



**PERFORMANCE ANALYSIS OF A SMALL  
STAND ALONE PHOTOVOLTAIC SYSTEM  
UNDER OUTDOOR CONDITIONS IN THE  
VUWANI REGION OF THE LIMPOPO PROVINCE**

*A Dissertation Submitted to the Department of Physics*

*For the fulfilment of a M.Sc Degree*

By

**RAVHENGANI TSHFHIWA SOLOMON**

**STUDENT NUMBER: 8703237**

**In the School of Mathematical and Natural Sciences,  
University of Venda**

**THOHOYANDOU, LIMPOPO PROVINCE**

Supervisor : Prof. V. Sankaran, UNIVEN

**FEBRUARY 2013**

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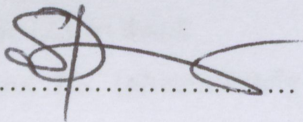
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## DECLARATION

This thesis is dedicated to my late sister Doctor Ruvhengani D.J. (Madonsela) who always dreamt of me becoming a doctor. I, TSHIFHIWA SOLOMON RAVHENGANI, hereby declare that the dissertation for the M.Sc. degree at University of Venda hereby submitted by me has not previously been submitted for a degree at this or any other university and that is my own work in design and execution and all the reference materials contained therein has been duly acknowledged.

Signature: .....



Date: .....

29/04/2013

## ACKNOWLEDGEMENT

This thesis is dedicated to my late sister Doctor Ravhengani D.J.(Madonsela) who always dream that her brother would, at least, graduate a master's degree. I thank her for years of constant support and for encouraging me to study.

My deepest appreciation and gratitude with greatest humility goes to Prof. V. Sankaran, my supervisor and mentor, for providing me with valuable and considerable suggestions and knowledge, encouraging me, shaping my project, guiding and for accepting to supervise me on this thesis. I thank him for his constant mentorship and patience.

It would not have been possible to write this master thesis without the support of the following people I would like to thank:

- (i) Dr. Kirui J.K (affectionately known as Makhulu), Head of department of Physics at UNIVEN for his support and encouragement. I remember his words and I quote 'Zwi do vhuayazwalugamuduhulu'.
- (ii) Dr. Maluta Eric, the Chief laboratory technician, for his wonderful technical support in the discussion, analysis, interpretation of data and conclusions thereof and also in taking I-V curves.
- (iii) Mrs. Mulaudzi T.S, for assisting in the computation of solar radiation data and also proof reading the final version of the thesis.
- (iv) Mr. Shandukani T.E., for his productive collaboration in the design and configuration of the small stand alone photovoltaic system at Vuwani Science Resource Centre.
- (v) Mr Nekhubvi V, and Nkhumeleni N.R. for fruitful discussions about our common project and
- (vi) The staff in Vuwani Science Resource Centre, for the wonderful assistance in data taking and safe- keeping of the small stand alone photovoltaic system at the research site.

Lastly I really want to thank my family, sisters and brothers especially my parents for the moral, educational and financial support throughout this challenging ordeal.

This research work was done at Vuwani Science Resource Center. If there are any advertent errors or omissions in the printed text, I accept the full responsibility.

## Abstract

Public awareness of the need to reduce global warming and the drastic increase in crude oil prices have encouraged many countries around the world to adopt new energy-policies that promote renewable energy applications to meet energy demands and to protect the environment. The solar electricity is presently a rapidly growing renewable energy form. The advantage of this type of energy is that it is renewable and environmental friendly. These advantages of using solar electricity over other energy forms still put it on top, for example, no rapid depletion and do not contribute towards growing global warming.

In the current study the outdoor performance of the photovoltaic module was monitored for a period of one year. An attempt has been made to understand the peak power and the peak voltage output of the module under study at the solar research station at Vuwani Science Resource Centre under University of Venda. This was done to assess the design of the stand alone solar photovoltaics system on the rural area of Limpopo, South Africa. Currently the design and use of the PV stand alone photovoltaic energy system is the solution to the rural remote area where there is no national grid line. The outdoor measurements of the peak power was performed to understand the energy output of the module under realistic condition and to make sure that it is possible to design and use this type of photovoltaic systems in this area.

Solar radiation data was estimated using a linear Angstrom model. The data computed were used to understand the performance of the PV module from its peak power and peak voltage. The value of these parameters was measured using the Maximum Power Point charge controller. The results obtained are discussed in details. It was found that the peak power monitored using the Maximum Power Point charge controller is nearly corresponding to the manufacturer listed data.

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## CHAPTER 1

### INTRODUCTION

#### 1.1 Introduction

Public awareness of the need to reduce global warming and the drastic increase in oil prices have encouraged many countries around the world to adopt new energy-policies that promote renewable energy applications to meet energy demands and to protect the environment. This is true in both the developed and developing countries. Also the level of greenhouse gas emissions taking place today is staggering and unprecedented. Many scientists, geologists and academics believe that global warming and climate change have indeed reached their tipping point. In particular, the level and momentum of polar ice sheet degradation has stunned scientists. Applications of renewable energy technologies represent opportunity for systemic change [1, 2]. They have the potential to empower governments and individuals to contribute to mitigate climate change, while at the same time facilitate employment and skill creation. Among the applications, photovoltaic solar energy technology is a relatively simple technology which has been around for many years but has demonstrated tremendous potential in reducing the level of greenhouse gas emissions. Thus, photovoltaics (PV) is rapidly becoming an integral part of worldwide measures to combat the effects of climate change and to solve the world energy crisis. Hence developing environmentally friendly, renewable energy technology is one of the challenges to the society in the 21st century [3].

However, most of the world's energy sources are derived from conventional sources-fossil fuels such as coal, oil, and natural gases. These fuels are often termed non-renewable energy sources. Although, the available quantity of these fuels are extremely large, they are nevertheless finite and so will in principle 'run out' at some time in the future. Renewable energy sources are essentially flows of energy, whereas the fossil and nuclear fuels are, in essence, stocks of energy. There are various forms of renewable energy, like solar energy, wind energy, bio energy, hydro energy, geothermal energy, wave and tidal energy [4, 5]. The advantage of using the PV technologies is that they are environmental friendly and renewable. The sun is responsible for the most physical and biological processes of earth. The energy from the sun reaching the earth

drives almost every known physical and biological cycle in the earth's system. The energy given off by the sun reaches the earth in the form of electromagnetic radiation, all of which can be collected to produce power. Thus all renewable solar energy technologies are powered by steady flux of solar energy from the sun [6].

The understanding of the outdoor performance and factors affecting the efficiency of the solar cells, together with the performance of the PV system is needed for designing the PV array or PV solar electricity station especially in developing countries. Apart of understanding these factors, the use of solar panels is becoming one of the options for some of the rural communities in Limpopo Province, South Africa. These are used to get electrical energy for their radio and television sets as the national grid may not reach them in the near future. Hence, dissemination of knowledge of how to use the solar devices and their maintenance is crucial for these communities. This will be possible only if there is appropriate information available for the potential end-users, installers and extension workers [7].

## 1.2 Solar radiation

Solar radiation is the energy that comes from the sun which is generated through the process of nuclear fusion. Knowledge of the solar radiation is essential for many applications, including architectural design, solar energy systems, crop growth models, etc [8, 9]. The global solar radiation on horizontal surface at the location of interest is the most critical input parameter employed in the design and prediction of the performance of solar energy devices. The best way of knowing the amount of solar radiation at a site is to install pyranometers at many different locations in a given region and look after their day to day maintenance and recording. With this situation, most researchers use available theoretical values of meteorological data to compute average irradiance of solar radiation for different locations within the country [8]. The lack of standard measured data obtained from reliable measuring instruments resulted to theoretical prediction of global solar radiation using different models [8].

Solar radiation drives atmospheric circulation. Since global solar radiation represents almost all the energy available to the earth, accounting for solar radiation and how it interacts with the atmosphere and the earth's surface is fundamental to understanding the earth's energy budget [10]. Solar radiation reaches the earth's surface either by being transmitted, scattered or reflected directly through the atmosphere. About 50% of solar radiation is reflected back into space, while the remaining radiation at the top of the atmosphere is absorbed by the earth's surface and re-radiated as thermal infrared radiation [10, 11]. The pyranometer used for measuring the intensity of solar radiation consists of a sensor enclosed in a transparent hemisphere that records the total amount of incoming solar radiation. That is, pyranometers measure global radiation; the sum of direct solar and diffuse sky radiation.

### 1.3.2 Diffuse radiation

## 1.3 Nature of solar radiation

Diffuse solar radiation is the portion of solar radiation that is scattered downwards by the atmosphere. The availability of solar energy in any location in the world can be studied by two methods. The first involves measurements from a radiation monitoring network and the second is based on the use of physical formulae and constants. Direct solar radiation (I), which is the solar radiation flux is measured normal to the beam on a plane which is perpendicular to the direction of the sun. Diffuse radiation (D), which reaches the ground from the rest of the sky hemisphere by scattering as it passes through the atmosphere. Global solar radiation (H) includes all the radiation, direct and diffuse, incident on a horizontal plane. The distribution of diffuse radiation is not uniform over the whole sky hemisphere. The solar radiation may also be reflected from the ground onto any inclined surface, though this is very difficult to assess. The relationship between direct radiation, I, the diffuse radiation, D, and the global radiation, H, is given [12],

$$H = D + I \sin \gamma \quad 1.1$$

Where  $\gamma$  is the solar altitude above the horizon.

### 1.3.1 Global solar radiation

The sensing element of most common pyranometers used for measuring global solar radiation is based on thermoelectric, thermo-mechanical or photovoltaic principles. Unlike the conical

absorber of some of the pyrheliometers, the sensing element of the pyranometers is flat surfaces. In routine meteorological measurements, pyranometers are always placed in a horizontal position [12, 13].

The incident global solar radiation ( $I$ ) received by a surface, such as a window, is a combination of direct beam radiation ( $I_b$ ), diffuse radiation ( $I_d$ ), and radiation reflected from the ground in front of the surface ( $I_r$ ). The following equation can be used to calculate incident global solar radiation [14]:

$$I = I_b \cos(\Theta) + I_s + I_r, \quad 1.2$$

where  $\Theta$  is the incident angle of the sun's rays to the surface.

### 1.3.2 Diffuse radiation

Diffuse solar radiation is the portion of solar radiation that is scattered downwards by the molecules in the atmosphere. During clear days, the magnitude of diffuse radiation is about 10 to 14% of the total solar radiation received at the earth's surface. Only diffuse radiation may reach the earth's surface during extremely cloudy days [12, 15, 16].

The same instrument which is used for the measurement of global radiation (a pyranometer) can be employed for the measurement of diffuse radiation, provided that a suitable device is used to prevent direct solar radiation from reaching the receiver. Shading of the pyranometer from direct solar radiation is done by a disc which is made to move with the sun so as always to cast its shadow on the pyranometer. Because a shading disc needs constant supervision and maintenance and an equatorial mount is expensive, the shadow ring is the more popular of the devices [13].

### 1.3.3 Direct radiation

Direct radiation is measured by a pyrheliometer, a telescopic type of instrument with a narrow aperture. This instrument faces the sun and follows its motion. Interest in establishing the value of solar constant has been the main force behind the development of this instrument. The Smithsonian Institute, from the beginning of the 20<sup>th</sup> century, has played a leading role in this

area. In 1905, Dr Charles Grealley Abbot of this institution developed a water flow pyrheliometer for the determination of solar radiation. Prior to this, in 1893, Kurt Angstrom, of Sweden had developed the Angstrom electrical compensation pyrheliometer which has proved to be a very stable instrument. But these days, more accurate cavity-type pyrheliometers are employed for direct irradiance measurement [12, 13].

