Solar-driven hydrogen generation for a fuel cell power plant

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Declaration

I, Amoo Akinlawon Olubukunmi declare that this research is my own, unaided work. It is being submitted for the requirements for the Magister Technologiae: Engineering: Electrical to the Department: Electronic Engineering at the Vaal University of Technology, Vanderbijlpark. It has not been submitted before for any assessment to any educational institution.

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Amoo Akinlawon Olubukunmi

Date: ....

Acknowledgements

I hereby wish to express my gratitude to the following individuals who enabled this document to be completed successfully:

Dedication

To my Heavenly Father, the Supreme Intelligence and my God for His faithfulness and wonderful acts in my life. Blessed be your name forever.

To my father, for his academic leadership and for directing my steps through positive discipline.

 To my mother, my spiritual backbone, my one and only, my ever-present friend for being there for me through thick and thin. I am grateful for your unchanging love and support.

Abstract

There are a number of ways to produce hydrogen using solar energy as the primary source. Water electrolysis, which uses solar electrical energy, is the rapidly available process. Hydrogen can be produced by using solar electric energy from photovoltaic (PV) modules for the electrolysis of water without emitting carbon dioxide or requiring fossil fuels.

Solar hydrogen energy systems are considered one of the cleanest hydrogen production technologies, where the hydrogen is obtained from sunlight by directly connecting the photovoltaic modules to the hydrogen generator.

This dissertation presents a designed solar photovoltaic electrolyser hydrogen production and storage system for various applications such as in the power generation and telecommunications industries.

Various experiments were performed on the designed system to ensure its reliability and conformity with theoretical findings. The purity of the generated hydrogen was determined. The relationship between the amount of solar irradiance reaching the surface of the PV panel, the PV panel surface temperature, the PV panel tilt angle and the maximum power point voltage and current of the PV panel array were also considered. The effect of dust on the panel voltage and current outputs was also determined.

Finally, the factors to consider when designing a solar photovoltaic electrolyser hydrogen system (based on this study) were enumerated.

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Glossary of abbreviations and definitions

A

AC: Alternating current

Array: A group of solar modules

B

Biofuel: Liquid fuel made from biomass, usually from plant matter

E

Electrolyser: an apparatus in which electrolysis is carried out, consisting of one or many electrolytic cells

Electrometer: An instrument for measuring voltage

F

Fermi level: A hypothetical level of potential energy for an electron inside a crystalline solid

FF: Fill factor

G

Geothermal: Of, relating to, or produced by the internal heat of the earth

GW: Gigawatt

H

HHV: Higher heating value

HOGEN: Hydrogen generator

Hydroelectric: Generating electricity by conversion of the energy of running water

I

Isotope: Each of two or more forms of the same element that contain equal numbers of protons but different numbers of neutrons in their nuclei

L

LCD: Liquid crystal display

LHV: Lower heating value

M

Module: A connection of solar cells in series and parallel

MPa: Megapascal

MPPT: Maximum power point tracker

MW: Megawatt

P

PEC: Photoelectrochemical cell

Photocurrent: An electric current produced by illumination of a photoelectric material

Photon: A particle representing a quantum of light or other electromagnetic radiation

PSP: Precision spectral pyranometer

Pyranometer: A type of instrument used to measure broadband solar irradiance on a planar surface

R

RMS: Root mean square

RTD: Resistance temperature detector

S

Solar irradiance: The amount of solar energy that arrives at a specific area at a specific time

STC: Standard temperature conditions

STP: Standard temperature and pressure

T

TCD: Thermal conductivity detector

U

USB: Universal serial bus

UV: Ultraviolet

Chapter 1   Introduction

1.1   Background

A fuel cell is an electrochemical energy conversion device where the chemical energy contained in hydrogen and oxygen is converted directly into electrical energy, water and heat. It is an electrical cell which unlike storage cells can be continuously fed with a fuel so that the electrical power output is sustained (Counihan 1981:63).

A fuel cell provides a DC voltage that can be used to power motors, lights or other DC electrical appliances. The DC can also be inverted to a more usable AC voltage (Viljoen 2008:2). According to Viljoen (2008:2), a promising application of fuel cells are fuel cell micropower plants generating electric power in the order of a few watts to power mobile devices such as cellphones, cameras and notebooks.

According to Engelbrecht, North and Hadley (2008:1), South Africa's primary fuel source is made up of the following components: coal 74.1%, oil 12%, renewable energy (hydro, biomass, solar and wind) 7.4%, nuclear 4.2%, and gas 2.3%.

Fossil fuels (especially coal) are the major fuel source. However, the use of fossil fuels for energy supply has negative environmental impacts (such as greenhouse emission and air pollution), which must be severely countered and reduced, if not completely resolved (Sayigh 1977: 385-386).

According to Sayigh (1977: 385-386), fossil fuels are finite in quantity and are being depleted at an ever-growing rate, and this raises the question of energy security. For these reasons, research and design is being focused on several alternative means of generating hydrogen for energy supply in fuel cells. He stated that many companies are involved in the research and development of hydrogen fuel cells and this will be a very important area in the near future. The only problem with hydrogen fuel cells is that there is a cost to produce the hydrogen used as fuel. There is however ongoing research towards an alternative, yet cost-effective way of producing hydrogen for use in fuel cells and automobiles. Russell (2007:1-2) explained the term 'alternative energy'

as encompassing a variety of power generation sources. It refers to electrical power derived from 'renewable' resources such as solar or wind energy, as opposed to 'single-use' resources such as coal or uranium. He also differentiated between alternative energy and renewable energy. According to him, alternative energy refers to any form of energy which is an alternative to the traditional fossil fuels of oil, natural gas and coal, while renewable energy are the forms of alternative energy that are renewed by the natural processes of the Earth, such as sunlight from the sun or wind from the air, and so are environmentally friendly.

Solar power arises from the light of the sun, which can be harvested through the use of solar power cells, which are also called photovoltaic cells. Sunlight is easy to harness and is free, but it can be difficult to harness solar power for large scale power plants. However, there are several solar power plant projects in existence. Solar power has a great deal of potential in the field of home electricity generation. Solar power is attractive because sunlight is free and the only cost involved is the cost of solar panels. Solar is also very environmentally friendly, as it produces no pollution or waste by-product, and it is therefore essential for a greener future (Russell 2007:2).

Solar panels come in various sizes and can be used on a small scale by mounting solar panels on a house for home electricity production, or they can be used on a large scale for electricity production. Solar is most commonly used for on-site local electricity production, by adding solar panels to the roofs of homes or commercial buildings. It is often used by consumers who want to help protect the environment, and also plays a vital role in supplying power to buildings that cannot easily access power lines. The three common solar power technologies are silicon, thin-film, and solar thermal (Russell 2007:2).

Wind power is also a very attractive field. Wind technology has grown in scope, and in various places wind is becoming a feasible source of energy. Wind has a lot of potential and investors should keep an eye on it. Wind is vulnerable to weather conditions, but in certain locations, mainly in coastal offshore areas and at high altitudes, there is a steady stream of wind. Wind power is harnessed through the use of wind turbines, which are turned by the wind to produce electricity. The technology is not unlike a more modern and sophisticated version of a windmill. Wind power can be used both for electricity production on a large scale with multiple turbines to form what is called a wind farm, or in other words a wind power plant, or, more infrequently, on

a smaller scale for home electricity production. Wind power is the most criticized of all forms of renewable energy, as there is a multi-national anti-wind lobby that accuses wind turbines of being ugly, noisy, interfering with radars and killing birds, all of which are completely unjustified claims (Russell 2007:2).

Geothermal energy is also an exciting new area. Geothermal energy draws heat from the planet's core. Thermal power stations are set up to absorb energy from the planet. The heat from the planet boils a liquid which evaporates to turn turbines, producing the electricity. This technology is feasible because thermal heat is free and the only cost is the station. However, the locations where geothermal heat is easily available are limited and change-based on tectonic movement and the arrangement of the surface of the Earth. Geothermal is renewable and does not pollute, and there are places in many parts of the world that are seeking geothermal power. Geothermal is also very well suited for home heating and cooling, in which pipes are placed underground and a liquid is circulated through them, so that heat from the ground comes up during cold times, and cool from the ground comes up during hot times. Geothermal heating is becoming very popular, and is a cost-effective alternative to oil or gas home heating (Russell 2007:2-3).

A highly developed form of alternative energy is hydroelectric. Hydroelectric power comes from dams which harness the power of rivers. The river water passes through turbines at the base of the dam, turning turbines which produce electricity. There are many dams in existence, and hydroelectric is a highly developed technology. Hydroelectric is a clean, green technology which produces no pollution. Unfortunately, most of the lakes and rivers that could easily be exploited with hydroelectric have been dammed already, so the future of hydroelectric power lies in the development of less appealing sites. There are a number of hydroelectric projects in existence, in Africa, Asia and elsewhere (Russell 2007:3).

Tidal power and wave power are two ocean-based technologies with high potential for providing clean, free energy in the future. Tidal power works when ocean water flows through tidal power stations as the water goes in and out with the tide, turning the turbines and producing electricity. Tidal power is not widely used, but as it develops it could become very promising. There are high potential tidal sites with very strong tides around the world, in Eastern Canada and Scotland among other places. Another renewable energy with high worldwide potential is wave power.

Wave power converts waves into electricity with equipment in the oceans that captures wave movement and converts it into power. There are also efforts to harvest energy from the salt content and temperature of the ocean. The oceans of the world offer a huge possibility for electricity generation projects and most of this potential is so far untapped and waiting to be explored (Russell 2007:3).

Another interesting alternative energy source is the development of biomass technology. Biomass is a term for any kind of organic biological matter that can be converted into energy. Biomass technology is being developed that will enable dung, for example, from cows or pigs, or dead vegetable matter to be converted into energy. The transformation of these common substances, which would otherwise end up as waste, into electricity is an exciting area that has a great deal of potential to produce energy from previously untapped sources without polluting the environment. Biomass is usually either plant matter, from either crops or forest waste, or faecal wastes. A subsection of biomass is biogas, natural gas produced from biological sources (Russell 2007:3).

A similar and very exciting alternative energy area is biofuel. Biofuel is liquid fuel made from biomass, usually from plant matter. Biofuel is an exciting prospect because it will enable farmers to turn excess crops into fuel. The biofuel that is the main focus of research is ethanol, a form of biofuel that can be made from corn or sugarcane. Ethanol can be used to run cars, and there is an increasing interest in the use of ethanol to replace or augment gasoline as a significant source of automotive fuel. Cars must be specially fitted to run on ethanol, but the price is worth it, as ethanol burns more cleanly than gasoline, producing fewer pollutants, and it can be made from domestic crops, reducing dependence on foreign oil. Ethanol from sugarcane already makes up about forty percent of the fuel used by automobiles in Brazil, and this is a huge factor in Brazil's energy independence (Russell 2007:3-4).

Russell (2007:4) explained that ethanol in the United States is made from corn, a plentiful crop in the American Midwest, and the United States government has ethanol initiatives and mandates to promote the use of ethanol. Additionally, there are many American states with their own ethanol initiatives and mandates. Major car companies are building ethanol-powered cars, and gas stations are creating ethanol fuelling stations, and the use of ethanol is definitely on the rise.

Petrol can be combined with ethanol to create gasohol, and a popular form is E85, a blend of eighty-five percent ethanol and fifteen percent petrol. There are also E10 and E15. Cars called 'flex-fuel' cars are available that are flexible in their fuel use, meaning that they are able to run on either gasoline or ethanol. There is a form of ethanol called cellulose ethanol, being developed in research laboratories, which is made from inedible biomass and burns more cleanly than normal ethanol (Russell 2007:4).

Explaining biodiesel which is another form of biofuel, Russell (2007:4) stated that it is a fuel that is like diesel but which is made from biomass. Biodiesel can be used in any engine that runs on diesel, making the switch to biodiesel very easy, and it is widely useful. Biodiesel can be made from waste vegetable oils produces from cooking, and also from palm oil and canola oil, and from jatropha plants. Biofuel is a high potential area as it will have a real effect in reducing our dependence upon foreign oil for petrol consumption, which is a key element in our addiction to oil. As a global demand for oil grows, the use of ethanol and biodiesel will grow as well.

This research is focused on the generation of hydrogen from a renewable energy source for use in fuel cells. The renewable energy source is solar energy, making use of contemporary photovoltaic technology.

It has been widely established that if a convenient way of utilizing solar energy can be found, it could be an answer to the aforementioned problems, since it is almost undepletable and is clean (Sayigh 1977: 385-386).

Almost all the renewable energy sources originate from the sun. The emergence of interest in solar energy utilization started since 1970, principally owing to the then rising cost of energy from the abovementioned conventional sources. Solar radiation is the world's most abundant and permanent energy source. The amount of solar energy received by the surface of the earth per minute is greater than the energy utilization by the entire population in one year. Solar energy is referred to as renewable and/or sustainable energy because it will be available as long as the sun continues to shine (Zekai 2008: 36-37).

Zekai (2008: 41-42) also pointed out that "among the many renewable energy alternatives, solar-hydrogen energy is regarded as the most ideal energy resource that can be exploited in the

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foreseeable future in large quantities. Solar-hydrogen energy does not give rise to acid rain, greenhouse effects, ozone layer depletions, leaks or spillages." Hydrogen is widely regarded as the fuel of the future, and in order to benefit from its unique properties, it must be produced by the use of a renewable source so that there will be no limitation or environmental pollution in the long run.

Hydrogen is found as an interstellar gas and as the chief constituent of main-sequence stars. However on earth it is found as part of molecules of water, methane and organic material, whether fresh or fossilized. Simply put, **hydrogen production is the extraction and isolation of hydrogen in the form of independent molecules, at a purity level required for a particular application** (Sorensen 2005: 5).

Zekai (2008: 42) noted that different methods have been developed by using direct or indirect forms of solar energy for hydrogen production. These methods can be viewed under four different processes, namely:

1. Direct thermal decomposition or thermolysis

2. Thermochemical process

3. Electrolysis

4. Photolysis.

Large-scale hydrogen production has been obtained so far from the water electrolysis

method, which can be used effectively in combination with photovoltaic cells.

Andreas (2005: 47) also noted that photoelectrochemical (PEC) cells illuminated by sunlight have the ability to split water into hydrogen and oxygen. Such cells use photoactive electrodes, immersed in an aqueous electrolyte or water.

Photoelectrochemical devices combine solar PV and electrolysis into a single monolithic device. This, according to Singliar, provides the possibility of higher conversion efficiency and lower cost for solar-driven hydrogen generation from water as compared to standard PV/electrolysis.

These systems offer some flexibility, as the output can be electricity from PV cells or hydrogen from the electrolyser (Singliar 2007: 44).

However, for the purpose of this research work, we shall focus on the electrolytic generation of hydrogen from solar energy using solar-photovoltaic cells.

1.2   Purpose

Fuel cell technology is growing rapidly in southern Africa and with the race to provide the most cost-effective and non-pollutant fuel for fuel cells, the need arises for information dissemination to up-and-coming students eager to be part of this growing technology.

The purpose of this research work is the solar-photovoltaic electrolytic generation of hydrogen, the determination of the purity of the generated hydrogen, the storage of the hydrogen gas, study of the electrical and physical properties and specifications of the different types of commercially available photovoltaic modules in order to determine essential parameters such as the maximum power point voltages and currents of the photovoltaic panels used for the study.

The relationship between the various parameters of the designed system will be compared to check their effects on the system and in order to come up with factors that should be considered when designing an optimized PV-electrolyser hydrogen generation system.

1.3   Problem statement

According to Sayigh (1977: 385-386), all countries want a cheap, abundant and clean supply of energy, since it is vital in the development of industry and in agricultural output. Energy shortage, depletion of fossil fuel sources, increasing pollution and water scarcity are salient world problems needing immediate solutions.

The world has finite size. Its resources, including the fossil fuels (coal, petroleum, and natural gas), are finite in quantity and are being depleted at an ever-growing rate. The fossil fuels have negative effects on the environment. Air pollution is caused mainly by fossil fuels used to obtain

energy for transportation and power stations. To satisfy part of this energy demand, solar energy is seriously being considered. It is almost undepletable and is clean (Sayigh 1977: 385-386).

Hydrogen has been described from previous and current research work as the most electroactive and environmentally clean fuel for all types of fuel cells. This has been widely recognized since the invention of the fuel cell by Sir William Grove in 1839. A simple explanation for this is the fact that hydrogen has exchange current densities for the anodic reaction that are at least three to five orders of magnitude higher than that of any fuel cell at low intermediate temperatures (Supramaniam 2006: 375).

According to Supramaniam (2006: 376), hydrogen is an energy carrier that must be produced from other primary resources. These resources include fossil fuels (natural gas or coal), renewable (biomass, hydropower, wind, and solar), and nuclear power.

Therefore, in the quest to produce hydrogen energy with near zero emission of greenhouse or air pollution, it is imperative to investigate the opportunities offered by solar energy. The photovoltaic-electrolyser generation of hydrogen shall be explored and applied. This will involve a proper and comprehensive study, understanding and application of photovoltaic solar cells.

1.4   Research methodology

The research will commence with an in-depth literature study of photovoltaic solar cells, photovoltaic hydrogen generation and the enumeration of the different types of commercially available photovoltaic panels. This will involve consulting with secondary and primary sources of information such as journals, articles, papers, conference proceedings, thesis, textbooks, as well as the internet and perhaps one or more visits to companies involved in the production of photovoltaic solar cells. This will serve as a platform on which the research work will be built.

The procurement and installation of the photovoltaic solar panels and the necessary laboratory and measurement setup and connection with existing fuel cells and electrolyser will follow.

Results will be recorded from all tests and measurements conducted on the specific photovoltaic modules chosen for the research.

Work done by previous and current student researchers in this line of research will also be visited and examined (conclusions are made from the tests and measurements carried out) in order to add value to the project and authenticate certain findings that may occur in the course of the research work. Research work in this line at other relevant institutions shall also be visited and studied and positive findings shall be applied to the current work.

Measurements and results will be finalized and tabulated. The results will be interpreted and relevant conclusions and recommendations will be made.

1.5   Delimitations

The study will focus primarily on the photovoltaic solar cells (bought for this research) and their application in the generation of hydrogen and so batteries, converters, inverters, electrolysers and fuel cells shall not be delved into deeply. It will also exclude photovoltaic cells that are not commercially available yet.

1.6   Importance of the research

Solar-photovoltaic generation of hydrogen is becoming increasingly relevant in today's world, particularly as a replacement for fossil fuels which are not environmentally friendly and whose future is uncertain because of their ever-increasing depletion rate.

The outcome of the research study will help in increasing the awareness of photovoltaic solar hydrogen technology at the university level and also help mainly in providing information about the design and practical use of solar-photovoltaic electrolytic hydrogen generation systems, their integration with fuel cell systems used as a possible replacement for existing sources of energy.

The study will also outline the environmental advantages involved in the generation of hydrogen from solar energy, as well as discuss the types of solar cells commercially available. It will present a solar-driven hydrogen generation, purity determination and storage system that can be adopted by appropriate industries.

It will also serve as a springboard for further research into the use of photovoltaic solar cells for hydrogen generation.

1.7 Overview of the report

This research work contains five chapters relating to the design of a solar-driven hydrogen generation system for a fuel cell power plant.

Chapter 1 contains an introduction with the background on the study of fuel cells, fossil fuels and hydrogen as an alternative fuel. It covers the purpose of the research as well as the problem statement, the methodology applied, the delimitations as well as the importance of the research.

Chapter 2 deals with solar-photovoltaic hydrogen. Operation of solar cells and solar cell parameters are outlined while solar cell types, modules and arrays are also explained. The study of hydrogen as a fuel, production of hydrogen, distribution and storage conclude the chapter.

Chapter 3 is devoted to the experimental setup and procedures followed in the research.

Chapter 4 details the results and discussions obtained from the experiments performed on the designed system.

In Chapter 5 conclusions are drawn and recommendations are made with respect to the solar-driven hydrogen generation and storage system. Suggestions for further improvements are also made.

1.8 Summary

This chapter explains the research proposal, gives a detailed explanation of what the research aims are and the methodology that will be involved in carrying out the research proposal.

Chapter 2   Fundamentals of solar-photovoltaic hydrogen

2.1 Solar energy

The sun is of great importance for the planet earth and the ecosystem of our society. Rays emitted by the sun, gamma rays, reach the terrestrial orbit a few minutes after they leave the sun surface, crossing approximately 150 million kilometres. Clouds reflect about 17% of sunlight back into space, 9% is scattered backward by air molecules, and 7% is actually reflected directly off the surface of the earth back into space. Therefore, the travel through the atmosphere decreases the radiation at earth's surface to about 35% less than the level in the stratosphere. At noon on a clear day, the luminous power at the ground level is approximately 1000 watts per square meter (or 1 sun = 1000 W/m^2) (Farret & Simoes 2006:130).

According to Honsberg and Bowden (1998:2), solar energy in one form or another is the source of nearly all energy on the earth. Human beings, like all other animals and plants, rely on the sun for warmth and food. However, people also harness the sun's energy in many different ways. As an example, fossil fuels, plant matter from a past geological age, is used for transportation and electricity generation and is essentially just stored solar energy from millions of years ago. In a similar manner, biomass converts the sun's energy into a fuel, which can then be used for heat, transport or electricity. Wind energy, used for hundreds of years to provide mechanical energy or for transportation, uses air currents that are created by solar-heated air and the rotation of the earth and today wind turbines convert wind power into electricity as well as its traditional uses. Even hydroelectricity is derived from the sun. Hydropower depends on the evaporation of water by the sun, and its subsequent return to the earth as rain to provide water in dams.

