ar (g)	0	0	154.84	20.79	...
C (graphite)	0	0	5.74	8.53	5.30
C (diamond)	1.895	2.900	2.38	6.11	3.42
CH ₄ (g)	-74.81	-50.72	186.26	35.31	...
C ₂ H ₆ (g)	-84.68	-32.82	229.60	52.63	...
C ₃ H ₈ (g)	-103.85	-23.49	269.91	73.5	...
C ₂ H ₅ OH (l)	-277.69	-174.78	160.7	111.46	58.4
C ₆ H ₁₂ O ₆ (glucose)	-1268	-910	212	115	...
CO (g)	-110.53	-137.17	197.67	29.14	...
CO ₂ (g)	-393.51	-394.36	213.74	37.11	...
H ₂ CO ₃ (aq)	-699.65	-623.08	187.4
HCO ₃ ⁻ (aq)	-691.99	-586.77	91.2
Ca ²⁺ (aq)	-542.83	-553.58	-53.1
CaCO ₃ (calcite)	-1206.9	-1128.8	92.9	81.88	36.93
CaCO ₃ (aragonite)	-1207.1	-1127.8	88.7	81.25	34.15
CaCl ₂ (s)	-795.8	-748.1	104.6	72.59	51.6

Cl ₂ (g)	0	0	223.07	33.91	...
Cl ⁻ (aq)	-167.16	-131.23	56.5	-136.4	17.3
Cu (s)	0	0	33.150	24.44	7.12
Fe (s)	0	0	27.28	25.10	7.11
H ₂ (g)	0	0	130.68	28.82	...
H (g)	217.97	203.25	114.71	20.78	...
H ⁺ (aq)	0	0	0	0	...
H ₂ O (l)	-285.83	-237.13	69.91	75.29	18.068
H ₂ O (g)	-241.82	-228.57	188.83	33.58	...
He (g)	0	0	126.15	20.79	...
Hg (l)	0	0	76.02	27.98	14.81
N ₂ (g)	0	0	191.61	29.12	...
NH ₃ (g)	-46.11	-16.45	192.45	35.06	...
Na ⁺ (aq)	-240.12	-261.91	59.0	46.4	-1.2
NaCl (s)	-411.15	-384.14	72.13	50.50	27.01
NaAlSi ₃ O ₈ (albite)	-3935.1	-3711.5	207.40	205.10	100.07
NaAlSi ₂ O ₆ (jadeite)	-3030.9	-2852.1	133.5	160.0	60.40
Ne (g)	0	0	146.33	20.79	...
O ₂ (g)	0	0	205.14	29.38	...
O ₂ (aq)	-11.7	16.4	110.9
OH ⁻ (aq)	-229.99	-157.24	-10.75	-148.5	...
Pb (s)	0	0	64.81	26.44	18.3
PbO ₂ (s)	-277.4	-217.33	68.6	64.64	...
PbSO ₄ (s)	-920.0	-813.0	148.5	103.2	...
SO ₄ ²⁻ (aq)	-909.27	-744.53	20.1	-293	...
HSO ₄ ⁻ (aq)	-887.34	-755.91	131.8	-84	...

SiO ₂ (α quartz)	-910.94	-856.64	41.84	44.43	22.69
H ₄ SiO ₄ (aq)	-1449.36	-1307.67	215.13	468.98	...



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APPENDIX B

Figure of Hydro-Genius Teach Experiment set.