### 1.3.4 Reflected radiation

When the solar radiation irradiates upon a surface which is opaque, a portion of radiation is absorbed and the remaining portion is reflected in diffuse or specular nature depending on the roughness of the surface. The reflected radiation falling on an adjacent surface,  $I_{ref}$ , is calculated as [12]:

$$I_{ref} = R_{ref}F_{r-s}(I_D + I_d) \quad 1.3$$

Where  $R_{ref}$  = reflectance of reflected surface,  $F_{r-s}$  = shape factor between reflected surface and the receiving surface,  $I_D$  = direct solar radiation and  $I_d$  = diffuse solar radiation.

Total intensity of solar radiation falling on a surface,  $I_t$ , is the sum of the direct radiation  $I_D$ , or diffuse radiation  $I_d$  and reflected radiation  $I_{ref}$  [12].

$$I_t = I_D + I_d + I_{ref} \quad 1.4$$

## 1.4 Factors affecting global solar radiation reaching the earth's surface

The most important factors influencing how much global solar radiation reaches the earth's surface and how much is absorbed are time and day of year, cloud cover, and albedo.

### 1.4.1 Time of day and year at a given location

The intensity of solar radiation varies significantly over the course of a year ranging from no solar radiation during the polar winter to a maximum of 350 to 400  $W/m^2$  in the summer in some part of the world. Over the course of a day, the sun's angle above the horizon influences the global solar radiation reaching the earth's surface; the noon sun is more intense than the rising or

setting sun [10]. The maximum altitude of the sun depends on time of year and altitude. Of course, during the polar winter the sun is below the horizon for 24 hours, and there is low solar radiation, while at midsummer the sun changes little in altitude over the course of a day and we can expect high solar radiation, like in Limpopo Province, South Africa.

### 1.4.2 Cloud cover

Clouds reflect some incoming radiation back to space, thereby reducing the amount of radiation that reaches the earth's surface. However, clouds also re-radiate infrared energy back toward the earth's surface, thereby moderating the temperature of the lower atmosphere. Globally, clouds have a cooling effect on the earth's atmosphere system, because of their high albedos. In Polar Regions however, clouds seem to have a net warming effect as the reduction in solar radiation is outweighed by the effect of clouds in increasing long wave radiation to the surface [10, 11].

### 1.4.3 Albedo

Incoming solar radiation that strikes the earth's surface is partially reflected and partially absorbed, in proportion to surface reflectivity (albedo). Darker surfaces have a lower albedo and absorb more solar energy than do lighter surfaces. The albedo of a surface is also a function of an incidence angle of solar radiation [10].

Newly fallen snow has an albedo of approximately 0.90, meaning that it reflects about 90 per cent (%) of incoming radiation. In contrast, melting snow has an average albedo of 0.50, meaning that it absorbs 50% and reflects 50% of the incoming radiation. Because a darker surface absorbs more solar radiation, snow covered by dust (dirty snow) melts faster than clean snow. The albedo of sea ice varies with ice age, but when snow covered is on the order of 0.70 [10]. Important changes in the surface albedo can occur seasonally. Over land, heavy winter snow cover increases surface albedo considerably. In middle and high altitudes, significant increases in surface albedo accompany the winter formation of lake and sea ice [10].

## 1.5 Atmospheric effects of incoming solar radiation

There are three atmospheric processes which modify the solar radiation passing through the atmosphere destined to the earth's surface. These processes act on the radiation when it interacts with gases and suspended particles found in the atmosphere. The process of scattering occurs when small particles and gas molecules diffuse part of the incoming solar radiation in random directions without any alteration to the wavelength of the electromagnetic energy [10, 11]. Scattering does, however, reduce the amount of incoming radiation reaching the earth's surface.

A significant proportion of scattered solar radiation is redirected back to space. The amount of scattering that takes place is dependent on two factors: wavelength of the incoming radiation and the size of the scattering particle or gas molecule. In the earth's atmosphere, the presence of a large number of particles with a size of about 0.5 microns results in shorter wavelengths radiation being preferentially scattered. This factor also causes the sky to look blue because this color corresponds to those wavelengths that are best diffused. If scattering did not occur in the atmosphere the daylight sky would be black [11].

The other process in the atmosphere that modifies incoming solar radiation is reflection. Reflection is a process where sunlight is redirect by  $180^{\circ}$  after it strikes an atmospheric particle. This redirection causes a 100% loss of incoming solar radiation. Most of the reflection in the atmosphere occurs in clouds when light is intercepted by particles of liquid and from water. The reflectivity of a cloud can range from 40 to 90% [11].

Sunlight reaching the earth's surface unmodified by any of the above atmospheric processes is termed direct solar radiation. Diffuse solar radiation is the radiation that reaches the earth's surface after it is altered by the process of scattering. Not all of the direct and diffused radiation available at the earth's surface is used to do work (photosynthesis, creation of sensible heat, evaporation, etc.). As in the atmosphere, some of the radiation received at the earth's surface is redirected back to space by reflection.

The reflectivity or albedo of the earth's surface varies with the type of material that covers it. For example, fresh snow can reflect up to 90% of the solar radiation that reaches its surface. Some other surface type reflectivities are:

- Dry sand 35 to 45%
- Broadleaf deciduous forest 5 to 10%
- Needle leaf coniferous forest 10 to 20%
- Grass type vegetation 15 to 25%

The earth's average albedo, reflectance from both the atmosphere and the surface, is about 30%. Of all the sunlight that passes through the atmosphere annually, only 51% is available at the earth's surface to do work. This energy is used to heat the earth's surface and lower atmosphere, melting and evaporate water, and run photosynthesis in plants. Of the 49%, 4% is reflected back to space by the earth's surface, 26% is scattered or reflected to space by clouds and atmospheric particles, and 19% is absorbed by atmospheric gases, particles, and clouds [11].

Examples of renewable energy are biofuels, biomass, geothermal, solar power, tidal power, wave power, and wind power. On the other hand examples of nonrenewable energy are coal, natural gas, petroleum and nuclear. Biomass comprises solid fuels such as wood, charcoal, wood wastes and agricultural residues and dung while natural gas comprises biogas, landfill gas, and other gases from biomass [19, 20].

Fossil fuels contribute up to 80% of the world's primary energy supply. The major disadvantages of fossil fuels are rapid depletion and their contribution towards growing global warming. These disadvantages challenge the whole world so much that there is a need for an alternate solution to meet global energy needs without inflicting any serious environmental impacts. Renewable energy sources such as solar, wind, hydropower and biogas provide a solution to meet global energy requirements in a sustainable way [21].

## 7.2 Energy crisis in South Africa

The year 2008 brought about a turning point in the history of energy in South Africa when almost every major social activity came to a standstill because of power cuts, black outs and

## CHAPTER 2

### ENERGY IN SOUTH AFRICA

#### 2.1 Introduction

Without energy there cannot be life on earth. Modern and clean energy services have direct benefits, indirect benefits and also induced benefits. That is, energy is a basic need and energy resources provide a tremendous assistance to humans in meeting daily needs such as water pumping, water transportation, water heating, cooking, keeping warm or cool, promoting good health, transportation, enhancing opportunities to become educated and in striving for improved security. It also assists humans in achieving a better level of economic and social development [17, 18].

The energy which humans use can be divided into renewable and nonrenewable energy. Examples of renewable energy are biofuels, biomass, geothermal, solar power, tidal power, wave power and wind power. On the other hand examples of nonrenewable energy are coal, natural gas, petroleum and nuclear. Biomass comprises solid fuels such as wood, charcoal, wood wastes and agricultural residues and dung while natural gas comprises biogas, landfill gas, and other gases from biomass [19, 20].

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#### 2.2 Energy crisis in South Africa

The year 2008 brought about a turning point in the history of energy in South Africa when almost every major social activity came to a standstill because of power cuts, black outs and

some load shedding. South Africa relies solely on electricity produced by the national utility Electricity Supply Commission (ESKOM) and municipalities, however the need for energy for the population of South Africa is growing so rapidly in such a way that ESKOM appears to be unable to provide for such an abnormally growing population. ESKOM applied to National Energy Regulation of SA (NERSA) for tariff increase as a solution to solve these energy crises. NERSA approved an average price increase of 31.3% for ESKOM on 25 June 2009. The increase was valid for nine months, from 01 July to 31 March 2010. Furthermore a loan application of R29 billion by ESKOM was approved by the World Bank on 08 April 2010 so that they can also build a multimillion Medupi Power Station in the Limpopo province. Medupi Power Station will generate electricity from coal. Coal which is used to generate electricity is a fossil fuel with a problem of rapid depletion and contributes towards global warming. South Africans need to refurbish with clean coal technologies and buy green power [22, 23, 24].

Although South Africa is a very big and developing country, millions of South Africans still find themselves stranded economically and socially. Many South Africans are staying in remote rural and isolated areas, where the supply networks are not connected with each other such that the connection with the main electric utility grid is not economical. These communities in rural areas, as well as those in fringe zones experience a lack of infrastructure, families, community facilities and refugee groups suffer under the increasing scarcity of traditional energy sources. Many studies suggest that renewable energy and particularly application of small stand alone photovoltaic systems is a solution to this kind of energy crisis [22, 23, 24].

However, the researcher aims to study the performance of small stand alone photovoltaic system at rural isolated settlement of Vuwani region of the Limpopo province. The study will benefit communities and community facilities in rural areas and some in urban fringe zones marked by a lack of infrastructure. The study will provide a tremendous assistance to uses in meeting daily needs in domestic and business activities.

## 2.3 Energy need and demand in South Africa

### 2.3.1 Programmes for rural electrification

The international community is putting pressure on all governments to focus on renewable energy sources; however, the application of renewable energy technologies in the rural areas of South Africa is desirable because of the economic, health and developmental benefits that they bring. A close correlation between the Per Capita Energy Consumption and Human Development Index has been shown by the energy statistics of developed and developing countries. It shows that the countries with lower per capita energy consumption have lower human development index (HDI) values. South Africa had a need to promote and disseminate at a rapid pace different energy technologies suitable to local conditions in order to meet the different priorities of the country in line with the Reconstruction and Development Programme (RDP) and Growth, Employment and Redistribution (GEAR) strategy. In that regard it was highlighted in the International Standard on Review Engagements (ISRE) that government's goal of access to electricity and the huge electrification backlog of 3.2 million households could only be met by the optimum exploitation of non-grid electrification within the overall scope of the National Electrification Programme [24, 25].

In order to achieve the targeted goal of universal access to electricity over the next two decades it required the launching of an ambitious non-grid electrification programme as an integral element of the National Electrification Programme where Photovoltaic Solar Home Systems should be installed in at least 1.5 million homes within 10 years to reduce backlogs. This programme included both rural and a small percentage of urban installations to debunk the myth that Renewable Energies imply an inferior electrical supply. That process commenced with a joint venture between Shell International Renewables and ESKOM in the Flagstaff district of Eastern Cape Province [25, 26].



Figure 2.1. School staff and pupils in the Eastern Cape Province, in front of one of the thousand EU-funded, 800 W<sub>p</sub> Solar power supplies installed in rural South Africa [26]

The National Electrification Forum (NELF) of 1991-1993 resulted from an agreement between the Electricity Supply Industry (ESI) and the Government of South Africa on an accelerated household programme. The programme was intended to substantially reduce the backlog experienced by the historically disadvantaged rural and urban communities. Through the employment of Reconstruction and Development Programme (RDP) Electrification Programme, the Electricity Supply Industry (ESI) undertook to connect 2.5 million new households to the national electricity grid in the period 1994 to 1999 which was to be funded by the industry itself. The National Electricity Regulator (NER) approved tariffs to ESKOM that allowed such electrification funding [27].