Zekai (2008: 37) also pointed out that occurrences of solar energy all over the world in the forms of wind, wave, and hydropower through the hydrological cycle dynamically provide abilities to ponder about their utilization, if possible instantly, or in the form of reserves, by various conversion facilities and technologies. It is also possible that in the very long term, human beings might search for the conversion of ocean currents and temperature differences into appreciable quantities of energy so that the very end product of solar radiation on the earth will be useful for sustainable development. He further pointed out that solar energy is being referred to as renewable and/or sustainable energy because it will be available as long as the sun continues to shine. Estimates for the life of the main stage of the sun are another 4 - 5 billion years.

2.2   Solar cell operation

Patel (1999:137) described the physics of the PV-solar cell as being similar to the classical p-n junction diode (Figure 1). He stated that when light is absorbed by the junction, the energy of the absorbed photons is transferred to the electron system of the material, resulting in the creation of charge carriers that are separated at the junction. The charge carriers may be electron-ion pairs in a liquid electrolyte or electron-hole pairs in a solid semiconducting material. The charge carriers in the junction region create a potential gradient, get accelerated under the electric field and circulate as the current through an external circuit. The current squared times the resistance of the circuit is the power converted into electricity.
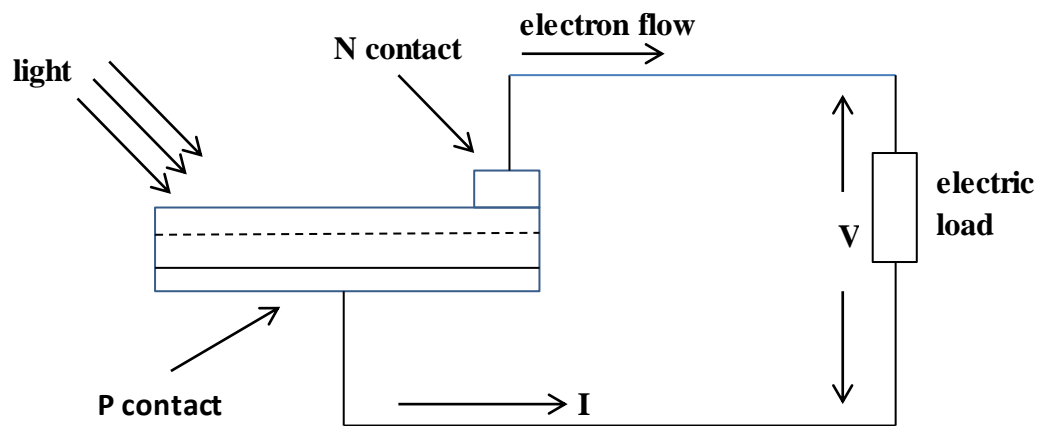
FIGURE 1 Photovoltaic effect converts the photon energy into voltage across the p-n junction (Patel 1999:138)

The remaining power of the photon elevates the temperature of the cell. He remarked that the origin of the photovoltaic potential is the difference in the chemical potential, called the Fermi level, of the electrons in the two isolated materials. When they are joined, the junction approaches a new thermodynamic equilibrium. Such equilibrium can be achieved only when the Fermi level is equal in the two materials. This occurs by the flow of electrons from one material to the other until a voltage difference is established between the two materials which have the potential just equal to the initial difference of the Fermi level. It is this potential that drives the photocurrent.

Figure 2 shows the basic cell construction. For collecting the photocurrent, the metallic contacts are provided on both sides of the junction to collect electrical current induced by the impinging

photons on one side. Conducting foil (solder) contact is provided over the bottom (dark) surface and on one edge of the top (illuminated) surface. Thin conducting mesh on the remaining top surface collects the current and lets the light through. The spacing of the conducting fibres in the mesh is a matter of compromise between maximizing the electrical conductance and minimizing the blockage of the light. In addition to the basic elements, several enhancement features are also included in the construction. For example, the front face of the cell has anti-reflective coating to absorb as much light as possible by minimizing the reflection. The mechanical protection is provided by the cover glass applied with a transparent adhesive (Patel 1999:137).
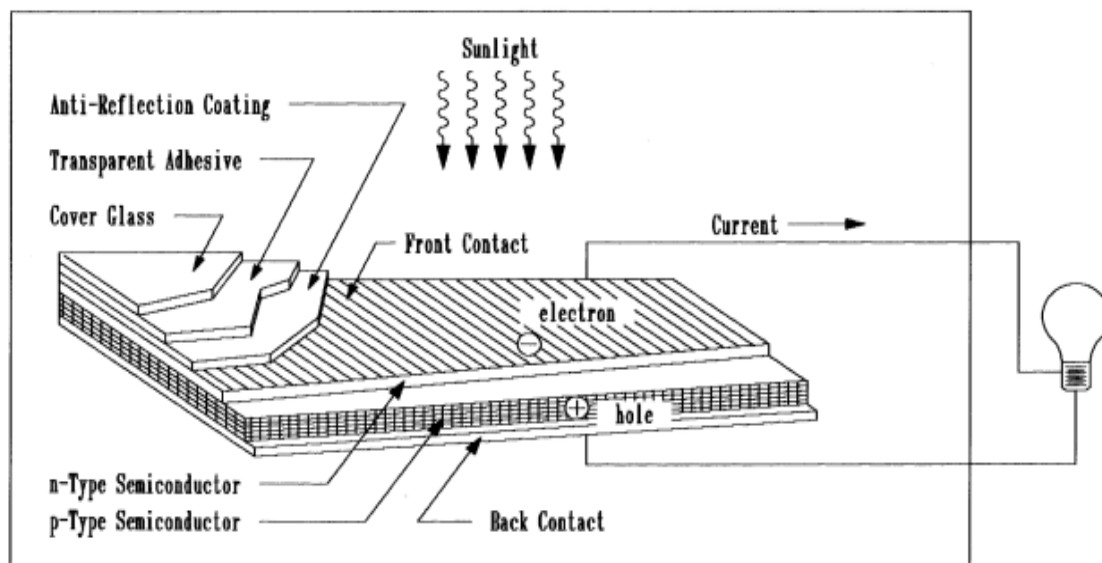
FIGURE 2 Basic construction of PV-solar cell with performance-enhancing features (current collecting mesh, anti-reflective coating and cover glass protection) (Patel 1999:138)

2.3 Solar cell types

Patel (1999:41) remarked that the continuing developmental efforts to produce more efficient low cost cells have resulted in various types of PV technologies available in the market today, in terms of the conversion efficiency and the module cost. His discussions of the major types are summarized in the following sections below.

2.3.1 Single-crystalline silicon

Patel (1999:41) explained that the single crystal silicon is a widely available cell material, and has been the workhorse of the industry. In the most common method of producing this material, the silicon raw material is first melted and purified in a crucible. A seed crystal is then placed in the liquid silicon and drawn at a slow constant rate. This results in a solid, single-crystal cylindrical ingot.

2.3.2   Polycrystalline and semicrystalline

There is a relatively fast and low cost process to manufacture thick crystalline cells. Instead of drawing single crystals using seeds, the molten silicon is cast into ingots. In the process, it forms multiple crystals. The conversion efficiency is lower, but the cost is much lower, giving a net reduction in cost per watt of power (Patel 1999:41).

2.3.3   Thin films

These are new types of photovoltaics entering the market. Copper Indium Diselenide, Cadmium Telluride, and Gallium Arsenide are all thin film materials, typically a few μm or less in thickness, directly deposited on glass, stainless steel, ceramic or other compatible substrate materials. This technology uses much less material per square area of the cell, hence, is less expensive per watt of power generated (Patel 1999:42).

2.3.4   Amorphous silicon

In this technology, amorphous silicon vapour is deposited on a couple of μm-thick amorphous (glassy) films on stainless steel rolls, typically 2,000-feet long and 13-inches wide. Compared to the crystalline silicon, this technology uses only 1 percent of the material. Its efficiency is about one-half of the crystalline silicon at present, but the cost per watt generated is projected to be significantly lower (Patel 1999:42).

2.3.5   Spheral

This is yet another technology that is being explored in the laboratories. The raw material is low-grade silicon crystalline beads, presently costing about $1 per pound. The beads are applied on typically 4-inch squares of thin perforated aluminium foil. In the process, the impurities are pushed to the surface, from where they are etched away. Since each sphere works independently,

the individual sphere failure has negligible impact on the average performance of the bulk surface. (Patel 1999:43).

2.3.6 Concentrated cells

In an attempt to improve the conversion efficiency, the sunlight is concentrated into tens or hundreds of times the normal sun intensity by focusing on a small area using low cost lenses (Figure 3).
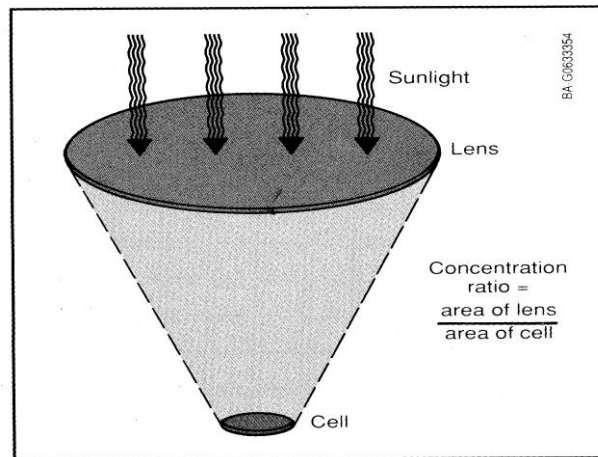
FIGURE 3 Lens concentrating the sunlight on small area reduces the need of active cell material (Patel 1999:44)

The primary advantage is that such cells require a small fraction of area compared to the standard cells, thus significantly reducing the PV material requirement. However, the total module area remains the same to collect the required sun power. Besides increasing the power and reducing the size or number of cells, such cells have the additional advantage that the cell efficiency increases under concentrated light up to a point. Another advantage is that they can use small area cells. It is easier to produce high efficiency cells of small areas than to produce large area cells with comparable efficiency. On the other hand, the major disadvantage of the concentrator cells is that they require focusing optics adding onto the cost (Patel 1999:44).

2.4   The behaviour of solar cells

2.4.1   Effect of light

According to Wenham, Green, Watt and Corkish (2007:43-47) a silicon solar cell is a diode formed by joining *p*-type (typically boron-doped) and *n*-type (typically phosphorous-doped) silicon. Light shining on such a cell can behave in a number of ways, as illustrated in Figure 4 below. To maximize the power rating of a solar cell, it must be designed so as to maximize desired absorption (3) and absorption after reflection (5). The electric field $\hat{E}$ at the *p-n* junction sweeps electrons to the *n* side and holes to the *p* side. The ideal flow at short circuit is shown in Figure 5. However, some electron-hole (e-h) pairs get lost before collection, as shown in Figure 6.
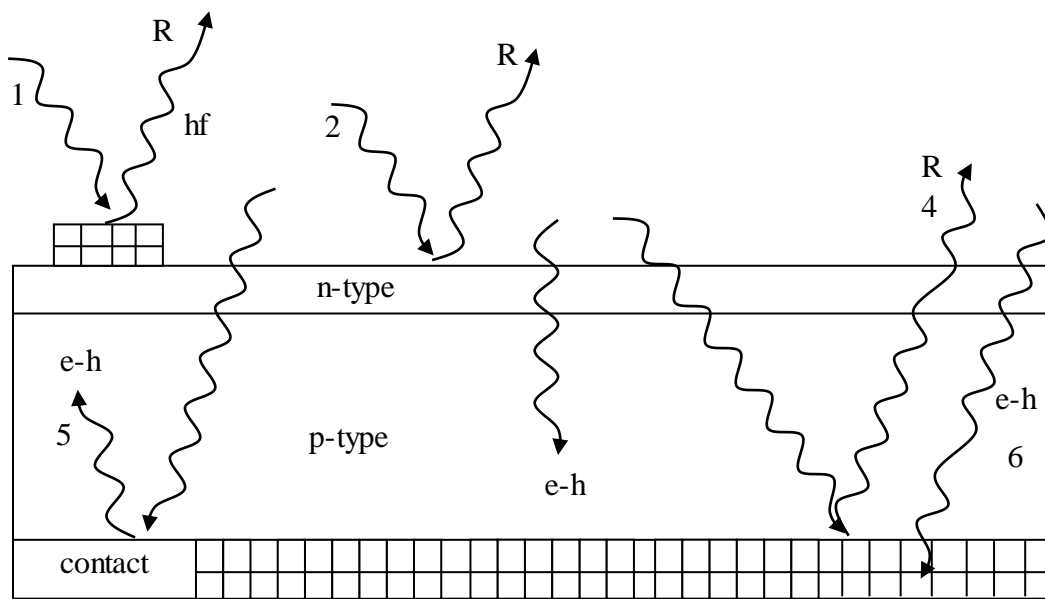
Figure 4 Behaviour of light shining on a solar cell: (1) Reflection and absorption at top contact (2) Reflection at cell surface (3) Desired absorption (4) Reflection from rear of cell - weakly absorbed light only (5) Absorption after reflection (6) Absorption in rear contact (Wenham *et al.* 2007:44)
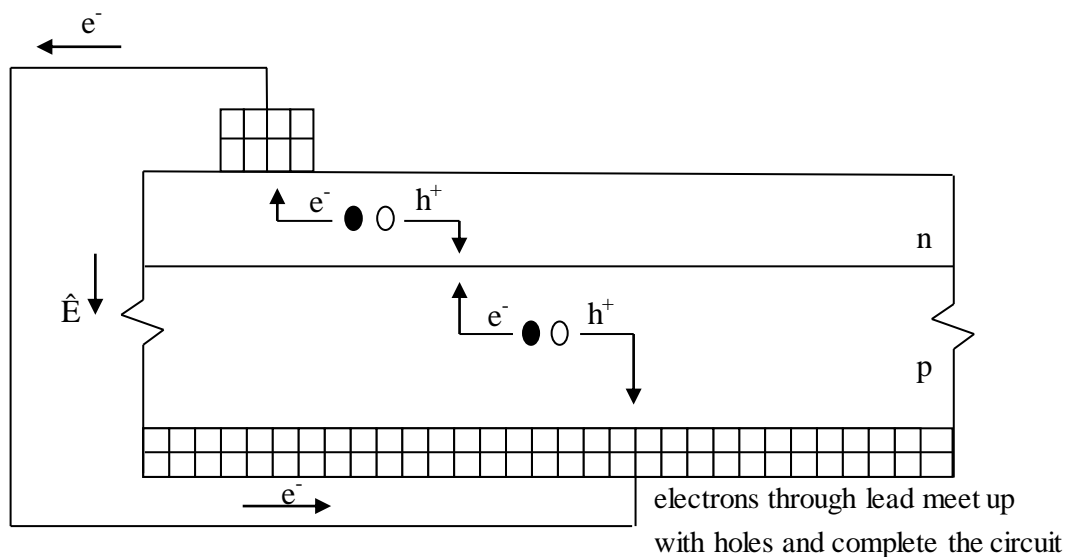
Figure 5 The ideal short circuit flow of electrons and holes at a *p-n* junction (Wenham *et al.* 2007:45)
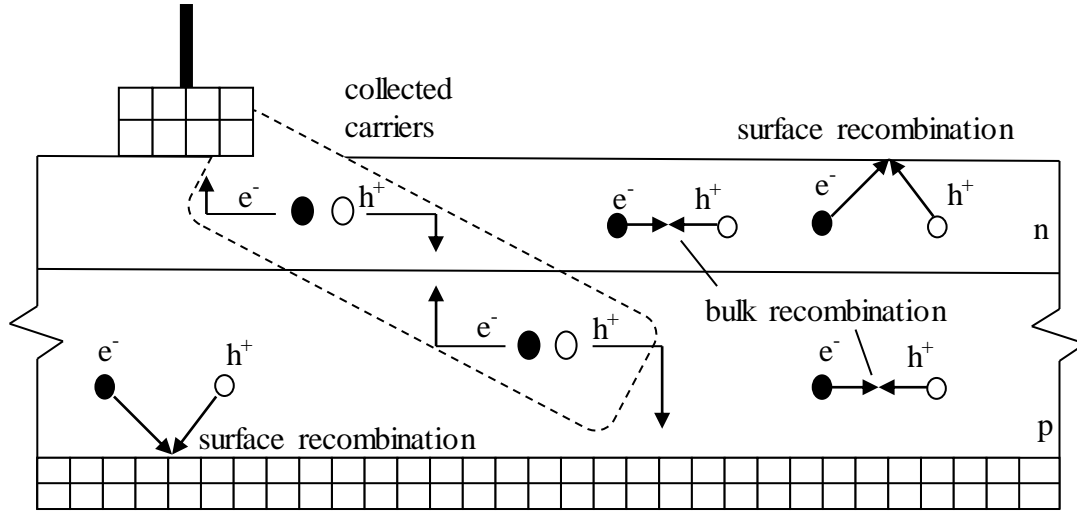
Figure 6 Possible modes of recombination of electron-hole pairs, showing 'collection' of carriers that do not recombine (Wenham *et al.* 2007:45)

Wenham *et al.* (2007:45) explained that, the closer the point of e-h generation to the *p-n* junction, the better the chance of 'collection'. 'Collected carriers' are those that generate a finite current when $V = 0$. Chances of collection are particularly good if the e-h pairs are generated within a *diffusion length* of the junction. The characteristic curves generated by plotting I against V for a diode (I-V curves) is shown in Figure 7 for I_0, with no light falling on the cell. Illumination of a cell merely adds to the normal 'dark' currents in the diode so that the diode law becomes:

$$I = I_0 \left[\exp\left(\frac{qV}{nkT} \right) - 1 \right] - I_L \tag{1}$$

where I_0 is the dark saturation current (the diode leakage current in the absence of light), V is the applied voltage, q is the charge on an electron, k is Boltzmann's constant, T is absolute

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temperature, n is the ideality factor, that is a number between 1 and 2 that typically increases as the current decreases and I_L is the light-generated current. The light has the effect of shifting the I-V curve down into the fourth quadrant where power can be extracted from the diode, as shown in Figure 8. The I-V curve characterizes the cell, with its power output being equal to the area of the rectangle in the bottom right-hand quadrant of Figure 8a. This I-V curve is most often shown reversed, as in Figure 9, with the output curve in the first quadrant, and represented by:

$$I = I_L - I_0 \left[\exp\left(\frac{qV}{nkT}\right) - 1 \right] \qquad (2)$$
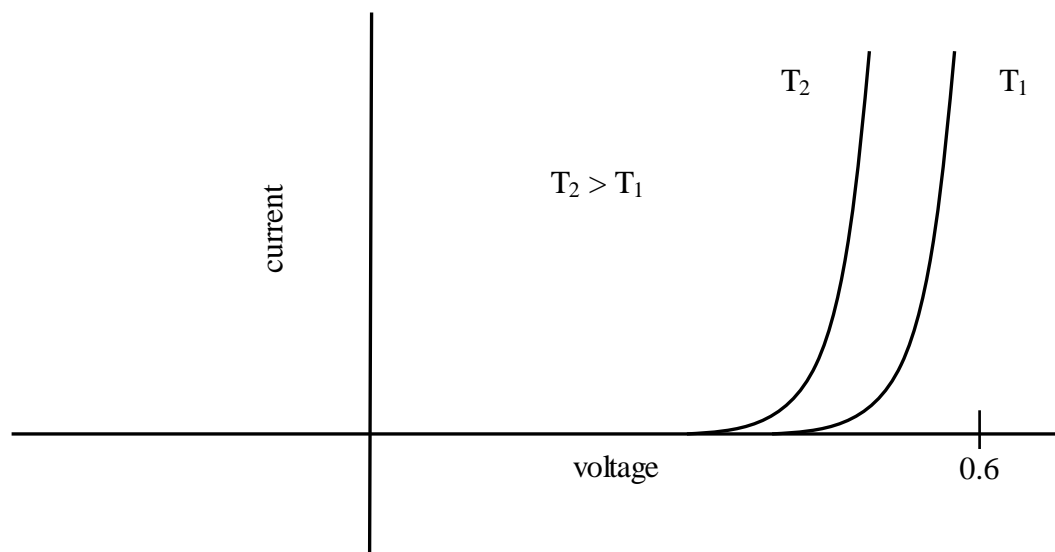
Figure 7 The diode law for silicon: current as a function of voltage for temperatures T_1 and T_2. ($T_2 > T_1$). For a given current, the curve shifts by approximately 2 mV/°C (Wenham *et al.* 2007:45)
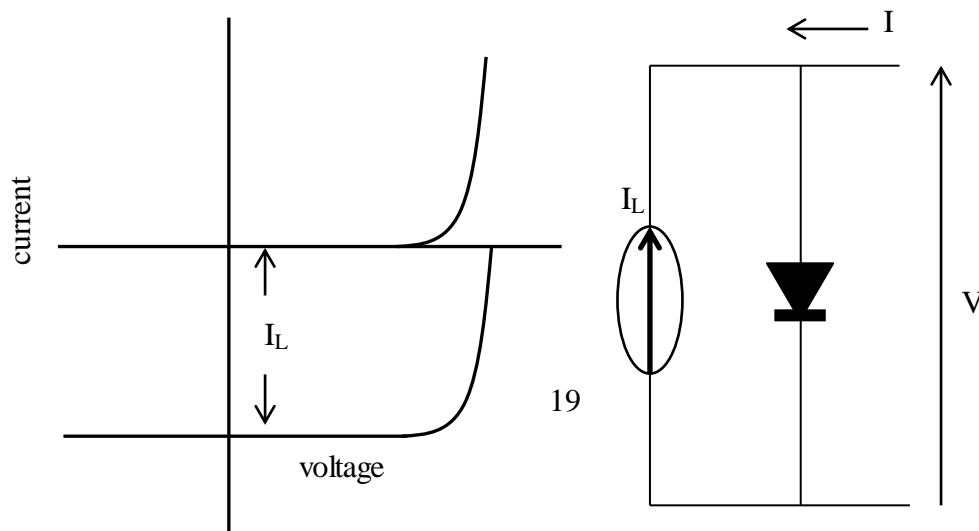
Figure 8 The effect of light on the current-voltage characteristics of a *p-n* junction (Wenham *et al.* 2007:45)
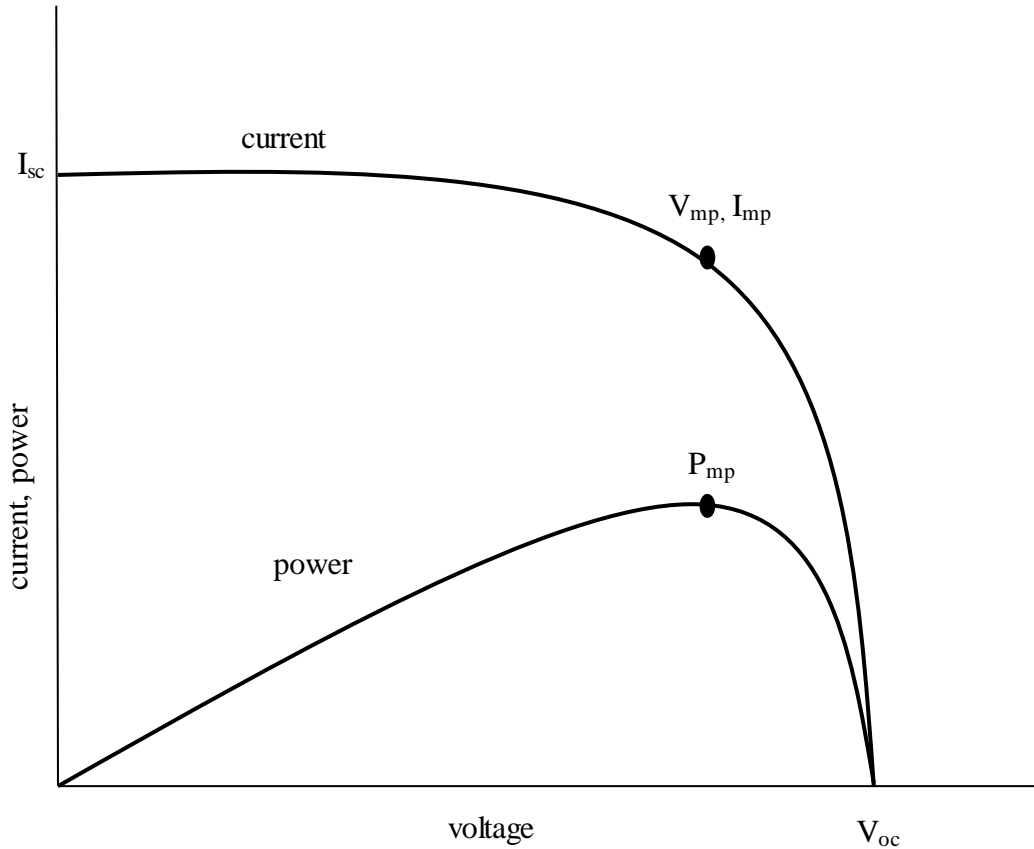
Figure 9 Typical representation of an I-V curve, showing short-circuit current (I_{sc} and open-circuit voltage (V_{oc}) points, as well as the maximum power point (V_{mp}, I_{mp}) (Wenham *et al.* 2007:46)

According to Wenham *et al.* (2007:46) the two limiting parameters used to characterize the output of solar cells for given irradiance, operating temperature and area are:

1. **Short circuit current** (I_{sc}) - the maximum current, at zero voltage. Ideally,
   $V = 0$, $I_{sc} = I_L$. Note that I_{sc} is directly proportional to the available sunlight.

2. **Open circuit voltage** (V_{oc}) - the maximum voltage, at zero current. The value of V_{oc} increases logarithmically with increased sunlight. This characteristic makes solar cells ideally suited to battery charging.

Note that at $I = 0$,

$$V_{oc} = \frac{nkT}{Q} In\left(\frac{I_L}{I_0} + 1\right) \qquad (3)$$

For each point on the I-V curve, the product of the current and voltage represents the power output for that operating condition. A solar cell can also be characterized by its *maximum power point*, when the product $V_{mp} \times I_{mp}$ is at its maximum value. The maximum power output of a cell is graphically given by the largest rectangle that can be fitted under the I-V curve. That is,

$$d\frac{IV}{dV} = 0$$

giving

$$V_{mp} = V_{oc} - \frac{nkT}{q} In\left(\frac{V_{mp}}{nkT/q} + 1\right) \qquad (4)$$

For example, if $n = 1.3$ and $V_{oc} = 600$ mV, as for a typical silicon cell, V_{mp} is about 93 mV smaller than V_{oc}. The power output at the maximum power point under strong sunlight (1 kW/m^2) is known as the 'peak power' of the cell. Hence photovoltaic panels are usually rated in terms of their 'peak' watts (W$_p$).

The *fill factor* (*FF*), is a measure of the junction quality and series resistance of a cell. It is defined as:

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \qquad (5)$$

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Hence

$$P_{mp} = V_{oc} I_{sc} FF \tag{6}$$

Obviously, the nearer the fill factor is to unity, the higher the quality of the cell. Ideally, it is a function only of the open circuit voltage and can be calculated using the approximate empirical expression

$$FF = \frac{v_{oc} - In\ v_{oc} + 0.72}{v_{oc} + 1} \tag{7}$$

where v_{oc} is defined as a 'normalized V_{oc}'; that is

$$v_{oc} = \frac{V_{oc}}{nkt/q} \tag{8}$$

The above expression applies to *ideal cases* only, with no parasitic resistance losses, and is accurate to about one digit in the fourth decimal place for these cases.

2.4.2 Effects of temperature

According to Wenham *et al.* (2007:49) the operating temperature of a solar cell is determined by the ambient air temperature, by the characteristics of the module in which it is encapsulated, by the intensity of sunlight falling on the module, and by other variables such as wind velocity. The dark saturation current I_0 increases with temperature according to the equation:

$$I_0 = BT^{\gamma} \exp\left(\frac{-E_{g0}}{kT}\right) \tag{9}$$

where B is independent of temperature, E_{g0} is the linearly extrapolated zero temperature bandgap of the semiconductor making up the cell and γ includes the temperature dependencies of the remaining parameters determining I_0.

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The short circuit current (I_{sc}) increases with temperature, since the bandgap energy (E_g) decreases and more photons have enough energy to create e-h pairs. However, this is a small effect. For silicon

$$\frac{1}{I_{sc}} \cdot \frac{dI_{sc}}{dT} \approx +0.0006 °C^{-1} \tag{10}$$

The main effect of increasing temperature for silicon solar cells is a reduction in V_{oc}, the fill factor and hence the cell output. These effects are illustrated in Figure 10.
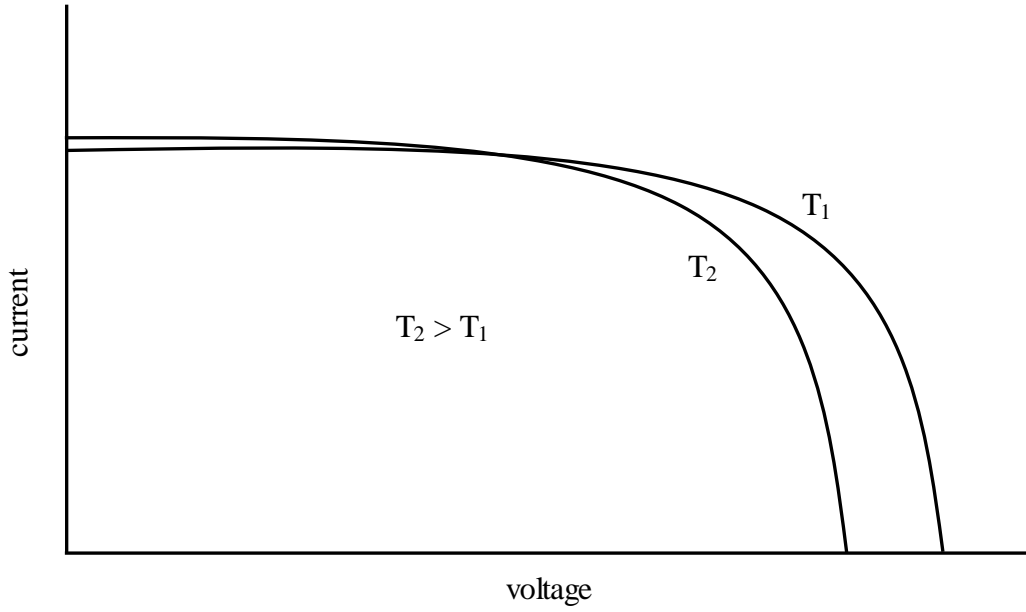
Figure 10 The effect of temperature on the I-V characteristics of a solar cell (Wenham *et al.* 2007:50)

The temperature dependency of V_{oc} and FF for silicon is approximated by the following equations:

$$\frac{dV_{oc}}{dT} = \frac{-\left[V_{g0} - V_{oc} + \gamma\, {kT}/{q}\right]}{T} \approx -2mV/°C \tag{11}$$

$$\frac{1}{V_{oc}} \cdot \frac{dV_{oc}}{dT} \approx -0.006 °C^{-1} \tag{12}$$

$$\frac{1}{FF} \cdot \frac{d \ FF}{dT} \approx \frac{1}{6}\left[\frac{1}{V_{oc}} \cdot \frac{dV_{oc}}{dT} - \frac{1}{T}\right] \approx -0.0015°C^{-1} \qquad (13)$$

For silicon, the effect of temperature on the maximum power output (P_{mp}) is as follows:

$$\frac{1}{P_{mp}}\frac{dP_{mp}}{dT} \approx - \ 0.004 \ \square \ 0.0015 \ °C^{-1} \qquad (14)$$

The higher the value of V_{oc}, the smaller the expected temperature dependence (Wenham *et al.* 2007:49-51).

2.5   Modules and arrays

Patel (1999:139) described the solar cell as the basic building block of the PV power system. Typically, it is a few square inches in size and produces about one watt of power. For obtaining high power, numerous such cells are connected in series and parallel circuits on a panel (module) area of several square feet (Figure 11). He defined the solar array or panel as a group of several modules electrically connected in series and/or parallel combinations to generate the required current and voltage.

Wenham *et al.* (2007:75) stated that cells with similar characteristics are those which must be connected and encapsulated to form modules which, in turn, are the basic building blocks of solar arrays. Since the maximum voltage from a single silicon cell is only about 600 mV, cells are connected in series to obtain the desired voltage. Usually about 36 series cells are used for a nominal 12V charging system.
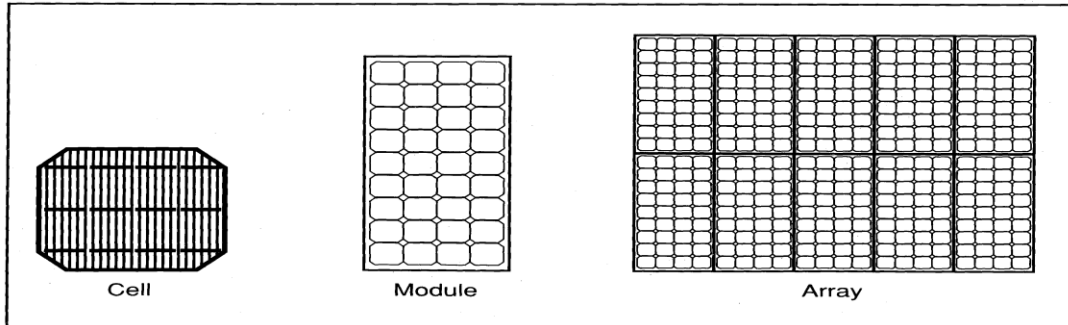
Figure 11 PV cell, module and array (Patel 1999:139)

Since PV systems are commonly operated at multiples of 12 volts, the modules are typically designed for optimal operation in these systems stating that the design goal is to connect a sufficient number of cells in series to keep V_m of the module within a comfortable range of the battery/system voltage under conditions of average irradiance (Messenger and Ventre 2004:52-53).

module
3 parallel strings
2 series blocks
2 cells per substring

branch circuit
3 parallel strings
6 series blocks
2 cells per substring
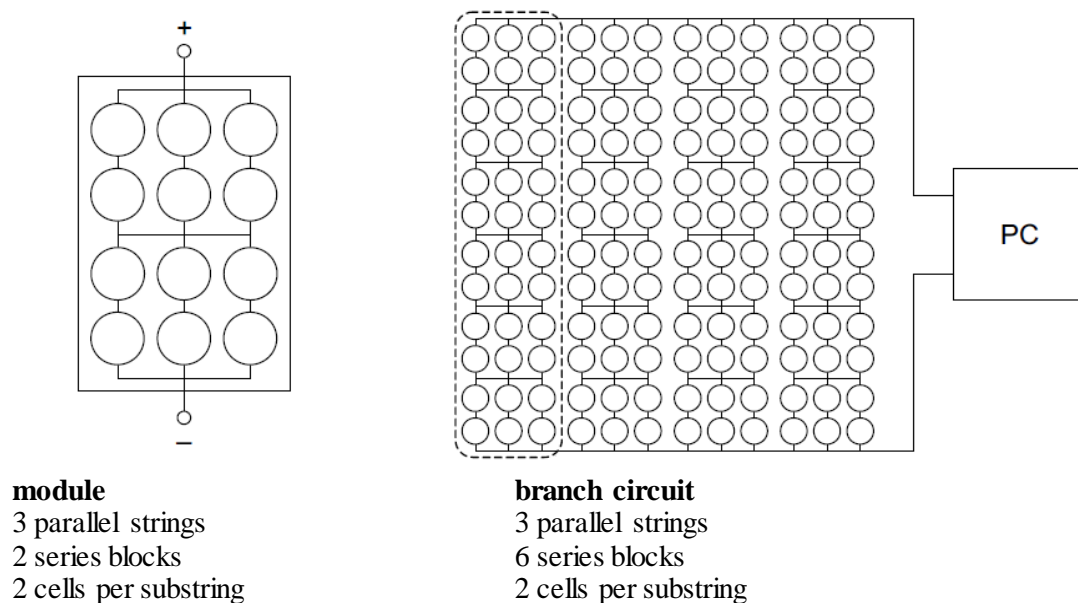
Figure 12 Typical connection systems and terminology used in module circuit design. PC = power conditioning equipment (Wenham *et al.* 2007:76)

Messenger and Ventre (2004:53) noted that if this is done, the power output of the module can be maintained close to maximum. This means that under full sun conditions, V_m should be approximately 16–18 V. Since V_m is normally about 80% of V_{oc}, this suggests designing the

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module to have a V_{oc} of about 20 volts. With silicon single cell open-circuit voltages typically in the range of $0.5 - 0.6$ volts, this suggests that a module should consist of $33 - 36$ cells connected in series. With each individual cell capable of generating approximately $2-3$ watts, this means the module should be capable of generating $70-100$ watts.

Under peak sunlight (100 mW/cm^2), the maximum current delivered by a cell is approximately 30 mA/cm^2. Cells are therefore paralleled to obtain the desired current. Figure 12 illustrates a typical connection system and the standard terminology used to describe such connections (Wenham *et al.* 2007:75).

2.6   Hydrogen as a fuel

According to Züttel, Borgschulte and Schlapbach (2008: 7) the history of hydrogen is linked to great scientists and engineers, fascinating discoveries and technical breakthroughs but also to throwbacks and tragedies. Hydrogen technology has become a keystone for daily life. For example, hydrogen in metals is used in batteries, sensors, ferromagnets, switchable mirrors, and heat pumps; and it is responsible for embrittlement causing corrosion in metallic materials. Hydrogen appears mainly in the form of hydrocarbons and is widely used in chemical engineering, in particular in the petrochemical industry. Hydrogen is involved in the processes of life, for example in photosynthesis and energy conversion in living cells. Still, hydrogen has had a bad reputation. A questionnaire in Munich in 1998 brought to the fore that 12.9% of those interrogated associated 'hydrogen' with 'hydrogen bomb', followed by non-specified dangers (risk of explosion, etc.).While some of the connotations originate from missing scientific knowledge, predominantly tragic events such as the Hindenburg and Challenger disasters coined the image of hydrogen in the population.

Rand and Dell (2008:28) stated that if hydrogen is to be employed as an energy vector and a non-polluting fuel, it is necessary to take account of its basic physical properties. Hydrogen is a colourless, odourless, tasteless and non-toxic gas. It is the lightest of all molecules (molecular weight = 2.016) and, consequently, has a density of only 0.0899 kgm^{-3} at normal temperature (273.15K) and pressure (101.325kPa), i.e., 7% of the density of air. Liquid hydrogen also has a

low density of 70.8 kgm^{-3} (7% of that of water). The liquid has a very low boiling point (20.3K) and therefore requires fairly sophisticated equipment to prepare and maintain it in this state.

By virtue of its exceptionally low density, hydrogen has the best energy-to-weight ratio ('heating value') of any fuel, but its energy-to-volume ratio is poor (Table 1). The thermodynamic heat of combustion of hydrogen (its heating value) equates to the standard heat of formation (ΔH_f^o) of the product water, i.e.,

$$H_2 \ (gas) + \frac{1}{2}O_2 \rightarrow H_2O \ (liquid) \qquad H_f^o = -285.83 \ \text{kJ mol}^{-1} \qquad (15)$$
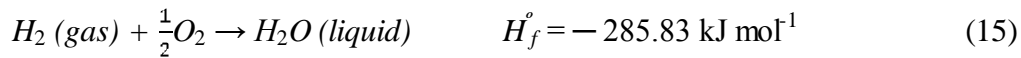
In alternative units, the standard heat of formation is 141.78 MJ per kg of hydrogen. This is the maximum amount of heat that can be derived from the combustion of hydrogen when the product water is condensed to 298.15 K; it is known as the 'higher heating value' (HHV) of hydrogen. In most engineering practice, the product water is released as steam whose calorific value (including the latent heat of condensation) is lost. If the steam is released at about 150 ºC, then the effective (or engineering) heat of combustion will be around 120MJ kg^{-1}. This is a practical value known as the 'lower heating value' (LHV) (Rand and Dell 2008:28).

For calculating the *absolute* efficiency of energy-conversion devices (e.g., fuel cells) it is important to use the HHV, but when comparing the *practical* or *relative* efficiencies of engineering devices (e.g., boilers) it is often convenient to use the LHVs. Modern condensing boilers do, however, recover a proportion of the lost heat and have efficiencies that lie between the two heating values (Rand and Dell 2008:28).

The speed of propagation of the wave front (the flame velocity) is determined by diffusion through the nitrogen of the air. Because hydrogen has a high diffusivity in air, its flame velocity is higher than that of conventional gaseous fuels. When mixed with pure oxygen in a 2:1 molecular ratio of hydrogen to oxygen and ignited, hydrogen detonates violently since there is no inert nitrogen to slow down the wave front.

Table 1 Technical comparison of hydrogen with other fuels (Rand & Dell 2008:29)

	Hydrogen	*Petroleum*	*Methanol*	*Methane*	*Propane*	*Ammonia*
Boiling Point K	20.3	350-400	337	111.7	230.8	240
Liquid density kg m^{-3}, NTP[a]	70.8	702	797	425	507	771
Gas density kg m^{-3}, NTP[a]	0.0899	-	-	0.718	2.01	0.77
Heat of vapourization/Kj kg^{-1}	444	302	1168	577	388	1377
Higher heating value[b] (mass)/MJ kg^{-1}	141.9	46.7	23.3	55.5	48.9	22.5
Lower heating value[b] (mass)/ MJ kg^{-1}	120.0	44.38	20.1	50.0	46.4	18.6
Lower heating value (liquid)[b] (volume) MJ m^{-3}	8520	31170	16020	21250	23520	14350
Diffusivity in air cm^2 s^{-1}	0.63	0.08	0.16	0.20	0.10	0.20
Lower flammability limit/vol % (in air)	4	1	7	5	2	15
Upper flammability limit/vol % (in air)	75	6	36	15	10	28
Ignition temperature in air/°C	585	222	385	534	466	651
Ignition energy/Mj	0.02	0.25	-	0.30	0.25	-
Flame velocity/cm s^{-1}	270	30	-	34	38	-

[a] NTP=normal temperature (273.15 K) and pressure (101.325 kPa).

[b] Different authors give slightly different figures for the heating values.

The energy required to ignite a hydrogen-air mixture is exceptionally low, 0.02 mJ (Table 1), and is only one-fourteenth of the energy needed to ignite natural gas. The combination of physical properties exhibited by hydrogen (low density, low boiling point, wide range of flammability, low ignition energy, high diffusivity in air, high flame velocity) is unique among fuels (see Table 1), and this combination has safety implications for the use of hydrogen in bulk (Rand and Dell 2008:30).

On the positive side, the low density of the gas and its high diffusivity in air mean that an outdoor leakage of hydrogen soon disperses safely. By contrast, liquid fuels remain on the ground and evaporate slowly, which poses a fire hazard. Even liquid hydrogen, if spilled, evaporates almost instantaneously on account of its low boiling point and then diffuses rapidly away. The situation is different in an enclosed space; the wide flammability and explosive range of hydrogen in air mean that a leakage is very likely to give rise to a fire or explosion. Since hydrogen contains no carbon, it burns with a non-luminous flame that does not radiate heat. Consequently, bystanders are not subject to radiation heat burns. The non-luminous flame does, however, have a negative feature; because it is almost invisible and does not radiate heat, there is always the possibility of inadvertently straying into the flame and being seriously burnt (Rand and Dell 2008:30-31).

Also, given the low ignition energy of hydrogen compared with other fuels, extreme precautions should be taken to avoid static electricity when working with hydrogen in bulk. These may include wearing garments of cotton or wool rather than synthetic materials and earthing (grounding) all tools that might give rise to a spark (Rand and Dell 2008:31).

The distinctive properties of hydrogen clearly make it a unique fuel. Operatives therefore need to be well-trained and experienced to handle it. For example, those skilled in the bulk handling of hydrogen have expressed reservations about allowing untrained personnel to participate in the refuelling of hydrogen-powered vehicles. Escape of hydrogen in enclosed areas (*e.g.*, garages and tunnels) would constitute a particular risk. The safety of hydrogen from both a technological and societal

perspective will be a key issue if the Hydrogen Economy is to be taken forward (Rand and Dell 2008:31).

In the space industry, extensive experience has been acquired in the safe handling of liquid hydrogen, both in physics laboratories and, on a tonnage scale for use as rocket fuel. No insuperable technical problems are encountered. The specialized equipment is, however, very costly and is one reason why liquid hydrogen has not been considered as a fuel outside the space industry, where its low density is a particularly valuable property. Experimentally, liquid hydrogen has been employed as a fuel in automotive applications and there has been some preliminary consideration of using it as an aircraft fuel (Rand & Dell 2008:31).

Rand and Dell (2008:32) reckoned that hydrogen is the obvious choice for a low-carbon economy in that it would liberate no pollutants to the atmosphere. The Hydrogen Economy concept is one that embraces a range of possibilities. Among the more important categories, it is therefore important to distinguish between:

- Hydrogen as a chemical and hydrogen as an energy vector, where the economics of these two applications are different;
- Hydrogen derived from fossil sources and that from non-fossil sources (hydro, nuclear or renewable electricity);
- Hydrogen combusted in internal combustion engines and that utilized in fuel cells;
- Hydrogen for stationary applications and for portable or mobile applications.

Within these broad categories, there are numerous detailed production routes from primary energy sources (both fossil fuels and renewable) and manifold applications to be evaluated, each of which will impose its own individual technical and economic specifications. The role that hydrogen will play in future energy scenarios will only be well known when all the remaining research and development have been completed, when demonstration projects have been conducted and when full technical and economic evaluations have been made within the context of the prevailing energy scene at that time.

2.7   Non-renewable production methods for hydrogen

2.7.1   Natural gas reformation

Züttel *et al.* (2008:49) stated that large amounts of elemental hydrogen are currently produced by the petrochemical industry for use in the desulfurisation of diesel fuels, hydrogenation of edible oils and as a feedstock for many hi-tech manufacturing processes. They explained that the majority of today's hydrogen is made from natural gas reformation with steam, some oxygen and air. The equation for this process is:

$$CH_4 + 2H_2O = 4H_2 + CO_2 \qquad\qquad (16)$$

Unfortunately, production of hydrogen from natural gas compared to other fossil fuel sources also has the following disadvantages:

1. Accelerating depletion of finite petrochemical resources.

2. Carbon dioxide as a major by-product of the process.

3. Process heating by natural gas contributes further carbon dioxide.

Although simple, well-established, commercially viable and being capable of meeting the initial demand for hydrogen, production of hydrogen from natural gas cannot be regarded as other than an intermediate solution. If the major economies are to move towards large-scale use of hydrogen as a fuel, other low carbon production routes for hydrogen must be exploited.

Züttel *et al.* (2008:49-50), stated that coal gasification has been explored as a possible mass production process for hydrogen. He explained that the process has advantages in that it could exploit the large coal reserves known to exist in many parts of the world. Unfortunately, without sequestration of the resultant carbon dioxide outputs, the process would be environmentally unacceptable. He stated that nuclear power, especially in its advanced variants, has also been proposed as a means of providing high quality heat to the many possible production routes for hydrogen. In terms of ease of scaling-up, engineering efficiency and the benefits of 50 years of operating experience, persuasive arguments can be made in favour of this, versus the

uncertainties of more novel approaches. Nuclear technology is, however, not strictly renewable and it brings the politically and economically unresolved problems of waste management. Hence, other production routes for hydrogen must be exploited to avoid the current spiral of increasing pollution and fossil fuel dependence. Fortunately, there are numerous renewable production processes for hydrogen.

2.7.2 Renewable processes for hydrogen production (electrolysis)

Züttel *et al.* (2008:50) stated that apart from the natural gas reforming processes, *electrolysis of water* is the most widely used method for hydrogen production. To electrolyse water, the minimum electrical energy required is determined by the free energy change of the underlying reaction:

$$H_2O = H_2 + \tfrac{1}{2}O_2 \tag{17}$$

With a free energy change of 237 kJ mol^{-1}, a theoretical decomposition voltage of 1.23 V (25 ºC and 1 bar pressure) is obtained. Under isothermal conditions, the cell voltage is 1.47 V and gives a process efficiency of 83 %. In practice, higher cell voltages (1.7 to 1.9 V) are used, giving lower energy utilisation and efficiencies (80 %). Practical efficiencies are in the range 70–75 %. Volume production of hydrogen by electrolysis of water is achieved using one of the following process variants:

- *Water electrolysis* with aqueous alkaline electrolytes (30% KOH) and asbestos electrodes is widely used in small- and medium-scale units (0.5 − 5.0 MW)

- *Solid polymer electrolyte water electrolysis* uses proton conducting ion exchange membranes as electrolyte and membrane. Commercial units with power ratings up to 100kW are available. Projected efficiencies are in the range 80–90 %.

- *High temperature steam electrolysis* exploits the marked decrease in operating cell voltage above 700 °C. Oxygen ion conducting membranes, operating at 700–1000 ºC are used as the electrolyte. The water to be

disassociated enters on the cathode side as steam, leading to a steam–hydrogen mixture. Production costs could be lower for this option, as process heat is cheaper than electrical power.

A significant consideration with all electrolytic options is the purity of the input water supply. Impure water can significantly reduce the lifetime of electrolytic cells and a front–end purification plant will add to the final hydrogen production costs (Züttel *et al.* 2008:49-50).

According to Züttel *et al.* (2008:51) a wide variety of electrical energy sources is currently in use, or being developed, for electrolyzing water via one of the above options. These are summarized in Table 2. Of the options shown, only hydropower, wind turbine and solar cells may be regarded as mature technologies. Nuclear power offers an apparently attractive route to the enhanced efficiencies of high temperature electrolysis.

Table 2 Existing and potential sources of electrical power for electrolysis
(Züttel *et al.* 2008:51)

Technology	Power output	Input energy
Nuclear power	GW	Nuclear fuel
Hydro power	GW-kW	Water heads
Solar power	MW	Solar radiation
Solar parabolic	GW-kW	Solar radiation
Wind turbine	GW-kW	On/off shore wind
Solar cell	GW-kW	Solar radiation

In addition, the nuclear route could make electrical power for hydrogen production available at GW levels, independent of naturally varying phenomena such as wind and/or solar. A further advantage claimed is that nuclear plants could be sited near to points of use. Several design studies are being conducted in the US, Japan and the EU. Whatever the attractions, nuclear technology remains dependent on depletable resources and continues to be a contentious issue for public debate, especially regarding the safety and economic viability of long-term waste storage.

2.7.3 PV-electrolysis systems for hydrogen production

According to Grimes, Varghese and Ranjan (2008:485) the electricity used today for water electrolysis is predominately obtained by the combustion of the fossil fuels that, like methane, are of finite supply and produce as a combustion product CO_2 as well as other noxious pollutants such as mercury vapour.

Electricity generated from sunlight offers a viable pathway for hydrogen production by water electrolysis with photovoltaics (solar cells) converting solar energy into the electric energy needed to achieve water electrolysis resulting in the production of very pure hydrogen. Solar cells are commonly referred to as *photovoltaic* (PV) cells, the adjective derived from *Photo* (light) and *Voltaic* (electricity).

Several review articles published in the International Journal of Hydrogen Energy (Carpetis (1982) A study of water electrolysis with photovoltaic solar energy conversion, Dahlberg (1982) Replacement of fossil fuels by hydrogen, Fischer (1986) Review of hydrogen production with photovoltaic electrolysis system, consider the characteristics and performance of such systems, comprised of a photovoltaic converter and electrolysis device.

The global efforts at developing thin-film solar cell technology over the past decade, moving towards low-cost (plentiful) raw materials for their manufacture coupled with inexpensive (low energy input) mass production techniques, suggest that electricity from PV systems (and therefore PV hydrogen) should become increasingly less costly. The 'less costly' equation becomes particularly meaningful when the true costs of fossil fuels are factored into the equation, e.g. the military costs spent on ensuring oil flow from the Middle East, the associated political bargains necessarily made to keep the oil flowing, pollution and their associated medical affects, and of course the consequences of undesired global climate change (Züttel *et al.* 2008:485-486).

Solar cells are silent, have no moving parts, cause no environmental pollution in operation, can generate power locally where it is needed, and can operate across extensive temperature regimes. Devices combining photovoltaic solar cells and water electrolysis may be described as integrated, or monolithic, tandem PV-electrolytic devices. Multiple bandgap PV devices lead to a

more efficient conversion of solar energy, hence a greater production of hydrogen but at greater cost (Züttel *et al.* 2008:486).

PV-Electrolysis systems for hydrogen production employ PV modules to generate electricity that is subsequently passed to a commercial-type water electrolyser as shown in Figure 13. Commercial single-crystal Si solar cells generally have efficiencies in the 12-16% range, while water electrolysis units have energy efficiencies of about 85%. The efficiency of the combined PV/electrolyser system using commercially available components is close to 10%.
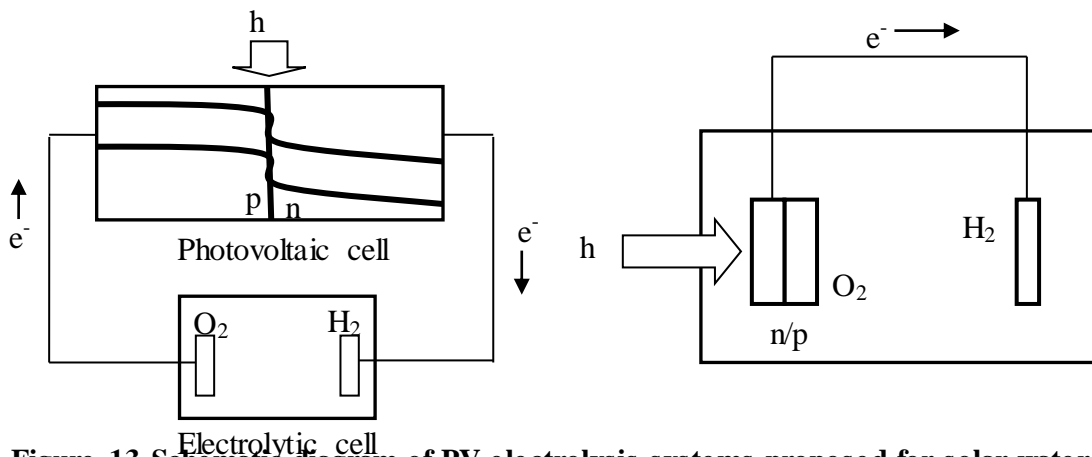
Figure 13 Schematic diagram of PV-electrolysis systems proposed for solar water splitting: (a) Electricity generated from photovoltaic cell driving water electrolysis; (b) PV assisted cell with immersed semiconductor p/n junction as one electrode (Grimes *et al.* 2008:499)

The system shown in Figure 13b eliminates the costs and mechanical difficulties associated with separate construction and interconnection of solar and electrochemical cells; in these systems the electrodes are composed of single or multiple semiconductor p/n junctions that are irradiated while they are within the cell. This apparatus can be constructed with proper encapsulation of the semiconductors to protect them from the aqueous environment. Since PV-electrolysis units for hydrogen generation are expensive to build, it is important to maintain maximum output power independently of variations in solar insolation and temperature. Consequently commercial systems will require the integration of PV arrays with maximum power point tracking (MPPT) devices, (see Figure 14) which are described by average power conversion efficiency as a function of partial load (Züttel *et al.* 2008:499).
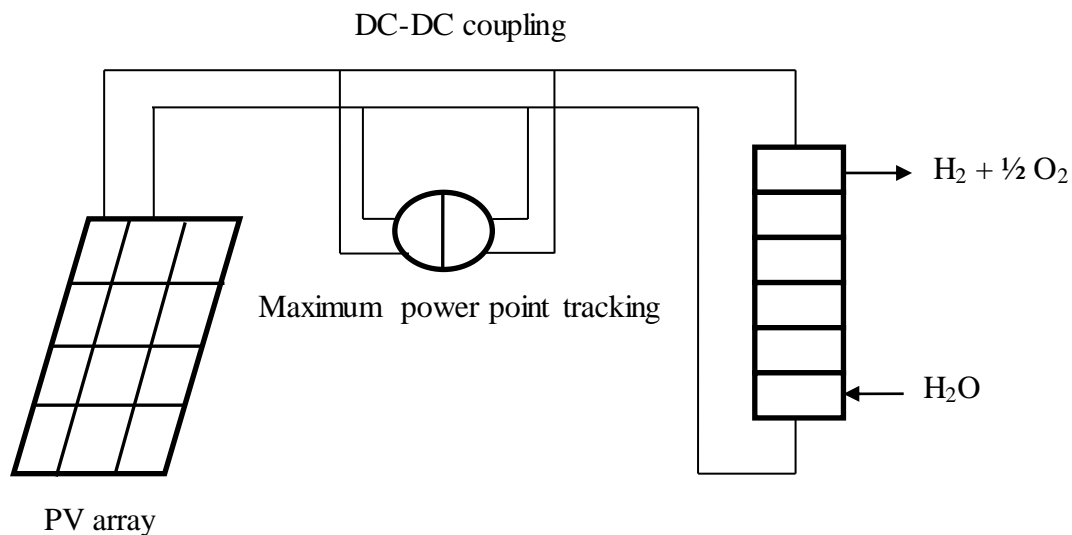
Figure 14 Schematic diagram of PV-electrolysis system pilot plant (Grimes *et al.* 2008:501)

2.8   Hydrogen distribution and storage

Hydrogen, particularly for use in fuel cell applications, can be stored in various ways. It can be stored as a compressed gas, liquid, solid or combined with other chemicals. Larger quantities of hydrogen can be stored in natural gas fields, aquifers and salt domes (Supramaniam 2006:421).

According to Grimes *et al.* (2008:28) mechanical compression is needed to raise gas pressure to levels needed for almost all applications. Unfortunately, this compression process carries with it an energy penalty, requiring capital expenditure for the compression equipment, and incurs on-going operation and maintenance costs. Two alternatives to pressurized gaseous hydrogen storage are available: liquified hydrogen and metal hydrides. However, liquefying hydrogen calls for expensive, elaborate equipment to cool the gas to –253°C, and all this takes energy. Metal hydrides are expensive, heavy and have a limited lifespan, showing decay in energy storage capacity after repeated cycling. Research is needed on approaches for hydrogen storage using the reversible formation of safely transportable chemical compounds.

Table 3 The six basic hydrogen storage methods and phenomena
(Züttel *et al.* 2008:168)

Storage Media	Volume	Mass	Pressure	Temperature	
	max. 33 kg $H_2 \cdot m^{-3}$	13 mass%	800 bar	298 K	Composite cylinder *established*
	71 kg $H_2 \cdot m^{-3}$	100 mass%	1 bar	21 K	Liquid hydrogen
	max. 150 kg $H_2 \cdot m^{-3}$	2 mass%	1 bar	298 K	Metal hydrides
	20 kg $H_2 \cdot m^{-3}$	4 mass%	70 bar	65 K	Physisorption
	150 kg $H_2 \cdot m^{-3}$	18 mass%	1 bar	298 K	Complex hydrides *reversibility ?*
	>100 kg $H_2 \cdot m^{-3}$	14 mass%	1 bar	298 K	Alkali + H_2O

According to Züttel *et al.* (2008:167-168), hydrogen storage basically implies the reduction of the enormous volume of the hydrogen gas. One kilogram of hydrogen at ambient temperature and atmospheric pressure takes a volume of 11m^3. In order to increase the hydrogen density in a storage system, work must either be applied to compress the hydrogen, or the temperature has to be decreased below the critical temperature or, finally, the repulsion has to be reduced by the interaction of hydrogen with another material. The second important criterion of a hydrogen storage system is the reversibility of the hydrogen uptake and release. This criterion excludes all covalent hydrogen carbon compounds as hydrogen storage materials, because the hydrogen is only released from carbon hydrogen compounds if they are heated to temperatures above 800°C or if the carbon is oxidized. There are basically six methods of reversibly storing hydrogen with a high volumetric and gravimetric density as seen in Table 3. This research is focused on hydrogen storage in composite cylinders.

The gravimetric density ρ_m, the volumetric density ρ_v, the working temperature T and pressure p are listed. RT stands for room temperature (25°C). From top to bottom in Table 3: compressed gas (molecular H_2) in a lightweight composite cylinder (tensile strength of the material is 2000 MPa); liquid hydrogen (molecular H_2), continuous loss of a few percent per day of hydrogen at

RT; hydrogen (atomic H) intercalation in host metals, metallic hydrides working at RT are fully reversible; physisorption (molecular H_2) on materials, for example carbon with a very large specific surface area, fully reversible; complex compounds ($[AlH_4]^-$ or $[BH_4]^-$), desorption at elevated temperature, adsorption at high pressures; chemical oxidation of metals with water and liberation of hydrogen, not directly reversible (Züttel *et al.* 2008:168-169).

2.9   Storage cylinder position consideration

The HOGEN GC300 hydrogen generator employed for this research produces hydrogen gas which is 99.999% clean and this gas needs to be stored in a cylinder for later use and therefore must be stored as clean as it was produced. The storage cylinder needs to be purged so it can store clean hydrogen gas and argon gas was used for this purpose. The choice of argon gas was based on its properties compared to that of hydrogen gas.

Argon is 1.4 times as heavy as air, nontoxic and is an inert gas. Argon has a molecular weight of 39.95 g/mol and its density is 1.7837 kg/m^3 (Universal Industrial Gases 2011). Hydrogen on the other hand is the lightest of all gases, approximately one-fifteenth as heavy as air. Hydrogen's molecular weight is 2.02 g/mol and has a density of 0.08988 kg/m^3 (Universal Industrial Gases 2011).

 This means that argon gas is almost 20 times as heavy as hydrogen gas. A mixture of the two gases in a container such as a storage cylinder will see argon gas settle at the base of the storage cylinder because of its superior weight and hydrogen gas occupying the upper part of the cylinder. When argon is used as a purge gas for a storage cylinder before filling with hydrogen gas, there is a need to ensure that the argon gas is completely flushed out of the storage cylinder before filling with hydrogen gas. The storage cylinder position (vertically or horizontally) could play a role in how quickly the storage cylinder is filled with clean (99.999%) hydrogen after purging with argon gas.

2.10   Hydrogen purity measurement technique

As mentioned earlier, the stored hydrogen gas needs to be as pure as the generated hydrogen gas. A thermal conductivity detector is employed for this purpose.

According to Systech Instruments (2003), each gas has a known thermal conductivity that is how well heat transfers through it. This property can be measured.
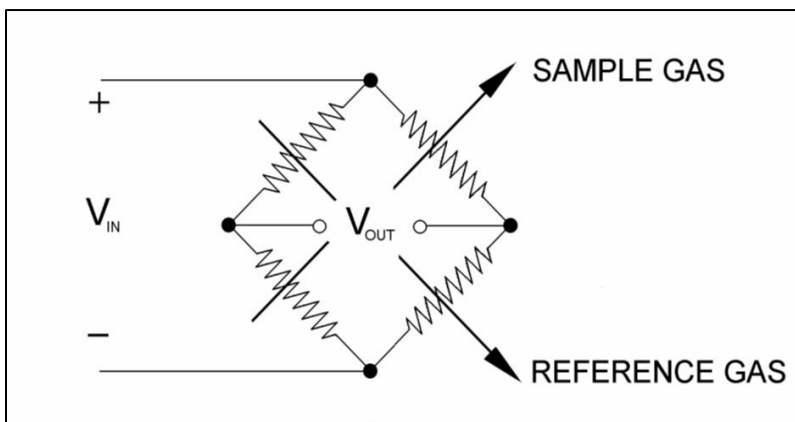
Figure 15 Wheatstone Bridge of the thermal conductivity detector (Systech Instruments 2003)

Thermal conductivity is measured with a sensor that employs four matched filaments that change resistance according to the thermal conductivity of the gas passing over it. These four filaments are connected in a Wheatstone Bridge configuration as shown in Figure 15.