The Independent Development Trust (IDT) clinics programme installed PV systems at about 210 rural medical clinics where the power is mainly used for light and vaccine refrigeration. The programme was very successful during the first year when maintenance contracts were still in place. Thereafter maintenance became a problem because of the Health Department budgets which are extremely stretched [28, 29]. The national telecommunications company Telkom used solar powered wireless systems in many rural areas for the provision of rural telephone systems. At that time Telkom purchased many PV modules [28].

Eskom piloted another electrification project known as the 2.5 electricity supply option in 1995 in the Mafefe Tribal Area in the Northern Province and the Tambo village in the Eastern Cape. The Mafefe Tribal Area comprises about 34 villages with a total population of more than 10000 people. The electrification project was introduced because of the reduction in capital costs it offers. In that project a user is limited to use the power of about 560W which prevents the use of most thermal appliances although a kettle and iron have been specially adapted for that purpose. The 2.5 electricity supply option was rejected by the residents of the Tambo village because of many reasons, for example one of the reason was inflexibility of the flat rate tariff. The Mafefe Tribal Area accepted the 2.5 electricity supply option, but there were three options, namely, a connection fee of R10 and the flat rate payment of R8.50, a connection fee of R300 with a monthly service of R37 and lastly a connection fee of R400 with a monthly service fee of R37. The Mafefe Tribal Area is still using the 2.5 electricity supply [30].

The European Union (EU) schools programme is an EU-funded programme to electrify 1000 schools only. The programme was initiated in 1998 and it was successfully completed [23].

The RDP schools programme was managed by the national utility Eskom. This programme is part of the RDP which was initiated by the African National Congress (ANC) government. The purpose of the programme was to electrify 1340 rural schools between 1996 and 1998. The programme was successful but there were still more than 16000 schools without electricity in South Africa in the year 2000 [29].

A few pilot projects were implemented; however, they failed to grow. For example, 1700 solar systems were installed in Free-State region of the country in a programme designed by local authorities who subsidized farmworker household electrification using solar systems. Also early in 1999 the remote village of Folovhodwe in the then Northern Province (Limpopo) was electrified with 582 households, 3 schools and 8 businesses immediately benefiting from the grant funded programme known as Folovhodwe Solar Village Project [28].

#### 2.4 Energy Sources used in South Africa

As an example, consider the implementation of a Renewable Energy Technology in 1996 at Myeka High School in the Maphaphete area of Ndwedwe which is about 60 kilometers of

Durban. Renewable Energy Technology at the school provided the mechanism to develop new and effective ways of bringing modern education facilities and techniques. Educators, learners and the community received the opportunity to use the computers and the internet. Many logistical problems were solved, many learners chose Physical Science and the overall enrollment at Myeka High School increased. These results of the implementation of a Renewable Energy Technology at Myeka High School indicated that education and technology could successfully make a meaningful contribution towards rural development [31].

## 2.3.1 RENEWABLE ENERGY OPTIONS

### 2.3.2 Results of rural electrification

ESKOM and the municipalities managed to connect 2.7 million households to the electricity grid between 1994 and the end of 1999. The achieved numbers of electrified households exceeded the original targets. The number of households with access to electricity in urban areas rose to 84% while in rural areas it is only at around 50%. At the same time more than 16000 schools and 2000 clinics were identified for non-grid electrification and 4000 rural schools were connected to the grid. Also 1344 rural schools and 495 clinics have been electrified by using photovoltaic systems with the aid of international donors [18].

The electrification programme since 1994 is rated very successful in terms of the number of electrified households; however, there are still a large number of people living in remote areas where the electricity grid will not reach even in the medium term. There will still be about 2 to 3 million households with no grid connection by 2012. The number of households with no grid connection will remain almost as high as presently while the share of grid connected on the total number of households will still increase constantly. Therefore for these areas off-grid connection on the basis of small solar home system (SHS) or with hybrid mini-grids will be the available options [18].

## 2.4 Energy Sources used in South Africa

In order to promote energy conservation we need to consider the following:

Approximately 70% of coal is used locally to produce electricity. Electricity is the most important secondary energy source used in South Africa. Most of the electricity in South Africa is used by industry, business and mining. These sectors can make the most significant contribution to any conservation programme [32].

If South Africa wishes to have a sustainable energy supply we need to investigate and develop available renewable energy options where appropriate.

## **2.4.1 RENEWABLE ENERGY OPTIONS**

### **2.4.1.1 Hydro-electricity**

Hydro-electricity is already utilized in South Africa on a limited scale. Hydro-electric systems operate at the Hedrick Verwoerd and Vanderkloof dams. In 1991 these hydro-electric systems provided less than 1% of South Africa's electricity. Two pump storage schemes, one in Drakensberg and the other in Western Cape also provide electricity. In a pump storage scheme potential energy of the water stored in the dam is converted to kinetic energy as water flows from the dam. The flowing water is used to drive turbines which generate electricity. Water is pumped to a dam using spare electricity when the demand for electricity is low, when the demand for electricity is high, water is then released through turbines and electricity is generated [32].

South Africa is relatively a dry country and lacks large rivers which are suitable for large scale hydro – electricity generation. Most of the large rivers of the Southern Africa region are north of South Africa's borders. If South Africa is to benefit from the large hydro- electric potential of rivers such as Zaire, Rufiji, Shire and Cunene regional cooperation will be necessary. However, the long investigation before such a programme is implemented.

### **2.4.1.2 Solar Energy**

Solar energy can be used for many different purpose, these include:

#### **2.4.1.2.1 Electricity Production**

Photovoltaics convert solar energy into electricity. South Africa's cheap grid electricity makes photovoltaic electricity a relatively expensive option. Photovoltaic are best suited to areas which are not supplied with grid electricity and can provide electricity for small scale low power applications such as communications systems, houses and schools [32].

#### **2.4.1.2.2 Water heating**

Solar energy can be used to heat water for both domestic and industrial purposes. A large proportion of domestic electricity energy costs are for water heating. Utilizing solar energy for water heating would reduce domestic electricity consumption and hence reduce monthly electricity costs [32].

#### **2.4.1.2.3 Wind**

Wind was one of first energy source to be harnessed. Wind energy is widely used in South Africa for water pumping. In some countries large wind turbines are used for generating electricity, for this strong reliable winds are needed. South Africa has fairly winds in many coastal areas. At present there are few wind generators operating. This is mainly due to the availability of cheap electricity generated by coal- fired power stations. Some South Africans staying in rural areas rely on wood for cooking food and heating their homes, however, in many areas the supply of wood is not keeping up demand as well [32].

### **2.4.2 NONRENEWABLE ENERGY OPTIONS**

#### **2.4.2.1 Coal**

About 46.5% of South Africa coal mining is conducted underground and about 53.5 produced by opencast methods. The coal-mining industry is highly concentrated, with five companies, namely

Anglo Coal, BHP Billiton, Sasol Mining, Exxaro Coal, Kumba Coal and Xstrata Coal accounting for 90% of the saleable coal production. The eight largest mines account for 61% of the output. South Africa coal for local for electricity production is among the cheapest in the world. The beneficiation of coal, particularly for export, results in more than 65 million tons (mt) of coal discard being produced annually [32].

#### 2.4.2.2 Nuclear

The South African cabinet approved the Nuclear Energy Policy for South Africa in June 2008. The policy aims to increase the role of nuclear energy as part of the process of diversifying South Africa's primary energy source to ensure security. The policy will ensure reducing the over-reliance on coal. Eskom is investing up to 20 000 MW on new nuclear capacity by 2025. Eskom's Koeberg Nuclear Power Stations two reactors outside Cape Town supply 1 800 MW to the national grid when both operate at full power, thus providing about 6.5% of South Africa's electricity. The National Nuclear Regulator is the prime safety regulator and is responsible for protecting persons, property and the environmental against nuclear damage by establishing safety standard and regulatory practices. It exercises safety-related regulatory control over the siting, design, construction and operation of nuclear installations and other actions. The Nuclear Energy Corporation of South Africa (Necsa) undertakes and promotes research and development in the field of nuclear energy, radiation science and technology, medical isotope manufacturing, nuclear liabilities management, waste management and decommissioning. It is a public entity reporting to the Minister of Minerals and Energy.

Necsa's reactor-produced radioisotopes are exported to more than 50 countries. The research reactor at Pelindaba, Safari-1, is the most commercialized reactor of its kind in the world with International Organisation for Standardizations 9001 – accreditation. It earns South Africa foreign revenue worth millions of Rands [32].

### 2.4.2.3 Liquid Fuels

The South Africa Petroleum Industry Association announced strong growth in the petroleum product sales in the first quarter of 2007. Aggregate sales of major petroleum products showed a strong increase of 7.3% in the first quarter of 2007, compared with the first quarter of 2006. The most significant increases were in diesel (13.1%), bitumen (35.3) and liquid petroleum gas (LPG) (15%). Petrol sales grew by 4.4% and jet fuel sales by 4.6%. Sales of paraffin, a source of household energy, dropped by 13.4%. In the first Quarter, the percentage split of petrol sales between unleaded petrol (ULP) and lead-replacement petrol (LRP) was 64% and 36% respectively. This shows a significant increase in the penetration of ULP from the level of 43% that prevailed in May 2006 and indicated lower demand for LRP [32].

### 2.4.2.4 Sasol

The Sasol group of companies comprises diversified fuel, chemical and related manufacturing and marketing operations, complemented by interest in technology development, oil and gas exploration, and production. Its principal feedstock's are obtained from coal, which the company converts into value-added hydrocarbons through Fischer-Tropsch-process technologies.

### 2.4.2.5 Oil and gas

South Africa has very limited oil reserves and imports from the middle East and Africa (Saudi Arabia, Iran, Kuwait, the United Arab Emirates, Yemen, Qatar, Iraq, Nigeria, Egypt and Angola) meet about 95% of South Africa' crude oil requirements. Refined petroleum products such as petrol, diesel, residual fuel oil, paraffin, jet fuel, aviation gasoline, LPG and refinery gas are produced by:

- refining crude oil (oil refineries)
- converting coal to liquid fuels and gas to liquid fuels (Sasol)

- turning natural gas into liquid gas (PetroSA)

Another major role-player in South Africa's liquid fuels industry is the Central Energy Fund (CEF). Its mandate is to engage in acquiring, exploring, generating, manufacturing, marketing and distributing any energy form, especially oil and gas. It also engages in research relating to the energy sector. The CEF's diversified portfolio of activities is housed in the following active subsidiaries [32]:

- The strategic Fuel Fund Association
- PetroSA
- The Petroleum Agency South Africa

Although gas usage has increased in recent years, the importance of gas in the South African energy economy is still small compared to other countries. Industry remains the largest customer.

## 2.5 Electricity in South Africa

Eskom generates about 95% of electricity in South Africa and about 45% in Africa. About 88% of South Africa's electricity is generated in coal power stations. Koeberg, a large nuclear station near Cape Town, provides about 6.5% of electricity. A further 2.3% is provided by hydroelectric and pumped storage schemes. South Africa supplies two thirds of Africa's electricity and is one of the cheapest electricity producers in the world. In South Africa there are few, if any, new hydro sites that could be developed to deliver significant amounts of power, owing to water scarcity [32].

## 2.6 Household energy use in South Africa

Table 2.1 gives the South African context of annual household income in rand by energy source for cooking in percentage. The energy sources in the study were electricity, gas, paraffin, wood, coal and others.

The table shows that in South Africa there is a larger proportion of low-income than more affluent households that use biomass fuels like wood and agricultural residues. The trend is in

this manner because the low-income group cannot afford modern fuels like electricity, gas and paraffin. The table also shows that paraffin is also used by the low-income group for cooking while electricity is a common cooking fuel for the rich [31].