When all four resistances are the same, V_{OUT} is zero and the bridge is considered balanced. When zeroing, the reference gas is passed over all the filaments, the resistances will be the same (because filaments are matched) and the bridge is balanced. When the sample gas is passed over half of the bridge, then V_{OUT}'s value correlates to the content of the sample gas in the reference.

The detector is a four element katharometer having two elements situated in the reference gas and two elements in the sample gas as shown in Figure 16.
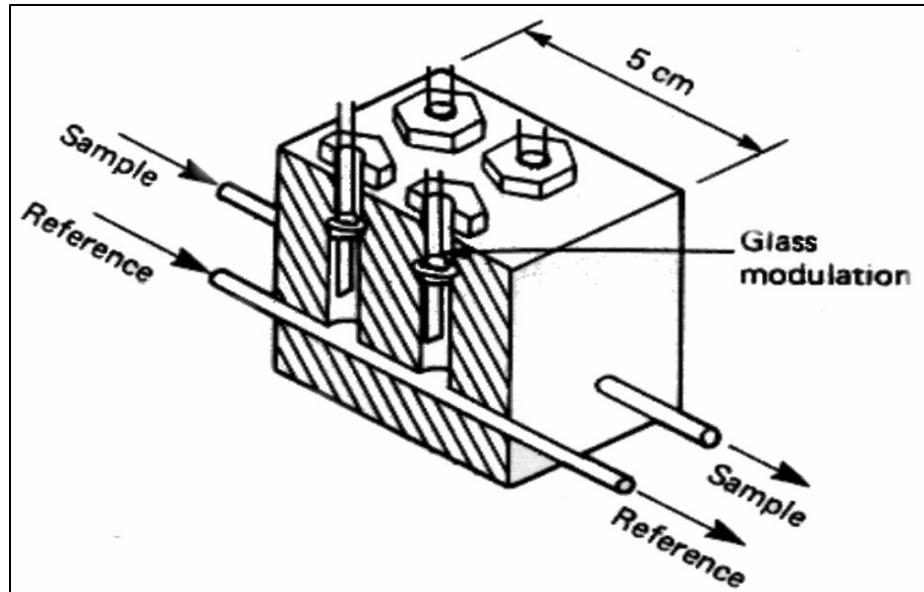
Figure 16 Cut-away view of the thermal conductivity sensor (Systech Instruments 2003)

The four elements are electronically connected in a bridge circuit and a constant current is passed through the bridge to heat the elements. If each element is surrounded by the same gas, then the temperature, and hence the resistance, of each element will be similar and the bridge circuit will be balanced. When the gas to be measured is introduced into the sample gas stream, the two Katharometer elements in this gas stream will be cooled to a greater extent than the two elements in the reference gas. The bridge circuit will be unbalanced, producing a signal voltage related to the measure gas content of the sample gas. This relationship is non-linear.

2.11   Summary

Chapter 2 gives a detailed literature review on solar cell technology as well as the non-renewable and renewable methods of hydrogen production with the focus of the research placed on the integration of solar-photovoltaic power and an electrolyser for hydrogen production. Storage options for hydrogen gas were also enumerated.

Chapter 3 Experimental setup and procedures

3.1   Introduction

The previous chapter dealt with solar energy and photovoltaics. Operation of solar cells and solar cell parameters were outlined while the literature on solar cell types, modules and arrays concluded the chapter. This chapter will focus on the layout and design of a photovoltaic-electrolyser hydrogen production and storage system.

3.2   Experimental setup

The overall photovoltaic-hydrogen production system consists of the photovoltaic array, a pyranometer, a thermocouple, electrolyser/hydrogen generator, the maximum power point tracker, the thermal conductivity detector, a vacuum pump and a storage cylinder.

a.   Photovoltaic panels

The design of the hydrogen production and storage system revolves around the photovoltaic (PV) panels used for the study.
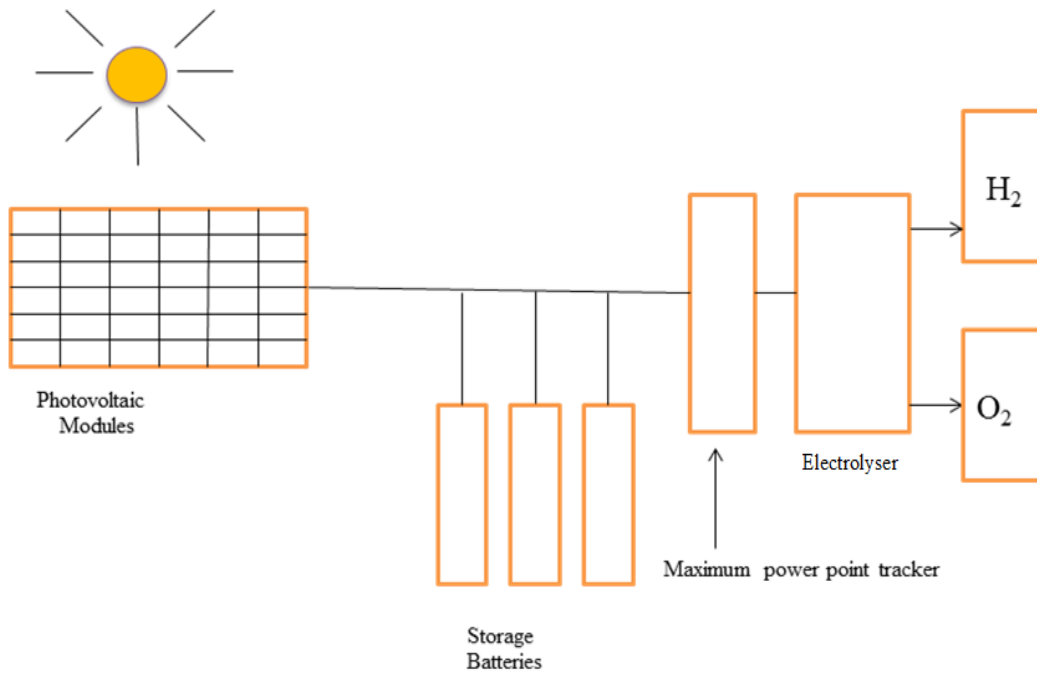
Figure 17 A conventional photovoltaic - electrolyser hydrogen generation system

Figure 17 shows the diagram of a conventional photovoltaic-electrolyser generation system, while Figure 18 shows the PV panels used for the study that are mounted on the university roof.

Figure 18 Photovoltaic panels mounted on the university roof

There are different types of solar panels with various specifications and applications. However, for this study, 8 PV panels with the same specifications and connected two-two in series (a total of four panel pairs) were used. The panels are polycrystalline silicon type with maximum output of 220 W, with an open circuit voltage of 36.6 V and short circuit current of 8.08 A at standard temperature conditions (STC). The PV modules are supported on a tilted steel frame structure for PV panel angle adjustment.

The panels are used to supply more than 1500 W (1760 W Maximum) to a maximum power point tracker (MPPT). Connecting all the panels in series could be a problem in that the supply voltage becomes too high. This panel setup results in an output voltage of 56 V (28 V per panel), depending on sunlight exposure. The panel pairs are connected through 20 A DC circuit breakers which makes it possible to isolate some or all the pairs (Viljoen & Pienaar 2011:560).

The panels are connected this way in order to accommodate a higher study based on the energy management of the overall solar/hydrogen-driven power plant also being carried out at the university. The design of the solar panel mounting brackets was done based on the position and space allocation available at the Vaal University of Technology and frames were designed for

each of the eight solar panels. This is done in order to eliminate the effects of wind disturbances on the panels.

All the panels can be swung from left to right in order to follow the sun and are controlled by a movement bar and thus only one motor mounted on the first panel is used to swing all the panels at the same time. The angle at which the PV panels are mounted needs to be adjusted manually to compensate for winter and summer, since it will not be cost-or energy-effective to motorize each panel on its own. The motor used is a 12 V DC motor and a chain system with a gear ratio of 1:22 to increase the torque on the motor and to decrease the speed of movement (Viljoen & Pienaar:560-561).

b.   Pyranometer

A LI-200 pyranometer was used for the measurement of solar irradiance. The LI-200 features a silicon PV detector mounted in a fully cosine-corrected miniature head. Current output, which is directly proportional to solar radiation, is calibrated against an Eppley Precision Spectral Pyranometer (PSP) under natural daylight conditions in units of watts per square meter (W/m^2). Under most conditions of natural daylight, the error is $< 5\%$.

The Vaal Triangle enjoys sunshine for up to 10 hours daily as shown in Figure 19. The peak sunshine period is between 10:00 in the morning and 16:00 in the afternoon. The solar radiation intensity increases rapidly between 8:00 and 9:00 in the morning and then drops rather slowly between 13:00 in the afternoon and 18:00 in the evening.

The HOGEN GC300 hydrogen generator employs a fuel cell in the reverse mode and it produces 300 ml of hydrogen gas per minute with only 0.3 ml of water consumption per minute and runs on a pressure of up to 1300kPa. It can therefore be concluded that on a 300ml hydrogen generator system, and 10 hours of sunshine, we can produce about 180 litres of hydrogen per day at 1300kPa pressure.

Daily Solar Irradiance for Vanderbijlpark
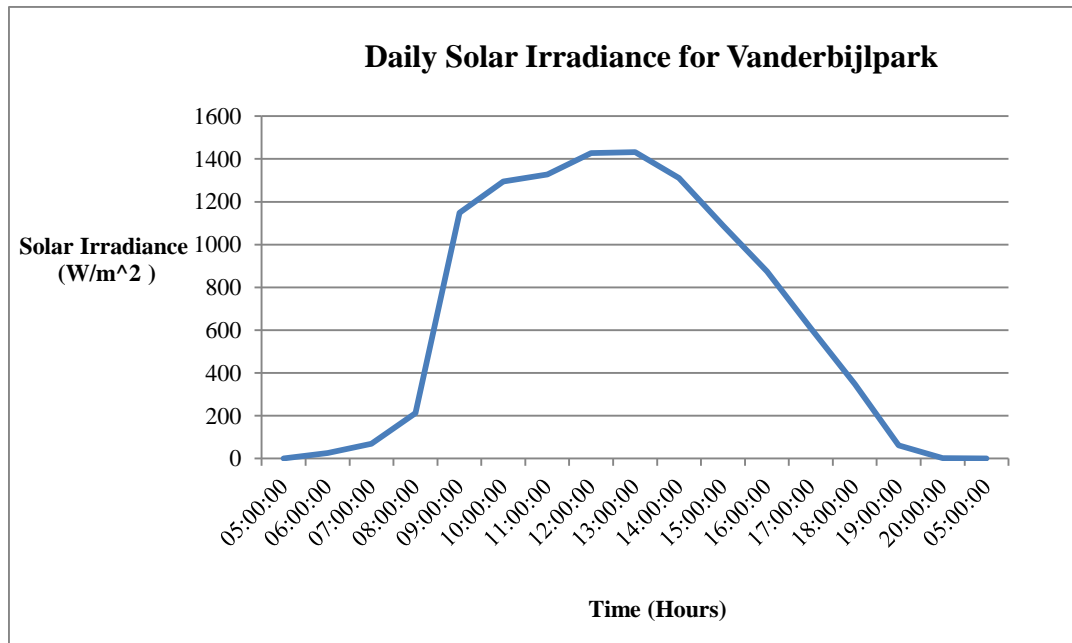
Figure 19 Solar irradiance graph for Vanderbijlpark

c.   Maximum power point tracker

The maximum power point tracker (flexmax 80 MPPT) is used to optimize the transmitted PV array power to increase the overall system efficiency. It consists of a step-down dc-dc converter with input and output filters, and a driving circuit. The MPPT drives the operating point of the PV module to the maximum power point detected by the control system.

d.   Thermal conductivity detector

The microvolume thermal conductivity detector (TCD), model TCD2 was used to measure the purity of the stored hydrogen. A TCD detector consists of an electrically-heated wire or thermistor. The temperature of the sensing element depends on the thermal conductivity of the gas flowing around it. The principle of operation is based on the relative change in the thermal conductivity of the gas passing across the detector filament as components elute from the column. Heat is lost continuously by the filament through the carrier gas to the cell wall of the detector. By measuring the amount of current required to maintain a constant filament temperature as gases of varying thermal conductivities cross the filament, a voltage corresponding to the gas crossing the filament is displayed on the TCD screen. This process is

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non-destructive of the sample and is concentration dependent. The Valco Microvolume TCD (model TCD2) used in this study is a stand-alone system. It consists of a detector and a control module which incorporates the electrometer and temperature controls.
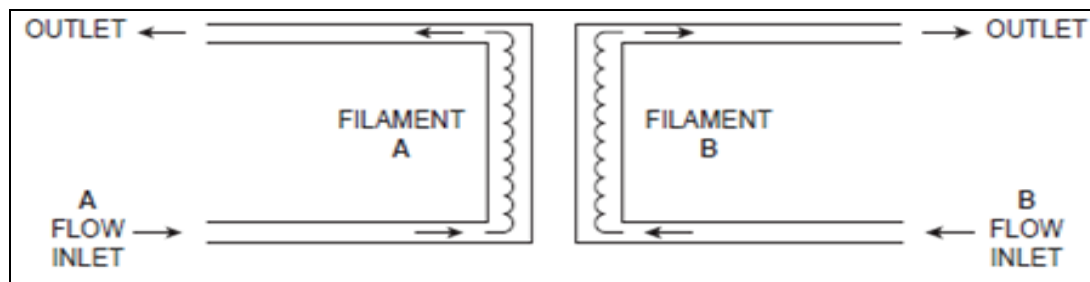
Figure 20 Unique dual filament design for the TCD

The detector cell includes two separate filaments, capable of independent or referenced (differential) operation as shown in Figure 20. An output signal is provided as 0-1 and 0-10 volts attenuated for chart recorders and 0-1 and 0-10 volts unattenuated for integrators and data systems. In this study, an output signal of 0 Volts was used as the reference value for pure hydrogen. The TCD is unique in its implementation, since changes in conductivity are measured only by the change in current required to keep the filament at a constant temperature. Each of the two filaments can be operated independently without referencing these changes to a matched filament with reference gas.

e.　Vacuum Pump

The vacuum pump used is a small and compact, directly motor-driven, piston-powered, oil-free Rocker 400 vacuum pump.

f.　Hydrogen Storage Cylinder

The storage cylinder used for this study is a Swagelok, 3.785 litre, double-ended cylinder with a working pressure of up to 34.5 MPa (344 bar). Owing to its low energy per unit volume, hydrogen is generally stored as a compressed gas or liquid for practical applications. Hydrogen becomes a liquid at 20K; a volume of liquid hydrogen weighs only 10% as much as the same volume of gasoline. Obviously, handling problems are severe at 20K. In order to serve as a practical fuel for transportation, hydrogen must be highly compressed to minimize fuel storage

volume. Typical hydrogen storage pressures are 13.9 to 34.5 MPa. Existing hydrogen generation technologies typically produce hydrogen gas at between atmospheric pressure and 2.6 MPa (Grimes *et al.* 2008:28).

According to Züttel *et al.* (2008:167-168), the most common storage systems are high pressure gas cylinders with a maximum pressure of 20 MPa. New lightweight composite cylinders have been developed which are able to withstand pressure up to 80 MPa and therefore the hydrogen can reach a volumetric density of 36 kg/m^3, approximately half of that in its liquid form at the normal boiling point. The gravimetric hydrogen density decreases with increasing pressure due to the increasing thickness of the walls of the pressure cylinder.

The hydrogen storage was later scaled up to a ballast of 9 cylinders with a storage capacity of 450 litres.

g.   Electrolyser/Hydrogen Generation

The HOGEN GC300 laboratory hydrogen generator was used as the electrolyser for hydrogen generation. The HOGEN GC hydrogen generator uses AC electric power and deionized water to produce a continuous stream of pressurized scientific grade (99.9999+ %), electrolytic hydrogen gas and automatically maintains a user-selected downstream pressure. The GC300 has three cells on the cell stack and normally runs from 6.6 – 7.6V. The current required varies from 19 - 23A. The HOGEN GC300 employs a fuel cell in the reverse mode and it produces 300 ml of hydrogen gas per minute with only 0.3 ml of water consumption per minute and runs on a pressure of up to 1300kPa.

Figure 21 shows the block diagram of the hydrogen storage system designed for this study. The system (for the purpose of hydrogen purity comparison and determination) employs an alternative source of hydrogen in addition to hydrogen gas generated from the HOGEN GC300.
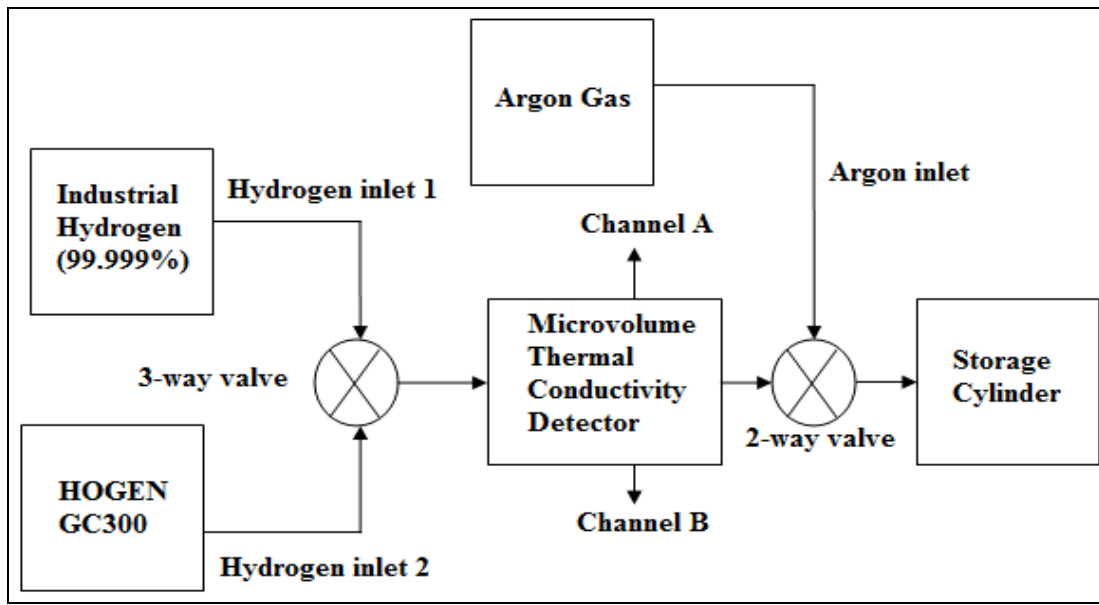
Figure 21 Block diagram of the hydrogen generation and storage system
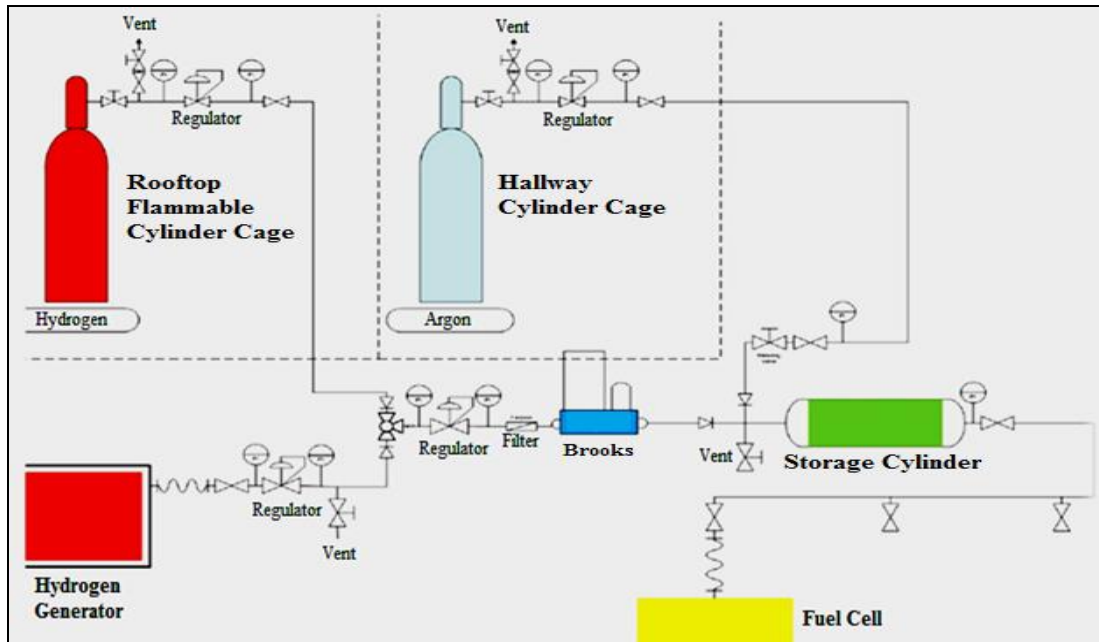
Figure 22 Designed hydrogen generation and storage system

Thus the two hydrogen generation sources are: (i) hydrogen produced by the HOGEN GC300 laboratory hydrogen generator mentioned above and purchased from Proton Energy Systems and (ii) industrial hydrogen purchased from a reputable gas company in South Africa. Figure 22 shows the schematic diagram of the designed hydrogen production and storage system. A three-

way valve is employed in the setup to allow switching from one source of hydrogen to the other and to also allow the closing of both sources of hydrogen when the system is not in use.
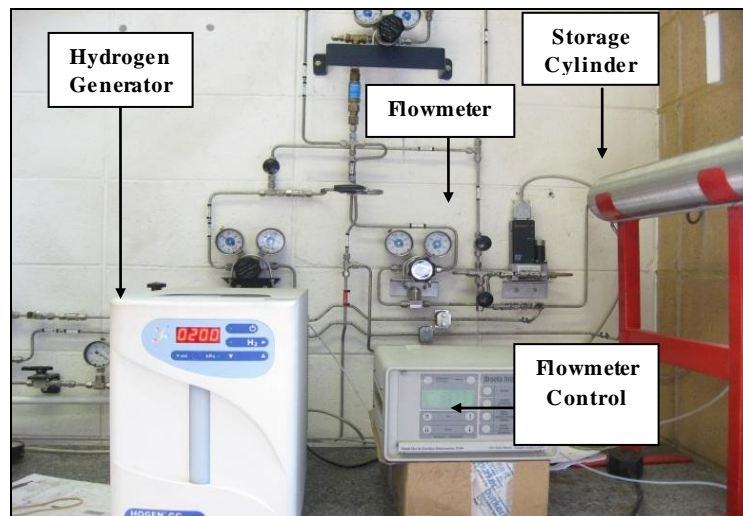
Figure 23 Laboratory hydrogen generation
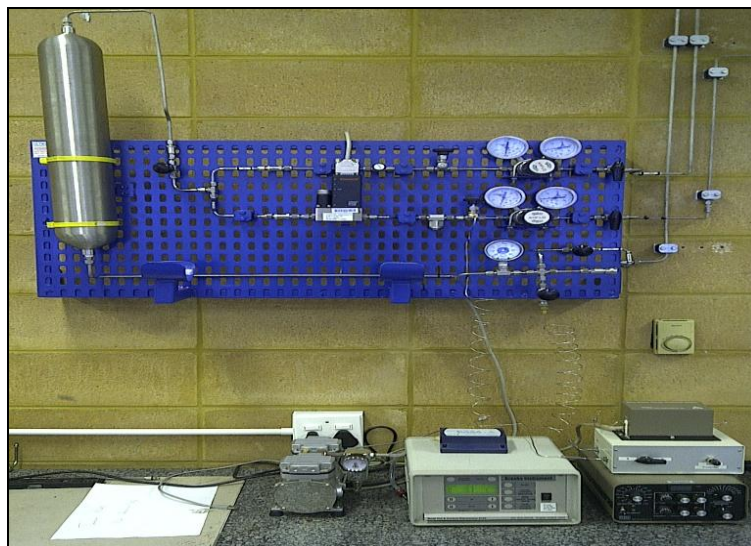
Figure 24 Laboratory hydrogen storage

This setup allows comparison of the purity of the generated hydrogen with that manufactured industrially and specified to be 99.999% clean. The laboratory setup for hydrogen generation and storage is shown in Figures 23 and 24.

3.3   System operation

The overall hydrogen purity system used consists of a cylinder of industrially produced hydrogen gas (99.999% pure) mounted in a cage on the university roof and directly supplying a sample storage cylinder with hydrogen gas. The HOGEN GC300 hydrogen generator, the microvolume thermal conductivity detector, the storage cylinder, a cylinder of industrially produced argon and a vacuum pump completes the system.

Argon was used to purge the storage cylinder. Argon gas is a rare atmospheric gas which is colourless, odourless, tasteless and non-toxic. It is considered extremely inert and forms no known chemical compounds. It was therefore employed in the study as a purge gas for the sample storage cylinder. This was also done to ensure that all the air that might have been trapped in the storage cylinder is completely displaced since a mixture of hydrogen with air is highly explosive. The aim of this study is to produce and store pure hydrogen, therefore it was necessary to ensure that the sample storage cylinder is void of any form of impurity. Figure 25a & b shows the experimental setup. The sample storage cylinder is fed from two inlets: one inlet for pure hydrogen gas and the other for argon gas. The storage cylinder is then vented of the argon gas and filled with hydrogen gas.

The TCD has two channels, A & B. The content of the storage cylinder is monitored on channel B of the TCD and compared to channel A, which is the channel for the reference pure hydrogen gas purchased from industry. Channel A of the TCD is connected to the inlet of the storage cylinder to measure the purity of the inlet gas, which in this study is pure or 99.999% hydrogen. It also provides a reference value (for pure hydrogen) to which the value of the purity of the outlet gas can be compared. Channel B of the TCD is connected to the outlet of the storage cylinder. The purity of the outlet gas is determined by comparing its value on the display screen to the reference value of the pure hydrogen gas measured by channel A. The reference value set for hydrogen gas is 0.000 V and the reference value for argon gas is 1.373 V. The position of the storage cylinder was also taken into consideration while purging with argon gas and also measuring the purity of the stored hydrogen.
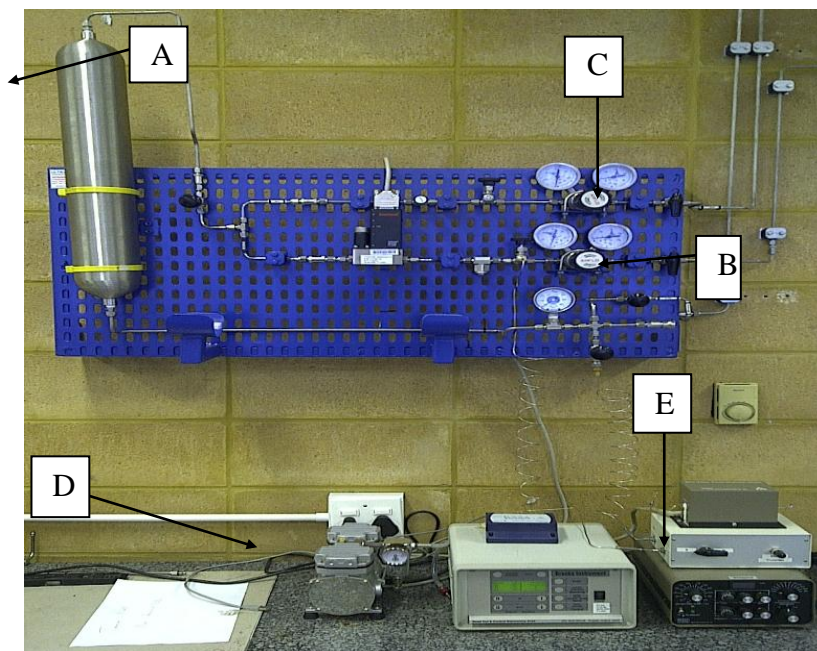
Figure 25a Laboratory setup with storage cylinder in vertical position− A: Storage cylinder, B: Hydrogen inlet, C: Argon inlet, D: Vacuum pump and E: TCD
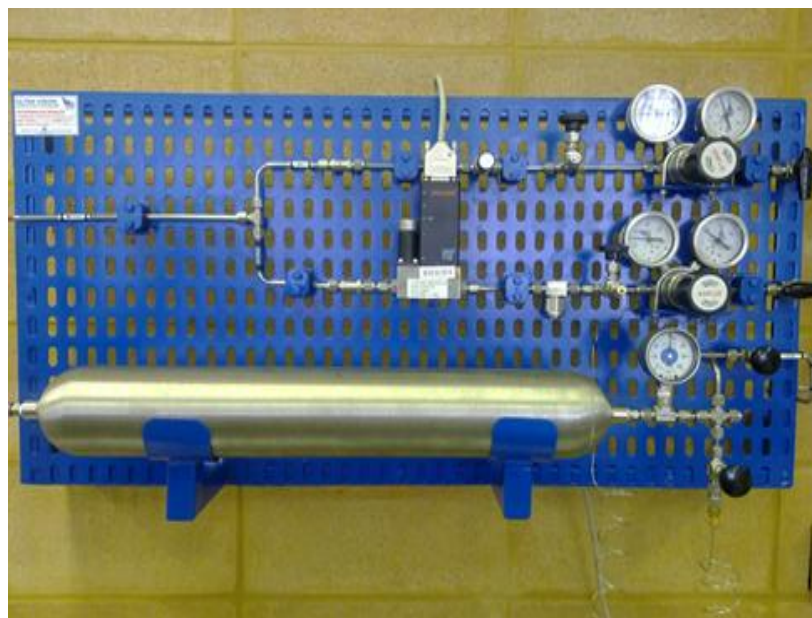
Figure 25b Laboratory setup with storage cylinder in horizontal position

The sample storage cylinder was placed vertically and horizontally to see if the weight of argon gas (used to purge the sample storage cylinder) will have any effect on the purity of the stored hydrogen gas.

Viljoen and Pienaar (2011:563-564) noted that the fuel cell produces energy based on the reduction reaction of hydrogen, which in turn reacts with oxygen from air to produce water vapour. The reaction set is as follows:

1      $H_2 \rightarrow 2H^+ + 2e^-$ (18)

2      $\frac{1}{2} O_2 + 2e^- \rightarrow O^{-2}$ (19)

3      $2H^+ + O^{-2} \rightarrow H_2O$ (20)

Net $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ (21)

Since oxygen from the air is supplied in excess to the fuel cell, the reaction of concern is the reduction of hydrogen, reaction 1. Using this reaction, the equivalent molar quantity and mass of hydrogen per hour-Amp can be determined by the following relation:

$$n_{H_2} = \frac{1 \, C/_{sec}}{1 \, Amp} * \frac{1 \, equiv. \, e^-}{96487 \, C} * \frac{1 \, mol \, H_2}{2 \, equiv \, e^-} * \frac{3600 \, sec}{hr} = 0.01866 \frac{mol}{hr * Amp} \quad (22)$$

$$m_{H_2} = \frac{0.01866 \, mol}{hr * Amp} * \frac{2.02 \, g \, H_2}{1 \, mol \, H_2} * \frac{1 \, kg}{1000 \, g} = 3.77 * 10^{-5} \frac{kg \, H_2}{hr * Amp} \quad (23)$$

$n_{H_2} \equiv$ molar quantity per ampere hour

$m_{H_2} \equiv$ molar mass per ampere hour

where: $1 \, C/_{sec} \equiv$ the equivalent formula for 1 Amp

$96487 \, C \equiv$ is the value for 1 equiv. e^-

and 1 mol H_2 yielded 2 equiv e^- from the reduction of hydrogen in reaction 1.

The amount of hydrogen needed can be determined for a given power and voltage specification. For example, for a Nexa fuel cell to provide 1.2 kW of power with a total voltage of 24 V at 45% efficiency at full load, the current, i, and the amount of hydrogen required can be determined as follows:

$$i = \frac{P}{V} = \frac{1200}{24} = 50 \, Amp \tag{24}$$

$$M_{H_2} = 50 \, Amp * \frac{3.77 * 10^{-5} \, kg \, H_2}{hr * Amp} = 18.85 * 10^{-4} \frac{kg \, H_2}{hr} \tag{25}$$

$$\varepsilon = \frac{U_{Consumed}}{U_{Feed}} \rightarrow 0.45 = \frac{18.85 * 10^{-4} \frac{kg \, H_2}{hr}}{U_{Feed}} \rightarrow U_{Feed} = 0.00419 \frac{kg \, H_2}{hr} \tag{26}$$

where:

$M_{H_2} \equiv$ Mass of hydrogen needed per hour for an ideal fuel cell.

$U_{Feed} \equiv$ Mass of hydrogen needed for a fuel cell with 45% efficiency.

3.4   Summary

In this chapter, the basic concepts of the system design were discussed. The equipment needed for the study was enumerated and the designed hydrogen production and storage system was shown. The next section will discuss the results obtained from experimental measurements performed on the designed system.

Chapter 4   Results and discussions

The previous chapter dealt with the experimental procedures of a designed pv-electrolysis hydrogen production system. Chapter 5 is devoted to the results obtained from the designed system.

4.1   Purity measurement results

In the purity determination experiment, two different positions as stated earlier were considered for the storage cylinder as shown in Figure 25a & b: (a) the storage cylinder was placed in a vertical position and (b) the storage cylinder was placed in a horizontal position. In both positions, argon gas was first fed into the cylinder to rid it of all impurities before being gradually replaced with hydrogen. After filling with hydrogen the purity level is checked on the TCD and if it is not close to the reference value of 0.000 volt set for pure hydrogen, it means the gas stored is a hydrogen-argon mixture. The cylinder is vented and then refilled with hydrogen. The purity level is checked for every step taken until a value close or equal to the reference value of the pure industry hydrogen is attained. The results obtained with the storage cylinder in the horizontal position are tabulated in Table 4.

Table 4 Purity measurements for horizontal sample storage cylinder position with argon as purge gas

Number of flushes	Hydrogen Purity (%)	Output B (V)	Argon Reference Value (V)
1	0.072833	1.372	1.373
2	0.218499	1.37	1.373
3	73.343044	0.366	1.373
4	92.352513	0.105	1.373
5	96.868172	0.043	1.373
6	98.324836	0.023	1.373
7	99.854334	0.002	1.373
8	99.927167	0.001	1.373

In the horizontal position it took 8 flushes with hydrogen to get rid of all the argon gas used to purge the storage cylinder. The reason for this is that argon is a heavier gas than hydrogen and it sits in the bottom of the storage cylinder. If the argon gas is not completely vented, it could affect the purity of the stored hydrogen gas.
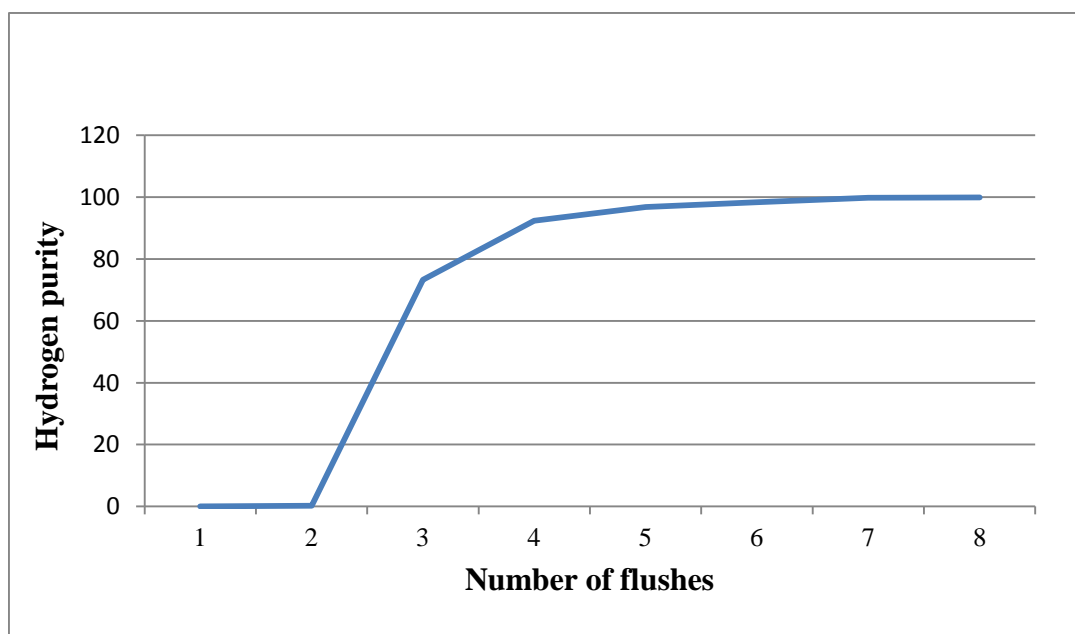
Figure 26 Hydrogen purity versus the number of flushes with argon gas for horizontal storage cylinder positions

Table 5 Purity measurements for vertical sample storage cylinder position with argon as purge gas

Number of Flushes	Hydrogen Purity (%)	Output B (V)	Argon Reference Value (V)
1	0.218499	1.37	1.373
2	0.509832	1.366	1.373
3	92.935178	0.097	1.373
4	98.543336	0.02	1.373
5	99.635834	0.005	1.373
6	99.854334	0.002	1.373
7	99.927167	0.001	1.373

The results obtained with the storage cylinder in the vertical position are shown in Table 5. In the vertical position, 7 flushes were required to rid the storage cylinder completely of argon gas. This offered little improvement on the horizontal cylinder position.
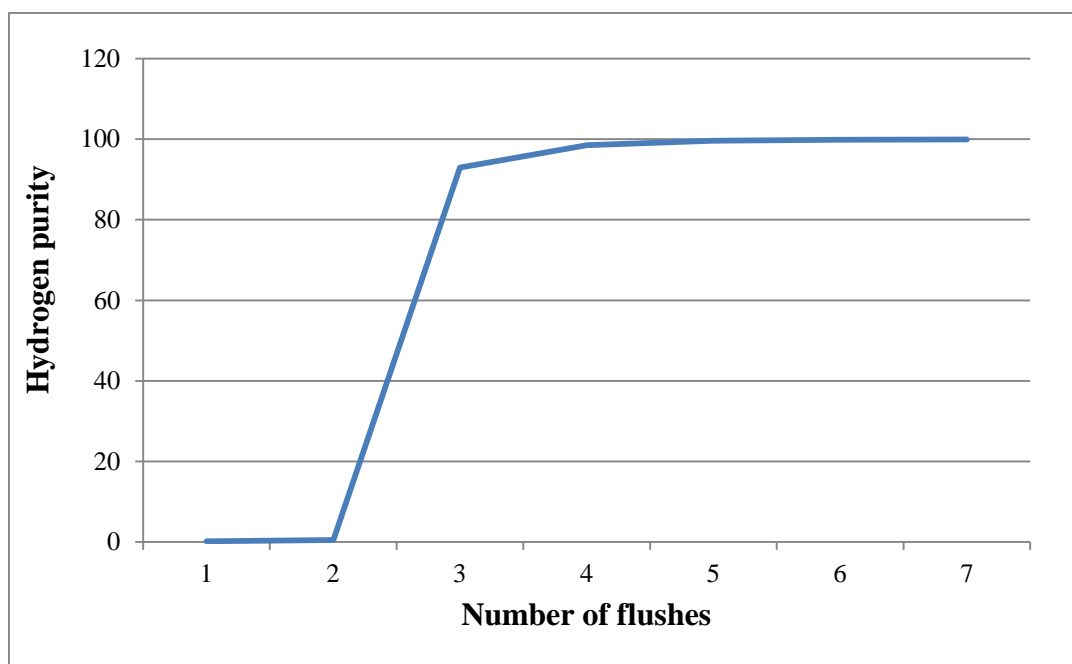
Figure 27 Hydrogen purity versus the number of flushes with argon gas for vertical storage cylinder position

A final approach towards the purity determination of the stored hydrogen was to evacuate the sample storage cylinder with a vacuum pump instead of purging with argon gas (storage cylinder vertical). The results obtained were recorded and tabulated in Table 6.

Table 6 shows a drastic reduction in the number of times needed to vent and fill the storage cylinder before 99.9% hydrogen was stored. It took only one vent with the use of the vacuum pump as the impurity extractor to reset the cylinder to store high grade hydrogen gas. Graphs showing the relationship between the purity of the generated hydrogen and the number of flushes required before pure hydrogen is stored for all three different scenarios are shown in Figures 26, 27 and 28. It is seen that pure hydrogen is obtained and stored faster when the sample cylinder is in the vertical position (Figure 27) than when in the horizontal position (Figure 26). It took seven flushes as opposed to eight in the horizontal position.

Table 6 Purity measurements for vertical sample storage cylinder position with a vacuum pump

Number of Flushes	Hydrogen Purity	Output B	Argon

	(%)	(V)	Reference Value (V)
1	98.980335	0.014	1.373
2	99.927167	0.001	1.373
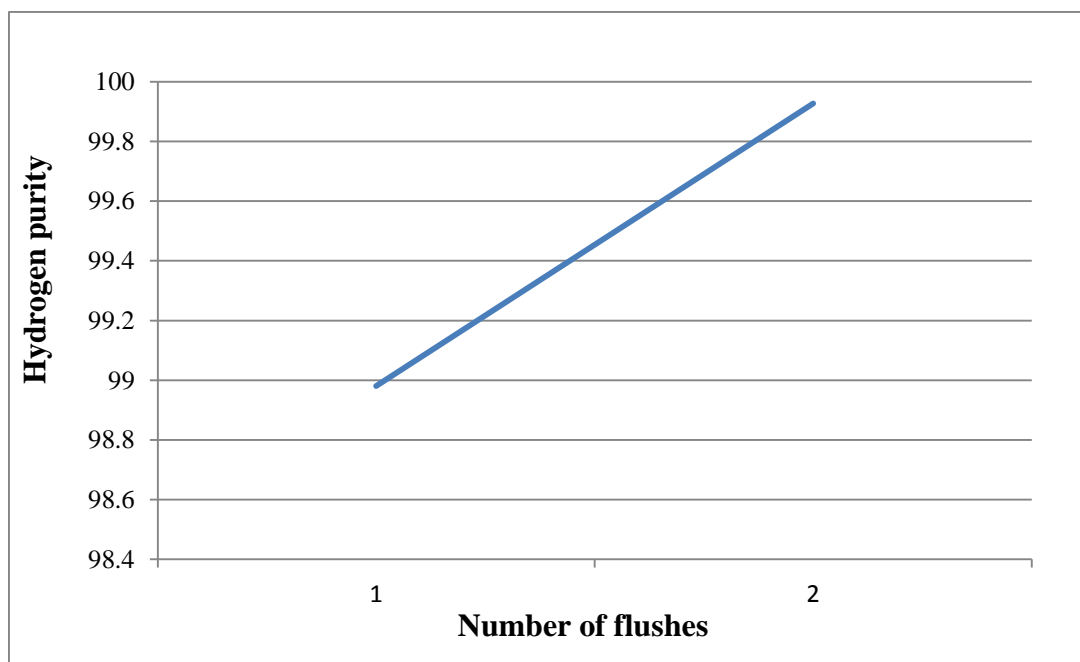
Figure 28 Hydrogen purity versus the number of flushes with a vacuum pump for vertical storage cylinder position

However, when the sample cylinder was evacuated with a vacuum pump (instead of flushing with argon gas) in the vertical position, hydrogen purity was achieved at a faster rate (Figure 28). This proved to be more appropriate and economical, as the number of times needed to fill and vent the storage cylinder with argon and hydrogen gas was considerably reduced. Thus on a laboratory scale, evacuating the storage cylinder with a vacuum pump is a more effective method than purging with argon gas. However, on a large scale evacuating with a vacuum pump may not be feasible. Purging with argon gas might then be the better and realistic method.