Table 2.2 gives the South African context of estimated electrification levels of rural and urban household by income quintile (Q). It shows that very poor households in rural areas have the lowest electrification rates in the country and it is only 41% (Q1) of the very poor households in rural areas that has access to electricity [31]. Comparing this percentage with the lowest electrification rates in urban households is 22% lower, which indicates that the urban electrification rates are higher.

Q1-R1800	36.0%	2.3%	31.4%	31.0%	3.3%	2.0%	100.0%
Q2-R1801-R33600	45.2%	3.0%	6.1%	3.3%	1.2%	0.5%	100.0%
Q3-R33601-R138600	85.3%	2.2%	1.9%	1.7%	0.5%	0.5%	100.0%
Q4-R138601-R57360	95.9%	1.9%	0.8%	0.8%	0.2%	0.4%	100.0%
Q5-R573601-R144000	94.7%	2.2%	1.1%	1.3%	0.3%	0.5%	100.0%
R14401-	92.3%	3.0%	1.7%	2.1%	0.4%	0.5%	100.0%
R1328001-							
R132801-	76.2%	2.8%	7.7%	10.6%	1.4%	1.2%	100.0%
R2457600							
R2457601 and	85.7%	1.7%	3.6%	6.5%	0.8%	0.7%	100.0%
More							
Total	51.4%	2.5%	21.4%	20.5%	2.8%	1.4%	100.0%

Table 2.2: Annual household income in Rand by energy source for cooking in percentages [26]

Income group	Electricity	Gas	Paraffin	Wood	Coal	Others	Total
0-R4800	30.0%	2.3%	31.4%	31.0%	3.3%	2.0%	100.0%
R4801-R9600	33.8%	2.3%	25.0%	33.0%	3.8%	2.0%	100.0%
R9601-R19200	47.7%	2.8%	25.2%	19.4%	3.4%	1.4%	100.0%
R19201-R38400	67.1%	3.2%	17.0%	9.3%	2.6%	0.8%	100.0%
R38401-R76800	85.8%	3.0%	6.1%	3.3%	1.2%	0.5%	100.0%
R76801-R153600	93.3%	2.2%	1.9%	1.7%	0.5%	0.5%	100.0%
R153601-307200	95.9%	1.9%	0.8%	0.8%	0.2%	0.4%	100.0%
R307201-614400	94.7%	2.2%	1.1%	1.3%	0.3%	0.5%	100.0%
R614401- R1228800	92.3%	3.0%	1.7%	2.1%	0.4%	0.5%	100.0%
R1228801- R2457600	76.2%	2.8%	7.7%	10.6%	1.4%	1.2%	100.0%
R2457601 and more	85.7%	2.7%	3.6%	6.5%	0.8%	0.7%	100.0%
Total	51.4%	2.5%	21.4%	20.5%	2.8%	1.4%	100.0%

Table 2.1: Annual household income in Rand by energy source for cooking in percentages [26]

Rural Households					Urban Households				
Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5
41%	45%	59%	68%	76%	63%	78%	87%	91%	98%

Table 2.2: Estimated electrification levels of rural and urban household by income quintile [31].

Table 2.3 gives a comparison between the mean household expenditure on electricity and other fuels and energy as a percentage of total household expenditure before and after government subsidy of 50 kWh free basic electricity. It shows that the average household expenditure on energy before an allocation of 50 kWh free basic electricity is 18%. Furthermore it shows that the average household expenditure on energy after an allocation of 50 kWh free basic electricity becomes 12% [26, 27].

Expenditure	Before Subsidy	After Subsidy	Difference	
Electricity(R/month)	38	31	7	18%
Fuels excluding electricity(R/month)	70	59	11	16%
Energy as % of household expenditure	18%	12%	6%	

Table 2.3: Mean household expenditure on electricity and other fuels and energy as a percentage of total household expenditure [27].

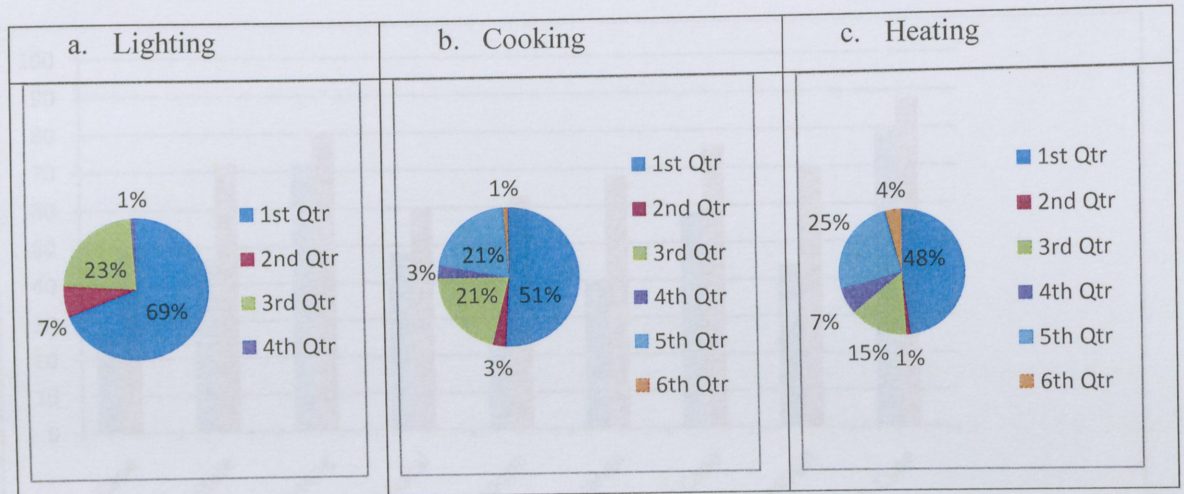


Figure 2.2: Distribution of the South African households by main energy source used for cooking, lighting and heating [32].

Figure 2.2 shows the distribution of the South African households by main energy source used for cooking, lighting and heating. A comparison of electricity use on lighting, cooking and heating shows that it is the connection to the electricity together with level of poverty that determine electricity use in South African households.

Figure 2.3 shows households using electricity for cooking and lighting by province in percentages. Series 1(left) shows households using electricity for cooking while series 2 (right) shows households using electricity for lighting. Furthermore the figure shows that the differences between electricity use for lighting and cooking in poor provinces like Limpopo and Mpumalanga is higher than in provinces with relatively high income like Gauteng and Western Cape [32].

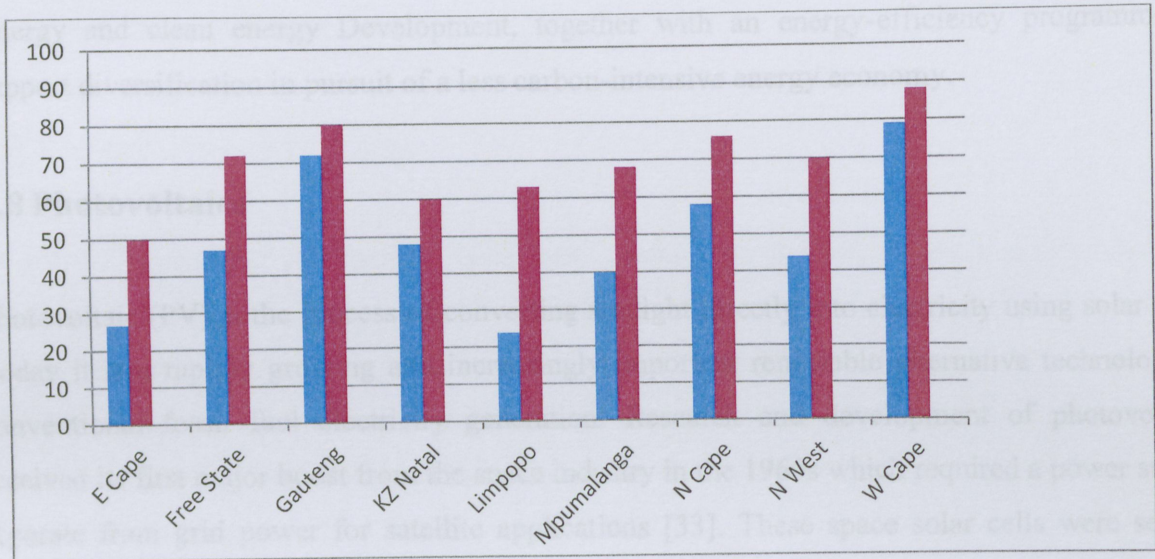


Figure 2.3: Households using electricity for cooking and lighting by province in percentages [32]

## 2.7 Energy and the environment

South Africa is among the top 20 emitters of greenhouse gases (GHGs) in the world and is the largest emitter in Africa, largely because of the economy's dependence on fossil fuels. The National Climate Change Strategy, developed by the Department of Environmental Affairs and Tourism, requires that government departments collaborate in a coordinated manner to ensure that response measures to climate change are properly directed and carried out with a national focus. The Department of Minerals and Energy is expected to respond to and mitigate climate change. South Africa is a developing country or a Non-Annex 1 country. This means that within the international political and negotiation context, South Africa is not required to reduce its GHG emissions.

However, the South African economy depends greatly on fossil fuels for energy generation and consumption and therefore is a significant emitter due to relatively high values being derived from emissions intensity and emissions per capita. South Africa must therefore proactively move the economy towards less carbon-intensive, with the Department of Minerals and Energy playing a prominent role. The department has introduced systems to access investment through the Clean

Development Mechanism of the Kyoto Protocol. It has developed a White Paper on Renewable Energy and clean energy Development, together with an energy-efficiency programme, to support diversification in pursuit of a less carbon-intensive energy economy.

## 2.9 History of photovoltaics

### 2.8 Photovoltaics

The first conventional photovoltaic cells were produced in the late 1930s, and throughout the Photovoltaic (PV) is the process of converting sunlight directly into electricity using solar cells. Today it is a rapidly growing and increasingly important renewable alternative technology to conventional fossil fuel electricity generation. Research and development of photovoltaics received its first major boost from the space industry in the 1960s which required a power supply separate from grid power for satellite applications [33]. These space solar cells were several thousand times more expensive than they are today and the perceived need for an electricity generation method apart from grid power was still a decade away, but solar cells became an interesting scientific variation to the rapidly expanding silicon transistor development with several potentially specialized niche markets. It took the oil crisis in the 1970s to focus world attention on the desirability of alternate energy sources for terrestrial use, which in turn promoted the investigation of photovoltaics as a means of generating terrestrial power. Although the oil crisis proved short-lived and the financial incentive to develop solar cells abated, solar cells had entered the arena as a power generating technology. Their application and advantage to the remote power supply area was quickly recognized and prompted the development of terrestrial photovoltaics industry. Small scale transportable applications (such as calculators and watches) were utilised and remote power applications began to benefit from photovoltaics [33, 34].

In the 1980s research into silicon solar cells paid off and solar cells began to increase their efficiency. In 1985 silicon solar cells achieved the milestone of 20% efficiency. Over the next decade, the photovoltaic industry experienced steady growth rates of between 15% and 20%, largely promoted by the remote power supply market. The year 1997 saw a growth rate of 38% and today solar cells are recognized not only as a means for providing power and increased quality of life to those who do not have grid access, but they are also a means of significantly

diminishing the impact of environmental damage caused by conventional electricity generation in advanced industrial countries [ 33].

## 2.9 History of photovoltaics

The first conventional photovoltaic cells were produced in the late 1950s, and throughout the 1960s were principally used to provide electrical power for earth-orbiting satellites. In the 1970s, improvements in manufacturing, performance and quality of PV modules helped to reduce costs and opened up a number of opportunities for powering remote terrestrial applications, including battery charging for navigational aids, signals, telecommunications equipment and other critical, low power needs.

In the 1980s, photovoltaics became a popular power source for consumer electronic devices, including calculators, watches, radios, lanterns and other small battery charging applications. Following the energy crises of the 1970s, significant efforts also began to develop PV power systems for residential and commercial uses both for stand alone, remote power as well as for utility-connected applications. During the same period, international applications for PV systems to power rural health clinics, refrigeration, water pumping, telecommunications, and off-grid households increased dramatically, and remain a major portion of the present world market for PV products. Today, the industry's production of PV modules is growing at approximately 25% annually, and major programs in U.S., Japan and Europe are rapidly accelerating the implementation of PV systems on buildings and interconnection to utility networks [33, 34,35].

## 2.10 Operation of PV cells

To understand the operation of a PV cell, we need to consider both the nature of the material and the nature of sunlight. Solar cells consist of two types of materials, often p-type silicon and n-type silicon. Light of certain wavelengths is able to ionize the atoms in the silicon and the internal field produced by the junction separates some of the positive charges ("holes") from the negative charges (electrons) within the photovoltaic device. The holes are swept into the positive

or p-layer and the electrons are swept into the negative or n-layer [33, 34, 36]. Although these opposite charges are attracted to each other, most of them can only recombine by passing through an external circuit outside the material because of the internal energy barrier. Therefore if a circuit is made power can be produced from the cells under illumination, since the free electrons have to pass through the load to recombine with the positive holes.

The amount of power available from a PV device is determined by;

- the type and area of the material;
- the intensity of the sunlight; and
- the wavelength of the sunlight

Single crystal silicon solar cells, for example cannot currently convert more than 25% of the solar energy into electricity, because the radiation in the infrared region of the electromagnetic spectrum does not have enough energy to separate the positive and negative charges in the material.

Polycrystalline silicon solar cells have an efficiency of less than 29% at this time and amorphous silicon cells, are presently about 10% efficient, due to higher internal energy losses than single crystal silicon. A typical single crystal silicon PV cell of  $100\text{cm}^2$  will produce about 1.5 Watts of power at 0.5 Volts DC and 3 Amps under full summer sunlight ( $1000\text{Wm}^{-2}$ ). The power output of the cell is almost directly proportional to the intensity of the sunlight. (For example, if the intensity of the sunlight is halved the power will also be halved) [35].

An important feature of PV cells is that the voltage of the cell does not depend on its size, and remains fairly constant with changing light intensity. However, the current in a device is almost directly proportional to light intensity and size. When people want to compare different sized cells, they record the current density, or Amps per square centimeter of cell area. The power output of a cell can be increased quite effectively by using a tracking mechanism to keep the PV device directly facing, due to the complexity of the mechanisms, and the need to cool the cells. The current output is relatively stable at higher temperatures, but the voltage is reduced, leading to a drop in power as the cell temperature is increased.

Other types of PV materials which show commercial potential include copper indium diselenide ( $\text{CuInSe}_2$ ) and cadmium telluride ( $\text{CdTe}$ ) and amorphous silicon as the basic material.

### 2.10.1 P-N junction in solar cells

A solar cell is essentially a pn junction with a large surface area. The n-type material is kept thin to allow light to pass through to the pn junction [34, 35, 37]. Light travels in packets of energy called photons. The generation of electric current happens inside the depletion zone of the pn junction. The depletion region as illustrated in figure 2.4 is the area around the pn junction where the electrons from the n-type silicon, have diffused into the holes of the p-type material. When a photon of light is absorbed by one of these atoms in the n-Type silicon it will dislodge an electron, creating a free electron and a hole. The free electron and hole has sufficient energy to jump out of the depletion zone.

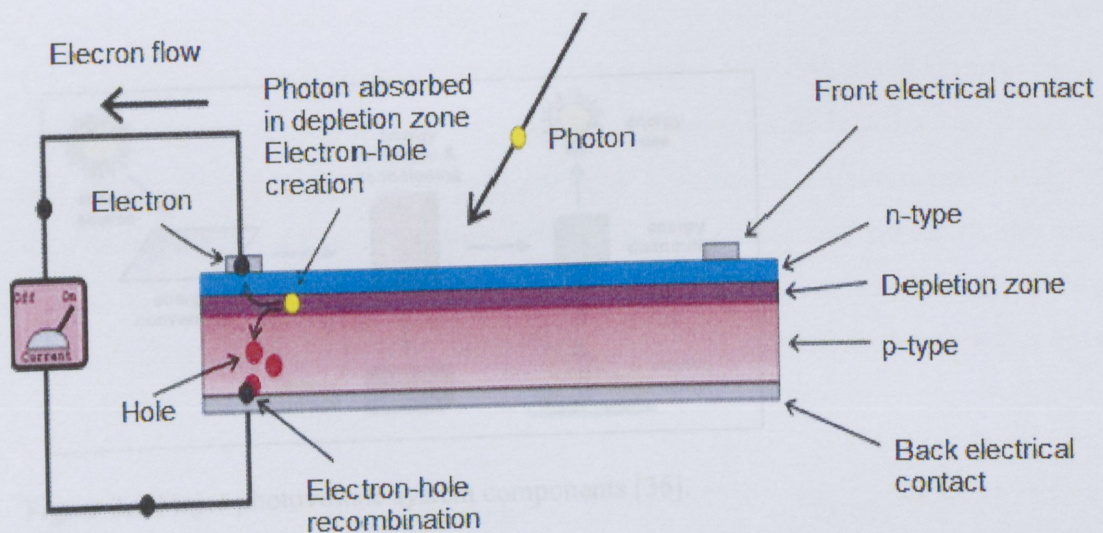


Figure 2.4, Illustration of a PN junction of silicon solar cells [37]

If a wire is connected from the cathode (n-type silicon) to the anode (p-type silicon) electrons will flow through the wire as illustrated on the figure. The electron is attracted to the positive charge of the p-type material and travels through the external load (meter) creating a flow of electric current. The hole created by the dislodged electron is attracted to the negative charge of n-type material and migrates to the back electrical contact. As the electron enters the p-type silicon from the back electrical contact it combines with the hole restoring the electrical neutrality [36].

## 2.11 The PV Array system

A PV array produces power when exposed to sunlight, but a number of other components are required to properly conduct, control, convert, distribute, and store the energy produced by the array. Depending on the functional and operational requirements of the system, the specific components required, and may include major components such as a DC-AC power inverter.

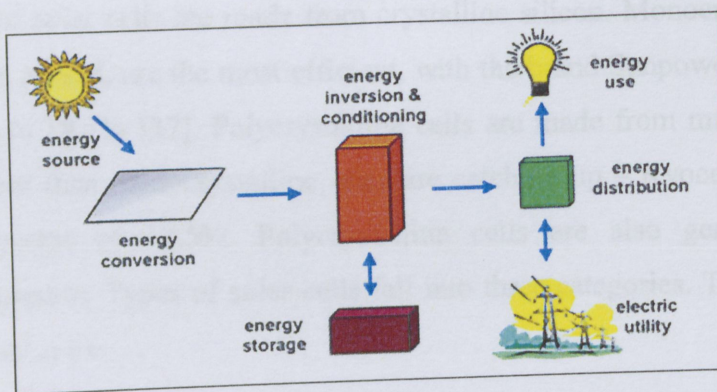


Figure 2.5 Major photovoltaic system components [36].

battery bank, system and battery controller, auxiliary energy sources and sometimes the specified electrical load (appliances). In addition, an assortment of balance of system (BOS) hardware, including wiring, overcurrent, surge protection and disconnect devices, and other power

processing equipment [36]. Figure 2.5 shows a basic diagram of a photovoltaic system and the relationship of the individual components.

Batteries are often used in PV systems for the purpose of storing energy produced by the PV array during the day, and to supply it to electrical loads as needed (during the night and periods of cloudy weather). Other reasons batteries are used in PV systems are to operate the PV array near its maximum power point, to power electrical loads at stable voltages, and to supply surge currents to electrical loads and inverters. In most cases, a battery charge controller is used in these systems to protect the battery from overcharge and overdischarge.

## 2.12 Types of Photovoltaics

A solar panel consists of cells that are put together in a module (an arrangement of rows and columns). The solar cells array is made up by a combination of different modules connected in series or parallel. There are basically three main types of solar cells on the market: monocrystalline, polycrystalline and thin film [33,35].

90% of solar cells are made from crystalline silicon. Monocrystalline cells, made from a single silicon crystal, are the most efficient, with the brand Sunpower leading the way with efficiencies of up to 18.1% [37]. Polycrystalline cells are made from many silicon crystals and, while less efficient than monocrystalline, they are catching up – Kyocera have panels on the market with efficiencies of 17.5%. Polycrystalline cells are also generally cheaper than their mono counterparts. Types of solar cells fall into three categories. Table 2.4 below shows the different types of cells.

Crystalline	Thin Film	Other
Crystalline Silicon (c-Si)	Amorphous Silicon (a-Si)	Quantum dot solar cells
	Thin film silicon	Dye sensitized photochemical cells

	Copper Indium Diselenide (CIS)	Polymer cells
Gallium Arsenide (GaAs) and Alloys	Cadmium Telluride (CdTe)	Photoelectrochemical cells

Table 2.4. Different types of solar cells [37]

Crystalline silicon currently makes up about 86% of the photovoltaic market. The reason for this dominance is that the material, technology, and equipment come right out the electronics industry. Whatever is wasted is used in the PV industry. The development of c-Si cells is very energy intensive. It is therefore very expensive to process these cells and the technology is leaning toward the production of polycrystalline Si cells and thin film technologies [37].

Polycrystalline silicon cells in the other hand uses less energy during production. The first step starts with molten Si, which is allowed to solidify under specific conditions. The solidified Si is then sliced into rectangles and then individual square cells. This process eliminates the time and energy intensive step of growing a single ingot and then slicing wafers. The end product leaves small crystalline silicon areas separated by grain boundaries. The grain boundaries decrease the efficiency of the cell. However, the benefit of lower energy consumption and cost make up for this loss [37].

Gallium arsenide can be alloyed with indium, phosphorous, and aluminium to produce multijunction cells with very high efficiencies. In forming multiple junctions with decreasing bandgap energies, the incoming photons can be shifted through with the longer wavelength photons being absorbed at the bottom. Currently two junction devices are used for spacecraft with GaInP as the top layer and GaAs as the bottom. Several researches are been conducted to make a four-junction device boosting its efficiency to more than 40% [37].

Thin film semiconductors are only a few microns thick and therefore use much less material than their crystalline counterparts. These materials are cheaper to manufacture and likely to lead solar

energy into a competitive market. Thin films are made by depositing the semiconductor material directly onto a low cost substrate.

Amorphous silicon makes up most of the remaining 14% of the PV market. Stable modules have efficiencies of 6-9%. The minimal material used and therefore the inexpensive price of modules account for this low efficiency. The p and n regions are made very thin with a thicker intrinsic layer between in order to lengthen the space charge region. To maximize light absorption and minimize recombination, the layers need to be thinner than that needed to absorb the light. Several layers are therefore stacked on top of each other. Germanium is added to each successive layer in order to decrease the band gap energy and therefore absorb wavelengths previously unabsorbed.

Cadmium telluride is a newer thin film technology with immature manufacturing steps. With time it is thought to be the most promising thin film to meet the cost goals needed for PV to be a competitive market. Laboratory cell efficiencies are around 16% coefficient, minimal amount of material, only 1 $\mu$ m and the 12 or more manufacturing steps that can be used to make the modules.

CIS and its alloys is also one of the promising thin film materials with laboratory efficiencies of 18% and module efficiencies greater than 11%. This product is currently on the market. Some of the problems include immature manufacturing steps, and a more complex structure than the other thin films. Another type of thin film is thin film crystalline silicon in which the inexpensive amorphous silicon is combined with the more efficient crystalline silicon. This is a new technology that is in the experimental stages.