4.2   Performance of the PV-electrolyser hydrogen generation system

According to Nobuyoshi, Takatoshi, Kazuhito and Masahiro (2002:1489), the actual maximum power points that can be obtained from a photovoltaic system vary with conditions such as the surface temperature and the quantity of solar radiation.

Relationship between the designed PV-electrolyser system's maximum power point and the system variables such as maximum output voltage and current, panel temperature , solar irradiance and solar panel tilt angles were examined under various conditions.

4.2.1 Relationship between the maximum output current and solar irradiance

Table 7 shows the maximum output current measured for different solar irradiance. The measured data are plotted and shown in Figure 29.

Table 7 Maximum output current against solar irradiance

Array Current (A)	Solar Irradiance (W/m²)
0.524	18.13
1.105	38.27
2.567	84.3
3.696	113.3
4.745	164.3
5.607	234.1
6.637	423.6
6.747	538.6
7.453	747.5
7.595	754.4
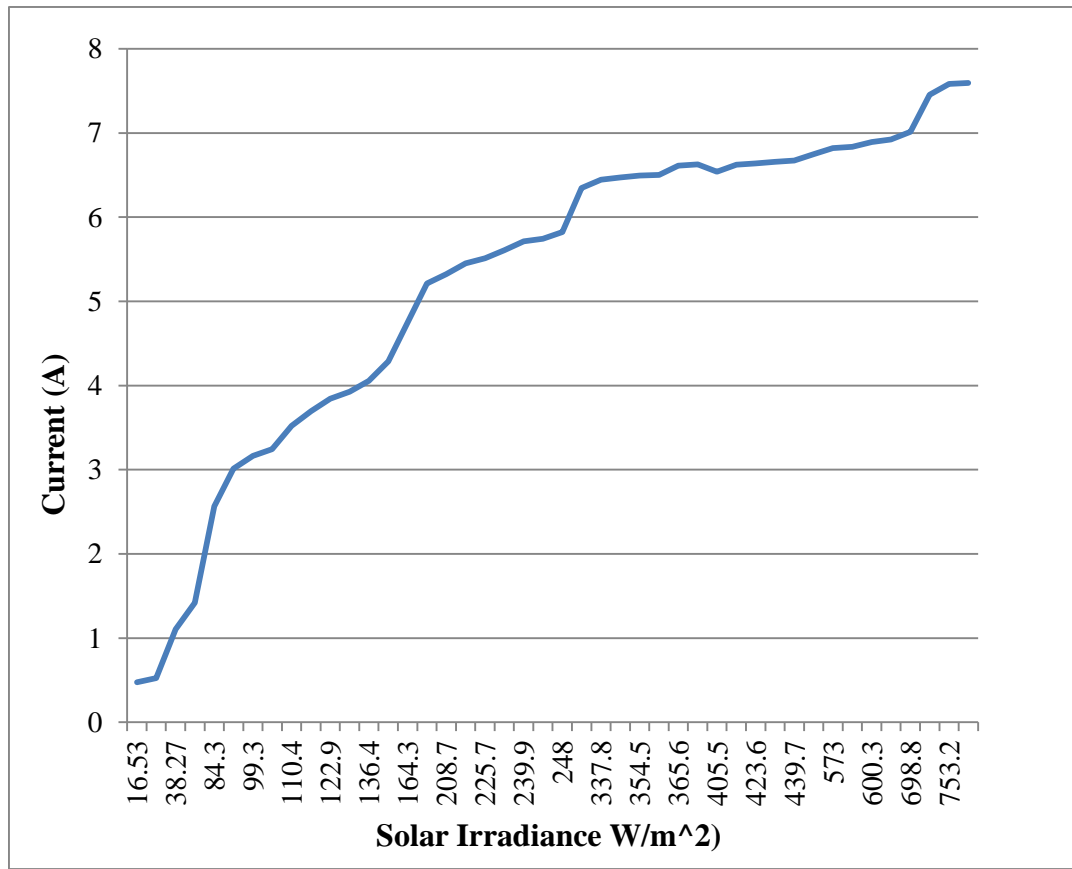
Figure 29 Maximum output current versus solar irradiance

Figure 29 shows the graph of the measured current supplied to the inverter through the maximum power point tracker for different solar irradiance over a two-day period. It is seen that the relationship between current and solar irradiance is almost linear on the whole. The variations seen in the diagram according to Nobuyoshi *et al.* (2002:1490) are due to the variations of the season and weather conditions and to the fact that the intensity of the solar irradiance radiated on the installed solar arrays differs from the intensity radiated at the position of the solar radiation sensor i.e. the pyranometer.

Ideally, the relationship between current and solar irradiance is linear i.e. current is directly proportional to solar irradiance. The red and linear scattered plots in Figure 30 shows the graph of the relationship between current and solar irradiance under ideal conditions and the blue scattered plots show the results obtained from the experiment conducted in this study.

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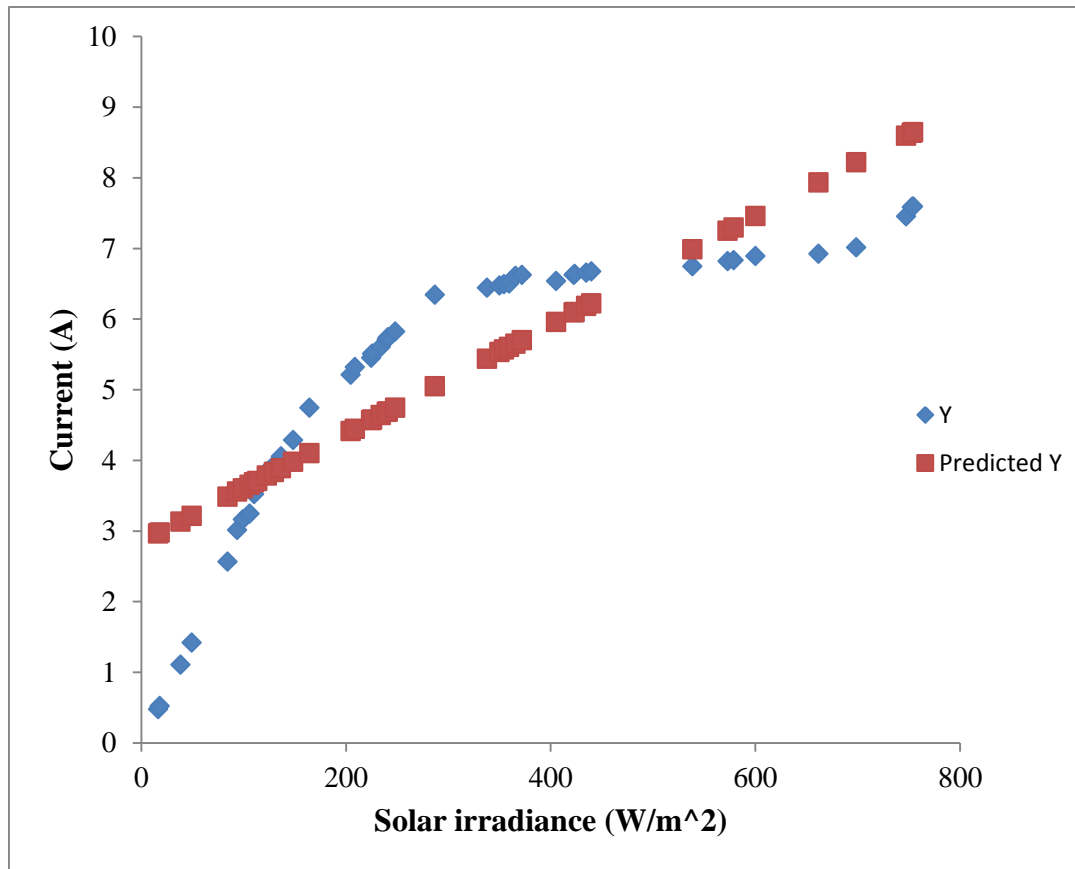
Figure 30 Maximum output current versus solar irradiance

4.2.2 Relationship between maximum output power and current

Table 8 contains the measured data for current and the maximum output power obtained from the PV-electrolyser power plant. The results obtained from the experiment are plotted and then analysed in order to determine the relationship between these two parameters for the PV-electrolyser hydrogen generation system.

The graph shows a linear relationship between maximum output power and the current. According to Nobuyoshi *et al.* (2002:1490), if the optimizing current can be found every time the intensity of the solar irradiance changes, it is possible to control the power output from the solar arrays so that the maximum output power may be obtained.

Table 8 Maximum output current against maximum output power

Array Current (A)	Power (kW)
4.432	0.1201
4.978	0.1348
5.296	0.1435
5.934	0.1503
6.694	0.1812
6.926	0.1874
7.695	0.1945
7.915	0.2174
9.838	0.2698
9.852	0.2701
10.483	0.2876
10.815	0.2968
11.644	0.3151
11.822	0.3245
12.375	0.3350
12.702	0.3486
13.439	0.3631
13.520	0.3660
14.696	0.3971
14.790	0.3648
15.695	0.4243
15.903	0.4301
16.887	0.4624
16.979	0.4591
17.602	0.4820
17.603	0.4753
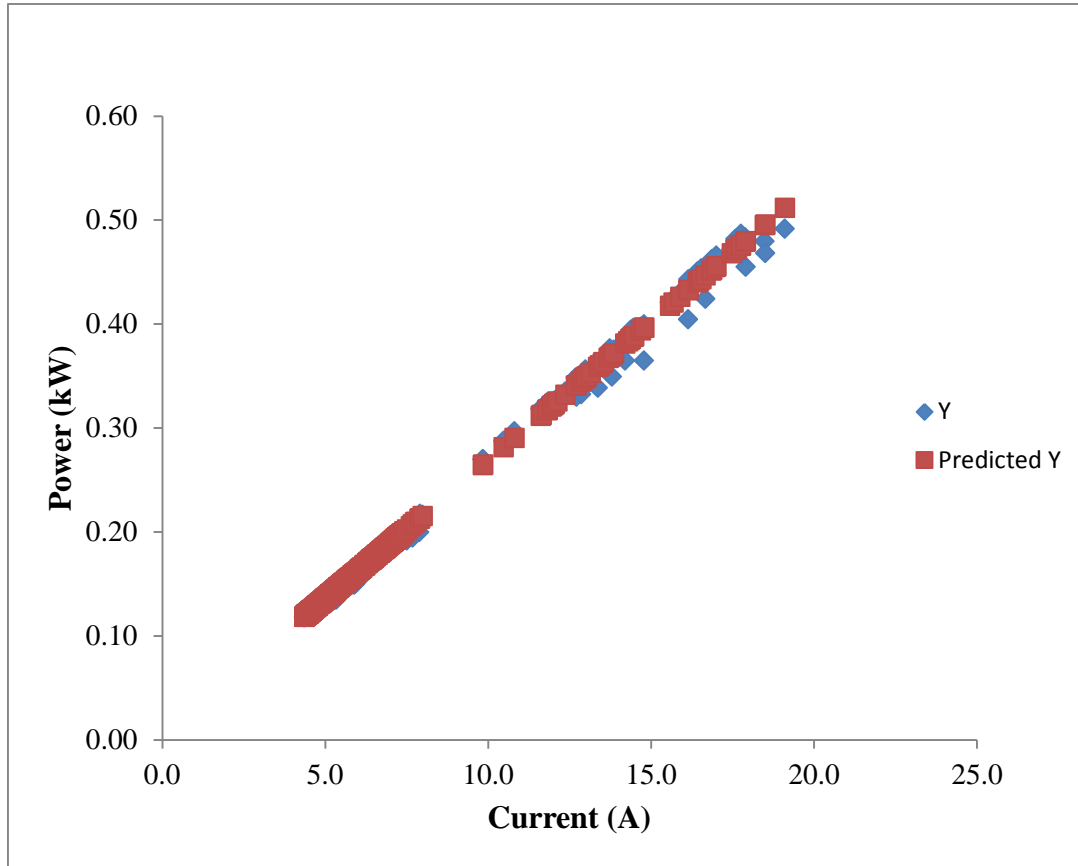
Figure 31 Maximum output power versus maximum output current

4.2.3 Relationship between solar panel temperature and maximum output voltage

Figure 32 shows the relationship between the solar panel temperature and maximum output voltage for the designed PV-electrolyser hydrogen generation system. It is seen that panel temperature has a considerable effect on the maximum output voltage obtained from the solar panel array.

The voltage is inversely proportional to the solar panel temperature. The voltage decreases as the panel temperature increases.

The voltage obtained from the system is highest when the solar panel temperature is cold. Table 9 shows the data measured for maximum output voltage against varying solar panel temperatures

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Table 9 Maximum output voltage against solar panel temperature

Panel Temperature (°C)	Array Voltage (V)
7.6	27.074768
7.8	27.07406
8.5	27.07094
8.7	27.068815
8.9	27.066545
9.3	27.063993
9.5	27.062008
9.7	27.062008
10.3	27.061441
10.5	27.061441
10.7	27.061157
10.9	27.060873
11.4	27.058889
11.6	27.058462
11.8	27.056337
12.3	27.054918
12.6	27.054352
12.8	27.049673
13.4	27.048538
13.5	27.047405
13.7	27.041733
13.9	27.041733
14.7	27.029823
14.8	27.028688
15.4	27.028688
15.7	27.017063
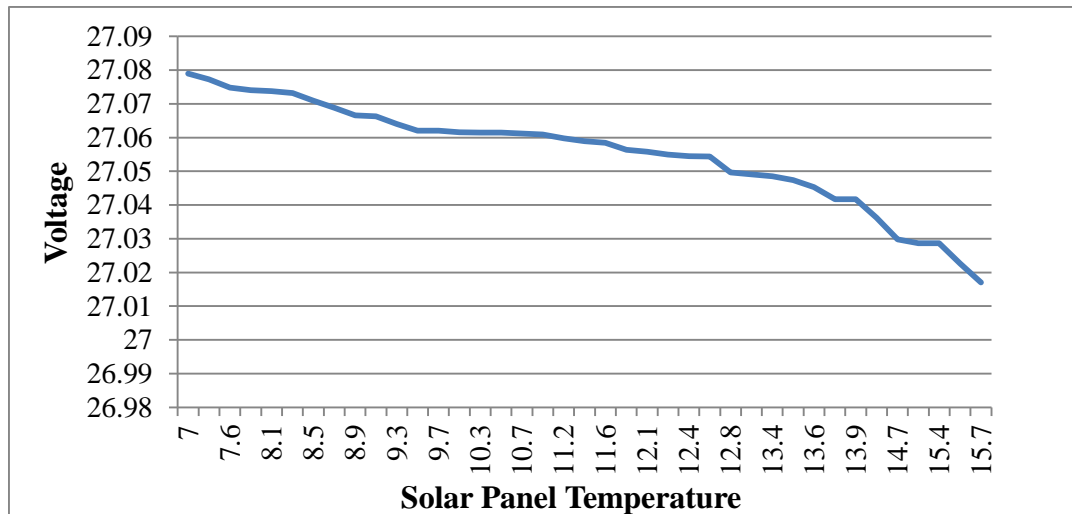
Figure 32 Maximum output voltage versus solar panel temperature

4.2.4 Relationship between maximum output power and solar irradiance

Table 10 Maximum power output against solar irradiance

Time	Solar Irradiance (W/m²)	Power (W)
05:00	0	0
06:00	0	0
07:00	16.53	13.141
08:00	148.4	116.129
09:00	350.2	175.262
10:00	538.6	182.707
11:00	661.7	187.311
12:00	747.5	190.289
13:00	754.4	192.005
14:00	698.8	189.842
15:00	573	184.744
16:00	422.7	179.295
17:00	224.7	147.571
18:00	49.16	39.081
19:00	0.203	0.161

20:00	0	0
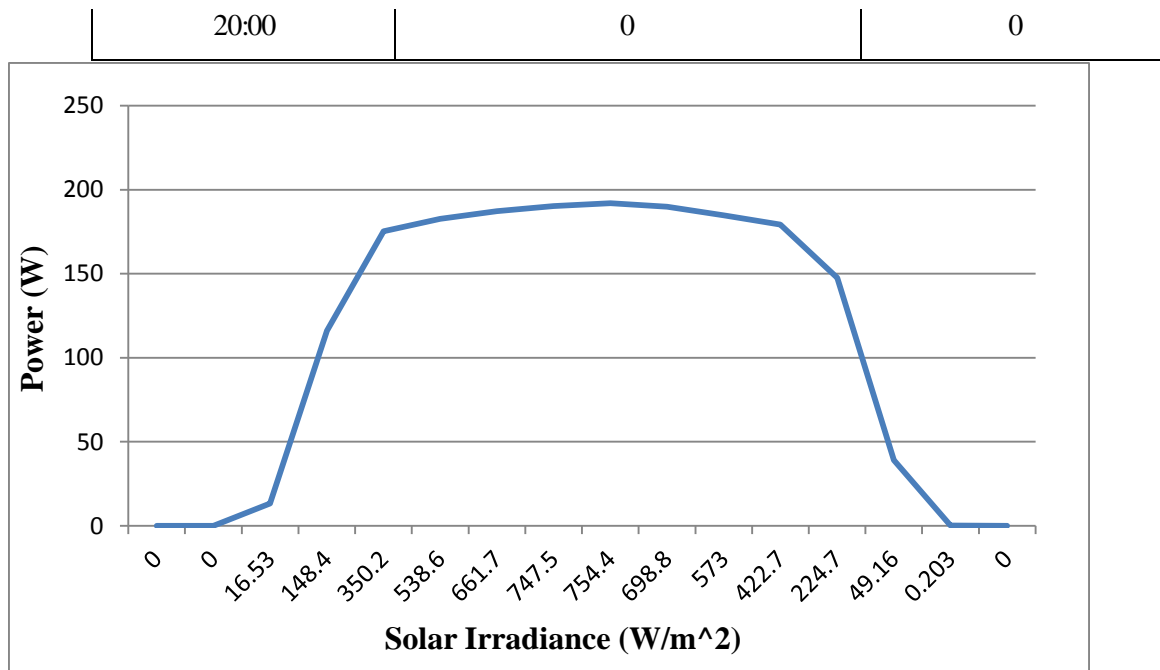
Figure 33. Maximum output power against solar irradiance
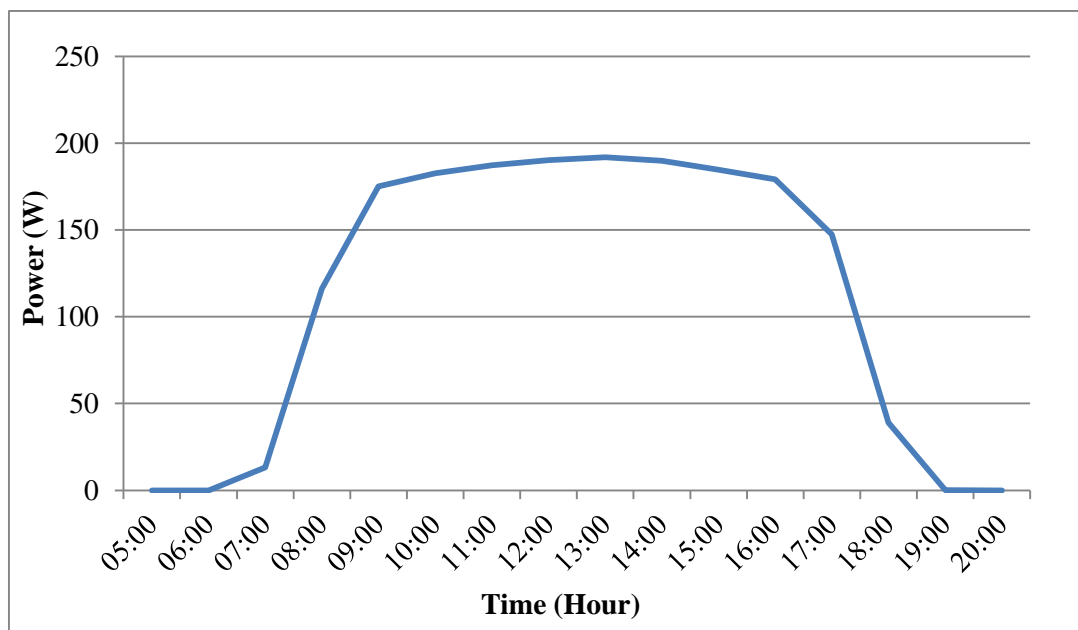
Figure 34 Maximum output power against time

Figures 33 and 34 show the trend of the measured maximum output power from the PV-electrolyser system against solar intensity and time for a typical sunny, non-cloudy winter's day. The power output increases during the early hours of the day and follows the trend of solar

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irradiance values over time as shown in Table 10. It then drops in the evening also in proportion to solar irradiance values. Thus, there is a direct relationship between the maximum output of the PV-electrolyser system and the intensity of solar irradiance reaching the surface of the solar panels.