Among the other category there are quantum dot solar cells in which a monocrystalline CdSe semiconductor is embedded in the conductive polymer/C60 composite. This has the potential for low-cost, large-area production. Apart from quantum dots we have dye-sensitised solar cells, polymer solar cells, etc. The DSSCs have a dye sensitizer that absorbs light and generates electrons in a nanocrystalline titanium dioxide semiconductor layer. Only certain wavelengths

can be absorbed but because the device is clear, research is being conducted to create a clear window that will absorb and convert UV light into energy [37].

### 2.12.1 Comparison between the different types of solar cells

Monocrystalline solar panels are first generation solar technologies that have been around for long time, providing evidence of their durability. The technology, installation, performance issues are all understood. Several of the early modules installed in the 1970's are still producing electricity today. Single crystal panels have even withstood the rigors of space travel.

In general, dye sensitized solar cells use photosensitive dye that generates electron-hole pairs by absorbing solar energy of visible rays. The photosensitive dye may be adhered on a metal oxide semiconductor layers such as titanium dioxide ( $\text{TiO}_2$ ). When solar light is absorbed by the photosensitive dye, molecules of the photosensitive dye are transitioned from a base state to an excited state to generate electron-hole pairs, and the excited electrons are injected into a conduction band of the semiconductor layer and moved to an adjacent electrode, that is, a photo electrode. Then, the excited electrons are moved to a counter electrode, that is, a positive electrode, via an external circuit. In addition, molecules of the dye which are oxidized by the transition of electrons are reduced in an electrolyte and electrolytic ion oxidized by the reduction of dye molecules is reduced by reaction with electrons that have reached a counter electrode [39]. As already mentioned, PV panels made from monocrystalline solar cells are able to convert the highest amount of solar energy into electricity of any type of flat solar panel. Apart from expensive silicon solar cells have high efficiency compared to the other cell technology. Even though the dye sensitized and polymer solar cells are said to be cost effective, but their efficiency is still low [38].

### 2.13 Theoretical Consideration of Photovoltaic

The basic property of a semiconductor, which makes them suitable for photovoltaic applications, is their energy band structure. The valence electron band of any semiconductor is fully occupied

at low temperature, while the conduction band is empty. However, at room temperature the thermal motion of electrons can excite some electrons to the conduction band. The probability of occupation of the state of energy  $E$  is given by Fermi-Dirac distribution [35, 39].

$$f(E) = \frac{1}{1 + e^{\frac{E - E_F}{k_B T}}} \approx \theta(E - E_F) \quad (2.1)$$

where  $F(E)$  is the occupation probability,  $E_F$  is the Fermi-level energy,  $K_B$  is Boltzmann constant,  $T$  is the temperature and  $\theta$  is a step function, i.e.  $\theta = 1$  if  $x > 0$ ,  $\theta = 0$ , if  $x < 0$   $T = 0K$ , the probability of occupation is equal to one for energy less than the Fermi energy ( $E < E_F$ ) and zero for energies greater than the Fermi energy ( $E > E_F$ ), as there is no occupation above the Fermi level, which is consistent with the Pauli exclusion which states that no two electrons can have identical energy states. At  $T > 0K$ , the occupation probability is reduced with increasing energy. The Fermi level is defined as the highest occupied molecular orbital in the valence band at  $0K$ , so that there are many states available to accept electrons. The density of states  $g(E)dE$  is the number of states per volume at energies  $E$  to  $E + dE$ .

In semiconductors and insulators, electrons are confined to a number of bands of energy and forbidden from the regions. The term band gap refers to the energy difference between the top of valence band and the bottom of the conduction band; electrons are able to jump from one band, it requires a specific amount of energy for the transition. Electrons can gain enough energy to jump to the conduction band by absorbing energy [35].

The total electron concentration,  $n = \int_0^\infty f(E) g(E) dE$ , in a material can be calculated as,

$$n = \int_0^\infty f(E) g(E) dE \quad (2.2)$$

where  $f(E)$  is the Fermi function  
and  $g(E)$  is the density of states.

## 2.14 Characteristics of Photovoltaic

The photocurrent generated by solar cells under illumination of short circuit is dependent on the incident light. To relate the photo current density,  $J_{sc}$ , to the incident spectrum we need the cell's

quantum efficiency,  $(QE)$  and  $QE(E)$  is the probability that an incident photon of energy  $E$  will deliver one electron to the external circuit. Then

$$J_{sc} = q \int b_s(E)QE(E)dE \quad 2.3$$

where  $b_s(E)$  is the incident spectral photon flux density, the number of photons of energy in the range  $E$  to  $E + dE$  which are incident on unit area in unit time and  $q$  is the electron charge.  $QE$  depends upon the absorption coefficient of the solar cell material, the efficiency of charge separation and the efficiency of charge collection in the device but does not depend on the incident spectrum. It is therefore a key quantity in describing solar cell performance under different condition.  $QE$  and the spectrum can be given as functions of either photon energy or wavelength,  $\lambda$ . Energy is a more convenient parameter for the physics of solar cell. The relationship between  $E$  and  $\lambda$  is defined by [33,34,35]

$$E = \frac{hc}{\lambda} \quad 2.4$$

where  $h$  is Plank's constant and  $c$  is the speed of light in vacuum. A convenient rule for converting between photon energies, in electron- Volts, and wavelengths, in nanometer (nm), is

$$\frac{E}{eV} = 1240 / \left( \frac{\lambda}{nm} \right) \quad 2.5$$

## 2.15 Solar Cell Operation

The four most important electrical characteristics of a PV module are the short circuit current ( $I_{sc}$ ), open circuit voltage ( $V_{oc}$ ), fill factor FF and the maximum power output  $P_{max}$ . The work done by a solar cell per unit time is quantified as its output power ( $P$ ), which is given by

$$P = IV \quad 2.6$$

where  $I$  is the current flowing out of the cell and  $V$  is the voltage across the cell.

### 2.15.1 Short circuit current

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as  $I_{sc}$ , the short-circuit current is shown on the I-V curve illustrated in figure 2.1. This current is due to the generation and collection of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell [35].

### 2.15.2 Opencircuit voltage

The open-circuit voltage,  $V_{oc}$ , is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current. The open-circuit voltage is shown on the IV curve illustrated in figure 2.6. When the load is connected to a solar cell a potential difference develops between the terminals of the cell. A solar cell can be treated as a diode. For an ideal diode the dark current ( $I_{dark}$ ) is given by [33, 34, 35],

$$I_{dark} = I_0 \left( e^{\frac{qV}{k_B T}} - 1 \right) \quad 2.7$$

where  $I_0$  is the reverse bias saturation current density,  $q$  is the electron charge and  $V$  is the voltage across the terminals.

The net current ( $I_{net}$ ) can be approximated by the difference between the short circuit current and the dark current given by [33, 34,35],

$$I_{net} = I_{sc} - I_{dark} = I_{sc} - I_0 \left( e^{\frac{qV}{k_B T}} - 1 \right) \quad 2.8$$

At open circuit condition,  $I_{dark} = I_{sc}$  so the open circuit voltage ( $V_{oc}$ ) is given by [33, 34, 35],

$$V_{oc} = \frac{k_B}{q} T \ln \left( \frac{I_{sc}}{I_0} + 1 \right) \quad 2.9$$

The above equation shows that  $V_{oc}$  depends on the saturation current of the solar cell and the light-generated current. While  $I_{sc}$  typically has a small variation, the key effect is the saturation

current, since this may vary by orders of magnitude. The saturation current,  $I_0$  depends on recombination in the solar cell. Open-circuit voltage is then a measure of the amount of recombination in the device. Silicon solar cells of high quality single crystalline materials have open-circuit voltages of up to 730 mV under one sun and AM1.5 conditions, while commercial devices on multicrystalline silicon typically have open-circuit voltages around 600 mV [33, 34, 35].

### 2.15.3 Fill Factor

The short-circuit current and the open-circuit voltage are the maximum current and voltage respectively from a solar cell. However, at both of these operating points, the power from the solar cell is zero. The fill factor, more commonly known by its abbreviation FF, is a parameter which, in conjunction with  $V_{oc}$  and  $I_{sc}$ , determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of  $V_{oc}$  and  $I_{sc}$ . Graphically, the FF is a measure of the "squareness" of the solar cell and is also the area of the largest rectangle which will fit in the IV curve. The FF is illustrated below [33, 34, 35, 39, 40],

$$FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}} \quad 2.10$$

The above equations show that a higher voltage will have a higher possible FF. However, large

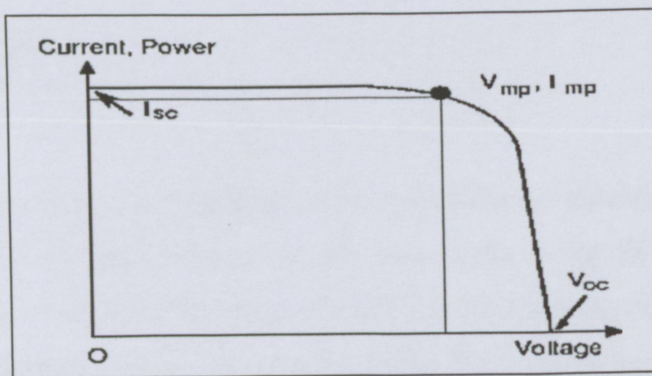


Figure 2.6: The current-voltage characteristics of a solar cell, illustrating the important factors of a PV system.

variations in open-circuit voltage within a given material system are relatively uncommon. For example, at one sun, the difference between the maximum open-circuit voltage measured for a silicon laboratory device and a typical commercial solar cell is about 120 mV, giving maximum FF's respectively of 0.85 and 0.83. However, the variation in maximum FF can be significant for solar cells made from different materials [35,40].

### 2.15.4 Efficiency

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another. Terrestrial solar cells are measured under Air Mass 1.5 conditions and at a temperature of 25°C. Solar cells intended for space use are measured under Air Mass 0 conditions. These conditions are usually understood as the standard testing condition. The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as [34, 35, 39, 41],

$$\eta = \frac{I_{sc}V_{oc}FF}{P_s} \quad 2.11$$

Apart from understanding these factors affecting the efficiency of the solar cell, there is a need to understand the performance of the solar cells using its power output. The evaluation and monitoring of the performance of the PV modules under outdoor condition is needed especially in a developing country like South Africa. This will enhance the installation and use of the PV system to the place where there is no national grid.

## 2.16 Factors that affect the efficiency of Solar Cells

Solar cell efficiency depends on several factors. This basically means that solar cells of the same type and size can have different efficiencies depending on the condition [42, 43, 44]. If you are looking around for a potential solar panel to buy for your home, this presents a major dilemma: which solar cell is the most efficient? Much of the energy from sunlight reaching a PV cell is lost before it can be converted into electricity. But certain characteristics of solar cell materials also limit a cell's efficiency to convert the sunlight it receives.

### 2.16.1 Cell temperature

Temperature effects are the result of an inherent characteristic of crystalline silicon cell-based modules. They tend to produce higher voltage as the temperature drops and, conversely, to lose voltage in high temperatures. Any solar panel or system derating calculation must include adjustment for this temperature effect [42, 43, 44].

It is a common misconception that the hotter the temperature of the area where the solar cell is located, the efficiency increases. This is not true; however, as solar cell efficiency actually decreases with high temperature. The technicalities of this is quite complex – suffice it to say that high temperature significantly lowers down the voltage produced by the cell. Solar cells work best at low temperatures, as determined by their material properties. All cell materials lose efficiency as the operating temperature rises. Much of the light energy shining on cells becomes heat, so it is good to either match the cell material to the operation temperature or continually cool the cell.

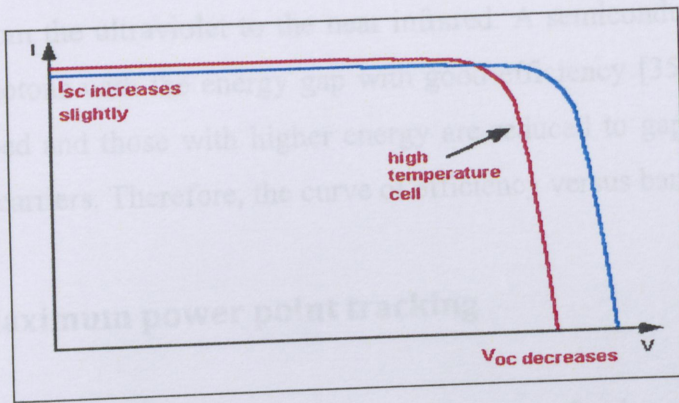


Figure 2.7: The effect of temperature on the IV characteristics of a solar cell.

Like all other semiconductor devices, solar cells are sensitive to temperature. Increases in temperature reduce the band gap of a semiconductor, thereby effecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material.

Lower energy is therefore needed to break the bond. In the bond model of a semiconductor band gap, reduction in the bond energy also reduces the band gap. Therefore increasing the temperature reduces the band gap. In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage. The impact of increasing temperature is shown in the figure 2.7[35, 42, 43, 44 ].

### 2.16.2 Energy conversion efficiency

A solar cell's energy conversion ( $\eta$ ), is the percentage of power converted and collected, when a solar cell is connected to an electrical circuit. This term is calculated using the ratio of the maximum power point,  $P_m$ , divided by the input light irradiance ( $E$ , in  $W/m^2$ ) under standard test conditions and the surface area of the solar cell ( $A_c$  in  $m^2$ ).

The solar module has a different spectral response depending on the kind of the module. Therefore, the change of the spectral irradiance influences the solar power generation. The solar spectrum can be approximated by a blackbody of 5900 K which results in a very broad spectrum

ranging from the ultraviolet to the near infrared. A semiconductor, on the other hand can only convert photons with the energy gap with good efficiency [35]. Photons with lower energy are not absorbed and those with higher energy are reduced to gap energy by thermalization of the generated carriers. Therefore, the curve of efficiency versus band gap goes through a maximum.

### 2.16.3 Maximum power point tracking

Currently, the electricity transformation efficiency of solar cells is very low that reach about 14%. The efficiency of solar cells should be improved with various methods. One of them is maximum power point tracking (MPPT) which is an important method. The MPPT operates with DC to DC high efficiency converter that presents an optimal and suitable output power. The photo generated current  $I_L$  is equal to the current produced by the cell at short circuit ( $V = 0$ ). The open circuit voltage  $V_{oc}$  (when  $I = 0$ ) can easily be obtained. No power is generated under short or open circuit. The maximum power  $P$  produced by the conversion device is reached at a point on the characteristic.

When the output voltage of the photovoltaic cell array is very low, the output current changes little as the voltage changes, so the photovoltaic cell array is similar to the constant current source; when the Voltage is over a critical value and keeps rising, the current will fall sharply, now the photovoltaic cell array is similar to the constant voltage source. As the output voltage keeps rising, the output power has a maximum power point. The function of the maximum power tracker is to change the equivalent load taken by the photovoltaic cell array, and adjust the working point of the photovoltaic cell array, in order that the photovoltaic cell array can work on the maximum power point when the temperature and radiant intensity are both changing.

### 2.17 PV Cells, Modules, & Arrays

Photovoltaic cells are connected electrically in series and/or parallel circuits to produce higher voltages, currents and power levels. Photovoltaic modules consist of PV cell circuits sealed in an environmentally protective laminate, and are the fundamental building block of PV systems.

Photovoltaic panels include one or more PV modules assembled as a pre-wired, field-installable unit [44]. A photovoltaic array is the complete power-generating unit, consisting of any number of PV modules and panels.

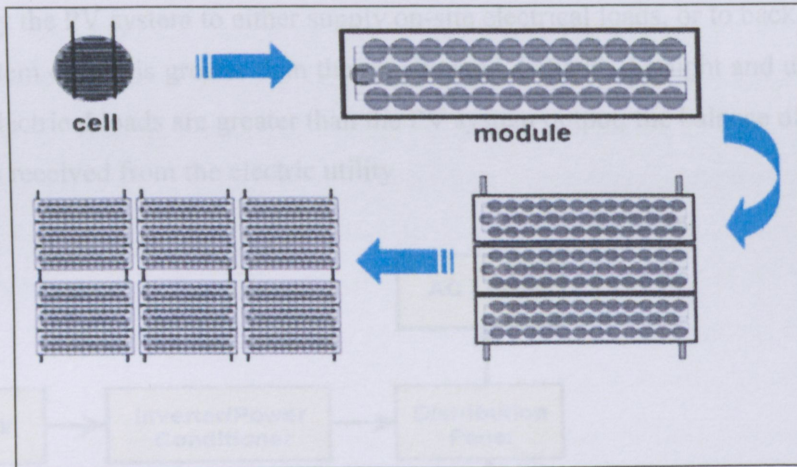


Figure 2.8: Photovoltaic cells, modules, panels and arrays.

## 2.18 Types of PV Systems

Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads. The two principle classifications are grid-connected or utility-interactive systems and stand alone systems. Photovoltaic systems can be designed to provide DC and/or AC power service, can operate interconnected with or independent of the utility grid, and can be connected with other energy sources and energy storage systems. 1.7.1 Grid-Connected (Utility-Interactive) PV Systems.

### 2.18.1 Grid-connected or utility-interactive

PV systems are designed to operate in parallel with and interconnected with the electric utility grid. The primary component in grid-connected PV systems is the inverter, or power conditioning unit (PCU). The PCU converts the DC power produced by the PV array into AC

power consistent with the voltage and power quality requirements of the utility grid, and automatically stops supplying power to the grid when the utility grid is not energized. A bi-directional interface is made between the PV system AC output circuits and the electric utility network, typically at an on-site distribution panel or service entrance. This allows the AC power produced by the PV system to either supply on-site electrical loads, or to back feed the grid when the PV system output is greater than the on-site load demand. At night and during other periods when the electrical loads are greater than the PV system output, the balance of power required by the loads is received from the electric utility

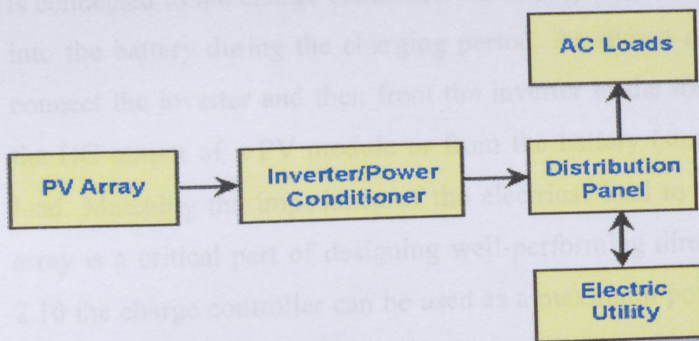


Figure 2.9: Diagram of grid-connected photovoltaic system.

This safety feature is required in all grid-connected PV systems, and ensures that the PV system will not continue to operate and feed back onto the utility grid when the grid is down for service or repair.

### 2.18.2 Stand alone solar system

Stand alone photovoltaic (PV) systems with an appropriate energy storage device have turned into one of the most promising solution for the urgent electrification problem of numerous remote consumers worldwide. In remote areas, the grid extension is either costlier or not feasible due to physical barriers. Several studies have been published concerning the utilization of small PV generators to cover the electricity requirements of isolated consumers in different countries.

Apart from utilization of PV systems, the performance and analysis of stand alone PV systems is important in order to monitor its outdoor performance and its suitability to the region of study.

The Stand alone PV systems are designed to operate independent of the electric utility grid, and are generally designed and sized to supply certain DC and/or AC electrical loads. These types of systems may be powered by a PV array only, or may use wind, an engine-generator or utility power as an auxiliary power source in what is called a PV hybrid system. The simplest type of stand alone PV system is a direct-coupled system, as illustrated on figure 2.10. The solar panel is connected to the charge controller. The charge controller is used to control the current flowing into the battery during the charging period. As shown on the figure 2.10, from the battery we connect the inverter and then from the inverter to the load or appliances. The inverter converts the DC output of a PV module or from the battery (storage) directly to AC to be used by the load. Matching the impedance of the electrical load to the maximum power output of the PV array is a critical part of designing well-performing direct-coupled system. As shown in figure 2.10 the charge controller can be used as a maximum power point tracker (MPPT) to help better utilize of the available array maximum power output [45].

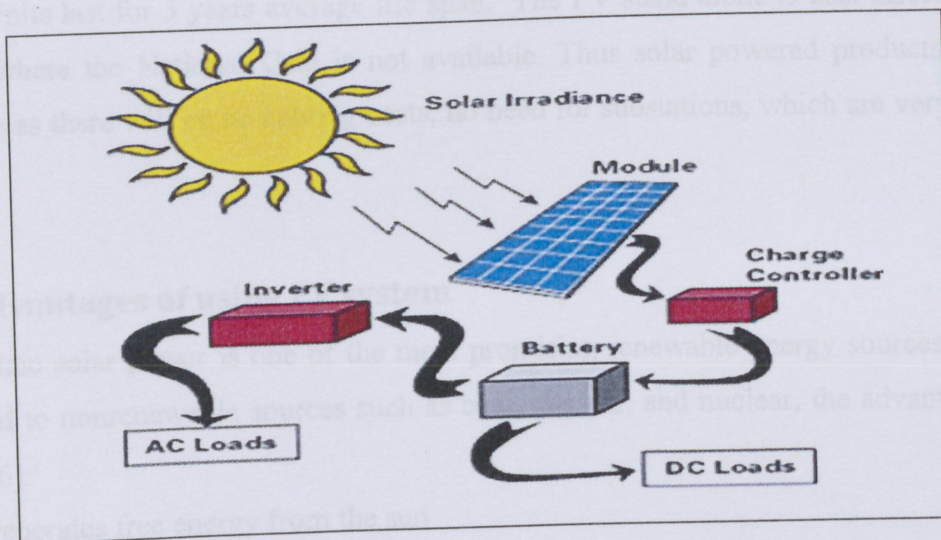


Figure 2.10: Stand alone Solar Photovoltaic system.

One of the crucial elements for mastering the performance of a stand alone PV system is the control and management of the energy storage. When designing a stand alone PV system, the preliminary work needed is to determine the needs and load requirement of the user. In this case, we must know mainly the electrical power that the system must supply and its battery capacity.

As discussed above, different systems have been installed in rural areas of South Africa, especially on schools and clinics. Few performance evaluations have been reported so far, but there are no trends of continuous monitoring to evaluate those installed systems. These study aim is to evaluate the outdoor performance of a stand alone PV system, installed at Vuwani Region, Limpopo Province South Africa.

The advantage of using a stand alone solar system is that even when it has a high installation cost, there is no monthly or daily bills to pay. Apart from the installation cost there is a minimal or no maintenance. Photovoltaic Panels are guaranteed for 20-25 years and the Photovoltaic Storage Units last for 5 years average life span. The PV stand alone is cost effective especially in areas where the National Grid is not available. Thus solar powered products have a clear advantage as there will be no cabling costs, no need for substations, which are very costly to put up.