4.2.5   Relationship between solar panel tilt angles and the maximum output voltage

Experiments were performed to see the effects of different tilt angles on the maximum output voltage the solar array can produce. Three different tilt angles were considered. The latitude of the exact location where the study was done i.e. Vanderbijlpark, South Africa is 26°, latitude + 4° for a typical winter day and latitude - 4° for a typical sunny day. According to Hurley (2004:66-68), to maximize the output of a solar array, the panels should be angled according to the location's latitude and to the season. He noted that the optimal angle for any latitude is the latitude angle itself. Figure 35 shows the result obtained in the study for the three tilt angles considered for the study.
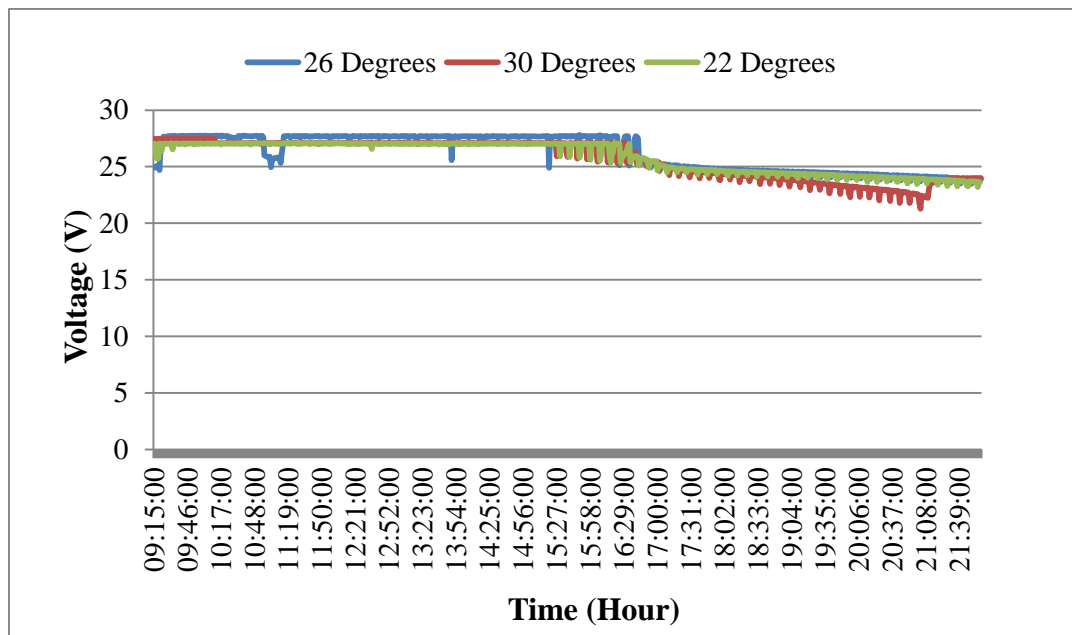

Figure 35 Maximum output voltage for different solar panel array tilt angles

From the diagram, output voltages for the different tilt angles are almost identical for the early hours of the day when solar intensity is on the increase. However, towards the evening, when the

intensity decreases, the maximum output voltage obtained when the solar panels are tilted at an angle of 26° (i.e. latitude) to the sun is higher than the values obtained when the solar panels are tilted at 30° and 22°, respectively. Thus the maximum output voltage of the solar panel array is maximized when tilted at an angle equal to the latitude of the location.

4.2.6   Effects of dust on the solar panel array

A test to determine the effect of dust on the designed system was carried out on the solar panels used for this study. It was stated earlier that the panels were connected two-two in series to make four panel pairs and that some or all the pairs can be isolated through a 20 A DC circuit breaker. This test made use of a variable load in connection with the various solar panel combinations through the maximum power point tracker to determine the maximum power point of the solar panel combinations.

The solar panel angle used was 30° (latitude + 4°) for all the panels. Two different solar panel conditions were considered: (i) slightly dirty panels and (ii) clean panels. This is to see whether dust will have any effect on the solar panel outputs. A Fluke 337 true rms clamp meter was used for current measurement and a Major Tech 889 true rms millimetre was used for voltage measurement. The electrolyser operating current needed for the calculation of solar-hydrogen efficiency was measured and found to be 13.10 A. The results obtained are tabulated and shown. Graphs of the various tables are also shown.

PV module combination 1 represents 2 solar modules connected in series. Combination 2 represents a parallel connection of 2 PV pairs connected two-two in series i.e. 2 modules connected in series and then in parallel with another 2 series. Combination 3 represents a parallel connection of 3 PV pairs connected two-two in series i.e. 2 modules connected in series and then in parallel with another 2 series and in parallel with another 2 series.

For different PV combinations, the change in the maximum power point voltage for a variable load is small while the maximum power point current is almost doubled for the combinations. The results obtained for slightly dirty panels are shown in Table 11 and Figure 36.

Table 11 Maximum power point voltages and currents for different (slightly dirty) solar module combination

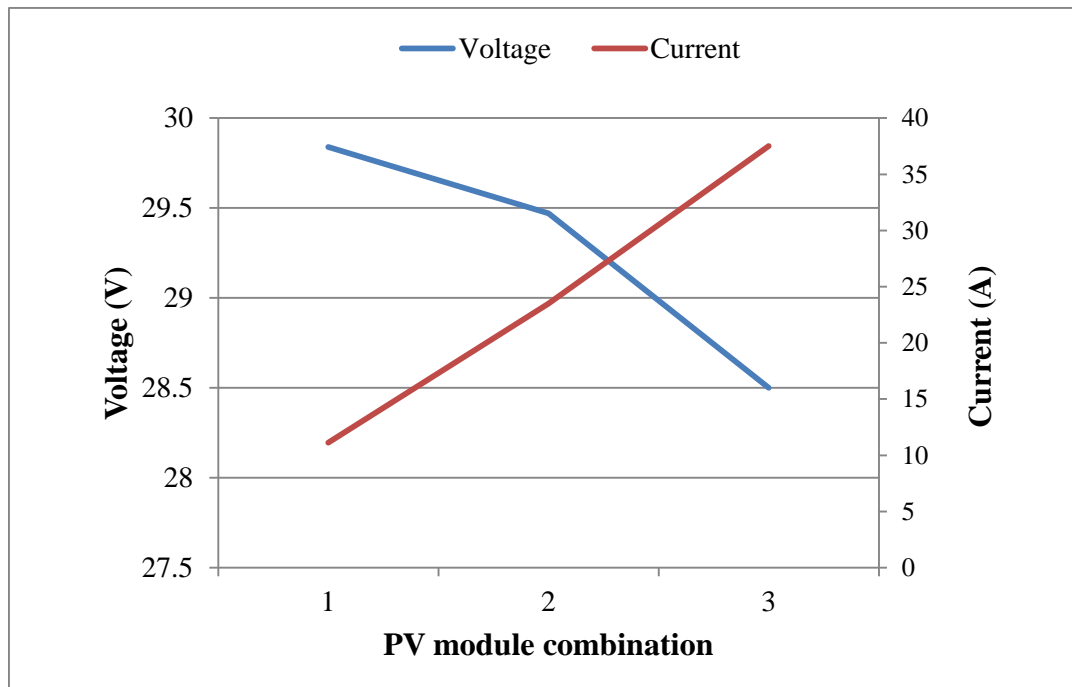| PV module combination	V_{mmp} (V)	I_{mmp} (A)
1 (2 in series)	29.84	11.13
2 (4 in series-parallel)	29.47	23.5
3 (6 in series-parallel)	28.50	37.5

Figure 36 Maximum power point voltages and currents for different (slightly dirty) solar module combinations

The results obtained with clean panels are shown in Table 12 and Figure 37.

Table 12 Maximum power point voltages and currents for different (clean) solar module combination

PV module combination	V_{mmp} (V)	I_{mmp} (A)

1 (2 in series)	32.5	12.60
2 (4 in series-parallel)	29.60	28.10
3 (6 in series-parallel)	28.73	40.20
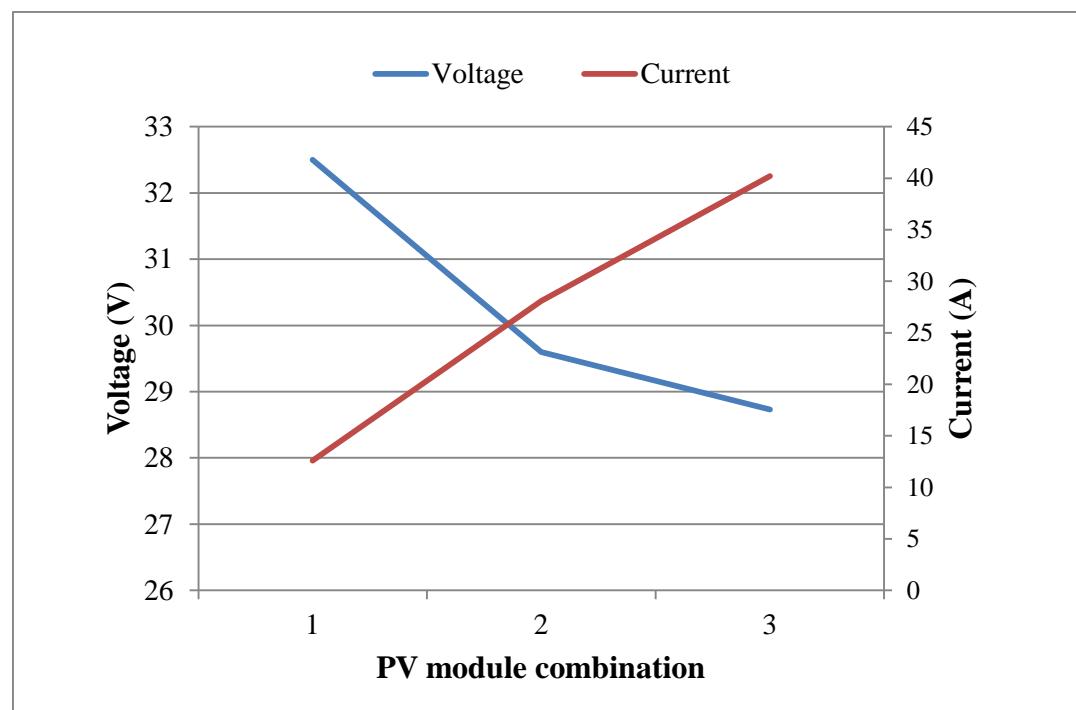
Figure 37 Maximum power point voltages and currents for different (clean) solar module combinations

Comparing the maximum power point voltage values obtained for the slightly dirty modules to that obtained for the clean modules, it was observed that the values obtained for the latter were slightly higher than that obtained for the former. The results obtained are shown in Table 13 and Figure 38 .

The maximum power point current values obtained for the clean modules were also higher than that obtained for the slightly dirty modules (see Table 14 and Figure 39). This shows that dust can have considerable effect on the voltage and current outputs of the solar modules. The solar modules thus operate optimally when the module surface is clean.

Table 13 Maximum power point voltages for slightly dirty and clean solar module combinations

PV module combination	V_{mmp} (V) (Slightly dirty modules)	V_{mmp} (V) (Clean modules)
1	29.84	32.50
2	29.47	29.60
3	28.50	28.73

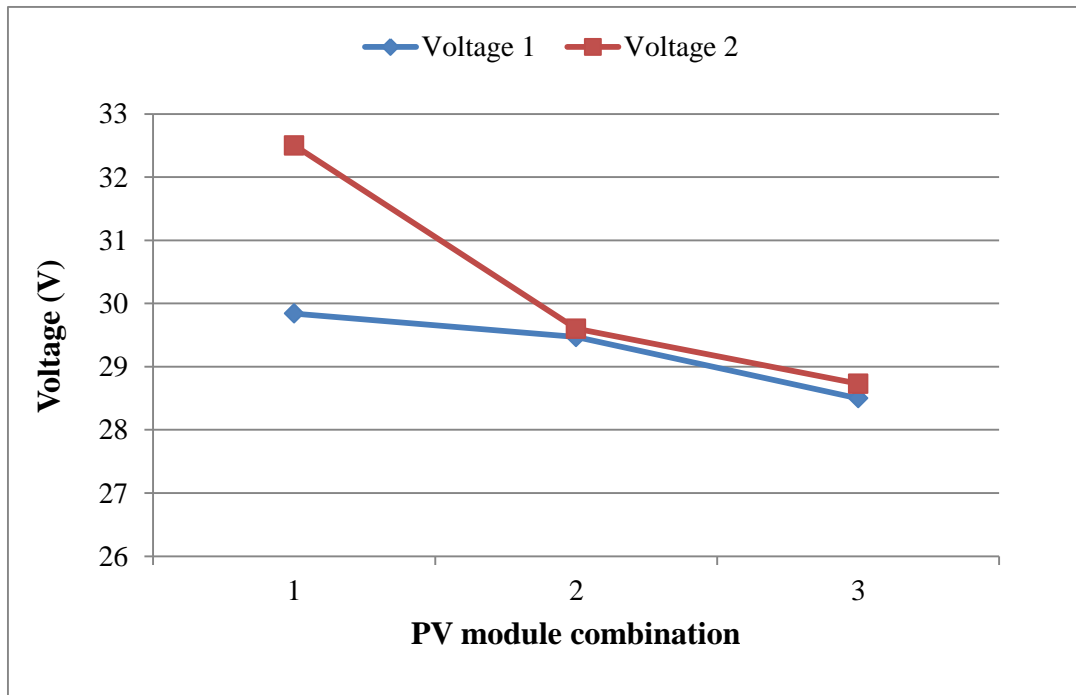**Figure 38 Maximum power point voltages for slightly dirty and clean solar module combinations**

Table 14 Maximum power point current for slightly dirty and clean solar module combinations

PV module combination	I_{mmp} (A) (Slightly dirty modules)	I_{mmp} (A) (Clean modules)
1	11.13	12.60

| 2 | 23.50 | 28.10 |
| 3 | 37.50 | 40.20 |
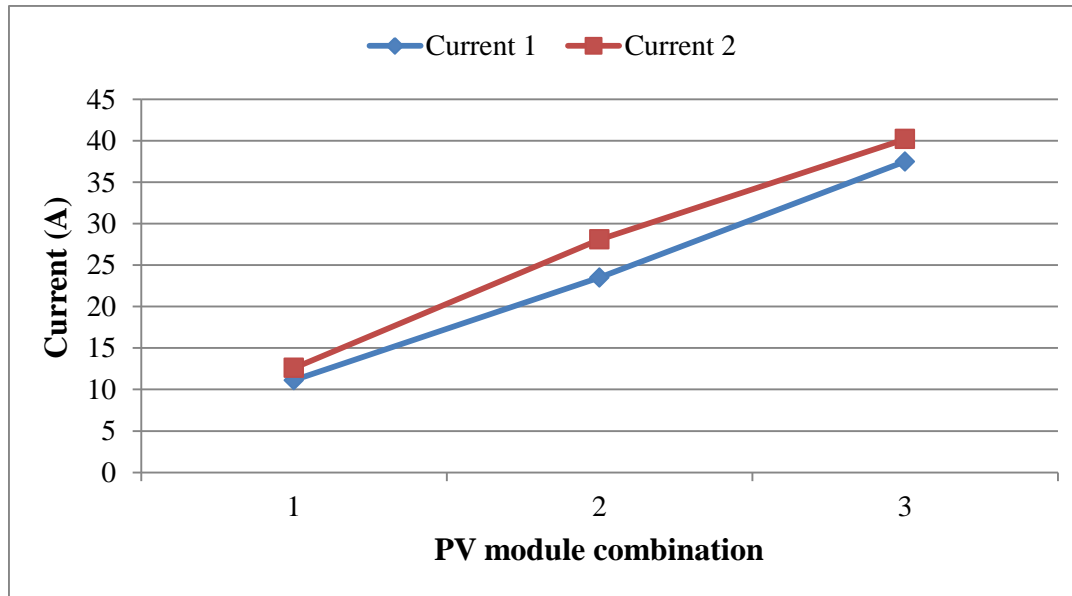
Figure 39 Maximum power point currents for slightly dirty and clean solar module combinations

4.3   Factors to consider when designing a PV-electrolyser system

Hydrogen production from a PV-electrolyser system depends on the efficiency of the electrolyser and photovoltaic array, and the sun irradiance at that site (Buasri 2010:641). In designing an effective PV-electrolyser hydrogen generation and storage system, there are certain factors which must be carefully considered and determined as discovered in this study:

- The amount of hydrogen required by the system should be determined. The onus is on the designer to determine the quantity of hydrogen needed for their system. In this study we chose the HOGEN GC300 which produces 300ml of hydrogen per minute and capable of producing about 180 litres of hydrogen per day.

- The energy needed by the hydrogen generator/electrolyser should be determined. The intended power generation for this power plant is based on a scale model that can produce 500 watts continuously for 24 hours per day (Viljoen & Pienaar 2011:560).

- The PV array required based on the energy needed should be determined. The PV modules are connected in series and parallel to form an array that has higher voltage and current. Power output of an array depends mainly on sun irradiance and the temperature of where the array is located.

- The number of PV modules needed should also be determined.

- The hydrogen storage medium should also be determined. For this study, hydrogen is stored in a compressed gaseous form in a standard, sample storage cylinder and then scaled up to a ballast of 9 cylinders capable of storing up to a total of 450 litres of hydrogen gas.

4.4   Summary

This chapter considered the determination of the purity of the generated hydrogen and the performance of the designed system based on results obtained from the experiments performed on the system.

Chapter 5 is the final chapter in the document. It will conclude this research and discuss recommendations that have evolved.

Chapter 5   Conclusions and recommendations

5.1   Concluding comments

This chapter presents the conclusions reached with regard to the designed PV-electrolyser hydrogen production and storage system. The recommendation for future research will complete the chapter.

5.2   Conclusions attained from the study

The theoretical study was completed and seeing that PV-electrolyser hydrogen generation for application in fuel cells is a new field of venture at the Vaal University of Technology, the commercial solar modules chosen for the research were polycrystalline solar modules. A

commercial hydrogen generator was chosen for the research instead of creating an electrolytic solution or water electrolyser.

A laboratory scale hydrogen production and storage system was also designed. This design was set up and purity measurements were carried out on the generated hydrogen using a customized thermal conductivity detector.

The purity measurements proved successful and it was discovered that the storage cylinder position has little but noticeable significance on the number of times the storage cylinder was purged with argon gas before pure hydrogen was stored. Pure hydrogen was stored faster when the sample cylinder is in the vertical position than when in the horizontal position. It took seven flushes as opposed to eight in the horizontal position.

When the sample storage cylinder was evacuated with a vacuum pump (instead of flushing with argon gas) in the vertical position, pure hydrogen storage was achieved at a faster rate. This proved to be more appropriate and economical as the number of times needed to fill and vent the storage cylinder with argon and hydrogen gas was considerably reduced. Thus on a laboratory scale, evacuating the storage cylinder with a vacuum pump is a more effective method than purging with argon gas. Scaling up the system might prove otherwise.

A number of experiments were also carried out on the designed system to determine its performance. The maximum output current of the designed system varies almost linearly with solar irradiance. The variations seen in the diagram (Figure 30) are due to the changing weather conditions and the intensity of solar irradiance reaching the surface of the solar panels. The maximum power output of the system varies proportionally with solar irradiance. The higher the solar irradiance, the higher the output power, and the lower the solar irradiance, the lower the output power obtained from the system.

The maximum output power in relation to the maximum output current shows a linear relationship. If the optimizing current can be determined every time the intensity of the solar irradiance changes, it is possible to control the power output from the solar arrays so that the maximum power output may be obtained.

Observing the relationship between different solar panel tilt angles and maximum output voltage obtained from the system shows that maximum output voltage is highest when the solar panel tilt angle is exactly equal to the latitude of the location where it was installed.

The tests carried out on the slightly dirty and clean solar modules showed the effect of dust on the output of the solar modules. The maximum power obtained from a clean solar module is more than that obtained from a dusty module. The modules must therefore be kept clean at all times for best operation.

5.3   Recommendations

This research has laid groundwork for more complex research in PV-electrolyser hydrogen generation, storage and application in appropriate industries such as the telecommunications industry where hydrogen is required to run the fuel cells powering the base stations. However, it leaves a lot of possibilities to be explored, some of which are:

- The choice of PV solar modules and sizing should be carefully considered for different systems.

- The use of a vacuum pump for evacuating the storage cylinder proved effective on a laboratory scale and should therefore be tested on a larger scale.

- The thermal conductivity detector used for the determination of the purity of the stored hydrogen on a laboratory scale should be applied to detecting the purity of stored hydrogen on a larger scale. The instrument is a highly sensitive instrument and less sensitive but effective detectors should be investigated and applied.

- The effect of tilt angles on system performance could be explored in-depth as it would provide some valuable data which can contribute to literature in this field of study.

- The system could also be tested with a conventional electrolyser as opposed to a commercial hydrogen generator and the performance compared to the latter. Some interesting results are sure to be uncovered.

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