## **2. 19 Advantages of using PV system**

Photovoltaic solar power is one of the most promising renewable energy sources in the world. Compared to nonrenewable sources such as coal, gas, oil, and nuclear, the advantages are clear [34,35, 36]:

- Generates free energy from the sun
- Has no moving parts to break down thus requiring minimal maintenance
- Non-polluting energy reduces emissions: Has no direct impact on the environment

- Photovoltaic (PV) cells are modular, you can start with a small system and expand as your needs increase
- Systems have a long life & durability. Cells last 20-25 years
- Can be installed and operated anywhere including areas of difficult access and remote locations
- PV cells make no noise and give off no CO<sub>2</sub>
- Allow the use of electricity in remote areas where it would be expensive or impossible to run power lines

### 3.1.1 The experimental site

Figure 3.1 shows the study area for the research project. The study area is Vuwani Science Resource Centre which is situated in Makhado Municipality in Vhembe Region of the Limpopo Province South Africa. Vuwani Science Resource Centre is labeled as Vuwani-University on Vhembe Region map. It is 30km away from UNIVEN and it is used as Solar research station for UNIVEN. The station has solar panels, storage batteries, DS-Tracer, MPPT charge controllers, Pyranometer and a weather station. Figure 3.2 shows how the Vhembe Region is located in the South African map.

## CHAPTER 3

### EXPERIMENTAL CONSIDERATION

#### 3.1 Introduction

The performance of a PV module strongly depends on the availability of global solar radiation at the required location and the PV-module temperature [46]. Thus, reliable knowledge and understanding of the PV module performance under different operating conditions is of great importance for correct product selection and accurate prediction of their energy performance. Because of the effects of both radiation and temperature on Maximum Power Point (MPP), a set of test conditions had to be established that establishes the values of both radiation and temperature at which PV manufacturers rate the output of their devices. This set of test conditions is known as the Standard Test Conditions (STC) for the PV industry [44, 45, 46]. By having the nameplate data of solar panels based upon these conditions, the PV designer who is evaluating various PV panel products knows the irradiance and temperature conditions under which the nameplate data was measured. The STC specifies a temperature of 25°C and of 1000 W/m<sup>2</sup> with an air mass 1.5 (AM1.5) spectrum [46]. These correspond to the solar radiation and spectrum of sunlight incident on a clear day upon a sun facing 37° tilted surface with the sun at an angle of 41.81° above the horizon.

##### 3.1.1 The experimental site

Figure 3.1 shows the study area for the research project. The study area is Vuwani Science Resource Centre which is situated in Makhado Municipality in Vhembe Region of the Limpopo Province South Africa. Vuwani Science Resource Centre is labeled as Vuwani-Univen on Vhembe Region map. It is 30km away from UNIVEN and it is used as Solar research station for UNIVEN. The station has solar panels, storage batteries, DS-Tracer, MPPT charge controllers, Pyranometer and a weather station. Figure 3.2 shows how the Vhembe Region is located in the South African map.

### 3.2 Estimation of Solar Radiation



Figure 3.1. Map of South Africa illustrating Vhembe Region

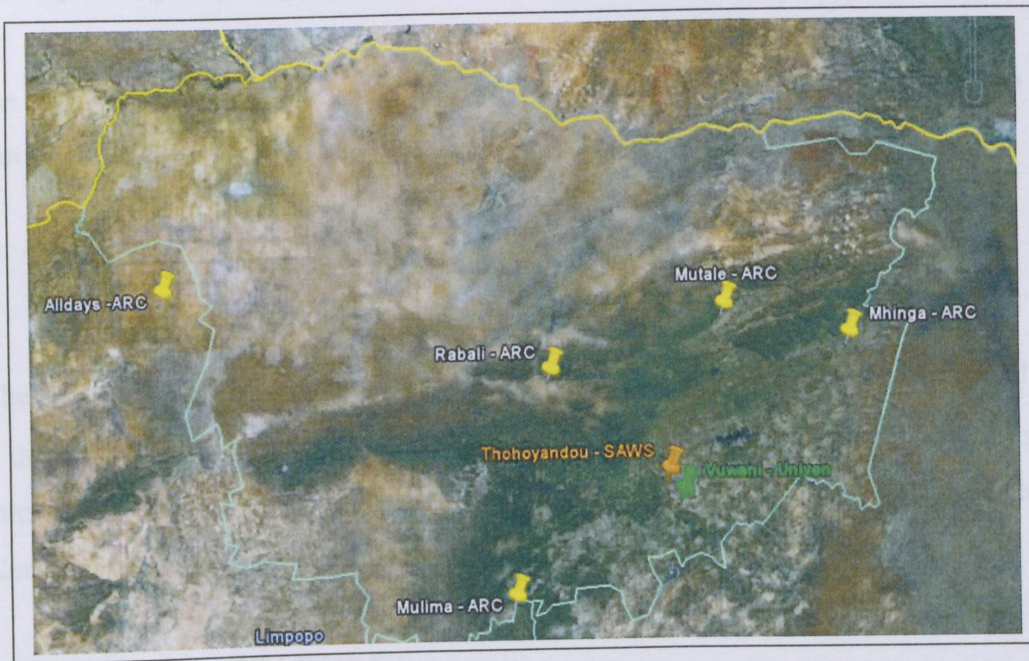


Figure 3.2. Location of the station for our current studies (VuwaniUniven).

### 3.2 Estimation of Solar Radiation

As mentioned above for a solar photovoltaic system to be installed, the first step is to determine the availability of solar radiation on the site. In this work the estimation of solar radiation was performed. Figures 3.1 and 3.2 illustrate the map of South Africa which shows the Vhembe region and our current Vuwani Univen station. The simple model used to estimate monthly average daily global solar radiation on horizontal surface is the modified form of the Angstrom type equation. The original Angstrom type regression equation related monthly average daily radiation to clear day radiation at the location in question and average fraction of possible sunshine hours. The modified method used is [8, 47, 48],

$$\frac{H}{H_0} = a + b \frac{S}{S_0} \quad 3.1$$

where  $H$  is the monthly average daily global radiation,  $H_0$  is monthly average daily extraterrestrial radiation,  $S$  is the monthly average daily hours of bright sunshine,  $S_0$  is the monthly average day length, and  $a$  and  $b$  are empirical coefficients.

The monthly average daily extraterrestrial radiation on a horizontal surface ( $H_0$ ) can be computed from the following equation [8,46, 47 ],

$$H_0 = \frac{24}{\pi} I_{sc} \left[ 1 + 0.033 \cos \frac{360n}{365} \right] \left[ \cos \phi \cos \delta \sin \varphi_s + \frac{\pi}{180} \varphi_s \sin \phi \sin \delta \right] \quad 3.2$$

Where  $I_{sc}$  is the solar constant ( $= 1367 \text{ Wm}^{-2}$ ),  $\phi$  the latitude of the site,  $\delta$  the solar declination,  $\omega_s$  the mean sunrise hour angle for the given month and  $n$  the number of days of the year starting from first January. The solar declination ( $\delta$ ) and the mean sunrise hour angle ( $\omega_s$ ) can be calculated by the following equations

$$\delta = 23.45 \left[ \frac{360 (284+n)}{365} \right] \quad 3.3$$

$$\varphi_s = \cos^{-1} ( - \tan \phi \tan \delta ) \quad 3.4$$

For a given month, the maximum possible sunshine duration (monthly average day length,  $S_0$ ) can be computed by using the following equation:

$$S_0 = \frac{2}{15} \varphi_s \quad 3.5$$

### 3.3 MPPT Charge Controller or Maximum Power Point Tracking (MPPT)

#### 3.3.1 Overview

Currently, the electricity transformation efficiency of the solar cells is very low and it is about 14%. The efficiency of solar cells should be improved with various methods. One of them is maximum power point tracking (MPPT) which is an important method. The MPPT operates with DC to DC high efficiency converter that presents an optimal and suitable output power [49].

Charge controllers for solar arrays are becoming increasingly popular because of the many advantages they afford the solar owner. Though a somewhat new technology next to traditional on/off charge controllers and the increasingly standard pulse width modulation (PWM) charge controllers, MPPT charge controllers are gaining market share because of their ability to turn excess energy into a significant benefit.

#### 3.3.2 The function of MPPT Charge Controller

As with any other type of charge controller, an MPPT solar charge controller's task is to regulate the energy being pumped into the system batteries in order to maintain battery life and reduce the chances of battery damage. Traditional methods for this involved a mechanical relay system that simply stopped and started the flow of energy through the circuit. But because this system lacked the ability to check the current state of the battery, it often resulted in battery damage due to overcharging [49].

Additionally, these traditional models connect the array directly to the battery, forcing modules to operate at the level of the battery's voltage which prevents them from producing the maximum

power possible. In a typical example, a 17 volt module of 75 watts will have to operate at 12 volts with a conventional charge controller, which therefore reduces the energy produced by the array to 53 watts instead of the full 75 watts.

Newer systems with PWM charge controllers are capable of checking the battery condition and adjusting the flow of energy accordingly to trickle in the final charge and avoid overcharging. This has been an important breakthrough in the charge controller market, but it still doesn't address the issue of lost efficiency due to differing voltages.

MPPT charge controllers, however, have gone a step further with their ability to attract additional power from the PV array and convert the excess voltage into amperage. An MPPT charge controller functions by calculating the ideal voltage for producing the most power and then connects the array to the battery at the voltage.

This type of charge controller maintains the maximum power point voltage for the solar panel. Since the amount of sunlight fluctuates throughout the day but the voltage at which maximum power is transferred does not, the MPPT is able to reduce the charge current as sunlight levels go down while maintaining panel voltage at the maximum power point.

Using the same specifications as above, the 17 volt module will operate at the full 17 volts, allowing it to send the full 75 watts of energy to the battery, with a DC – to – DC converter that converts the energy to the current battery voltage, whatever that may be at the time. This results in a 93% to 97% efficiency in conversion, which can mean a 20% to 45% power increase in the winter and 10% to 15% power increase in the summer.

### **3.3.3 Control current loop**

MPPT charge controllers use an extra current control loop that reduces the charge current as the sunlight reduces. This in turn maintains panel voltage around the maximum power point voltage.

### 3.3.5 Warranties and Standards for MPPT charge controllers

### 3.3.4 The advantage of choosing an MPPT charge controller for your solar system

In real solar systems, a MPPT charge controller offers several significant advantages such as

- Higher battery charge when fully discharged: When the battery is at its lowest charge, it requires the most current in order to reach a complete charge. An MPPT charge controller is able to increase the power going to fully discharged batteries to effect a more efficient charge cycle.
- Better short day performance: Cold weather often coincides with shorter days and therefore fewer solar hours, cold weather is generally the time when efficiency needs to be at its best. Though solar panels put out more power in lower temperatures, without a charge controller that can adapt the energy voltage, this advantage is lost. An MPPT charge controller is capable of determining the output of the panels, comparing it to the voltage of the battery, and figuring out the most ideal voltage to get the maximum amps. This results in better short day performance.
- Reduced distance restrictions: Long distances between batteries and panels can significantly reduce the voltage of an array without a large, expensive wiring system. But an MPPT charge controller can convert high voltage to the necessary battery voltage to reduce the power loss and keep costs at a minimum.
- Higher ampere sizes: Though traditional charge controllers, including PWM charge controllers, are often limited to 60 amperes or less, MPPTs can handle up to 80 amperes.
- System growth: MPPT charge controllers, because of their ability to adjust to varying voltages, also permit the owner to size the system up without too much trouble.

These are significant advantages for those looking to maximize the output of their solar array. They are, however, more expensive than PWM charge controllers and larger in size, requiring a larger physical footprint. Additionally, each of the modules in a photovoltaic array must be similar in order to be connected in strings to an MPPT charge controller.

### 3.3.5 Warranties and Standards for MPPT charge controllers

In addition to the other advantages of MPPT charge controllers, they also generally come with longer warranties and last longer than old – style and PWM charge controllers. Most MPPT charge controllers are UL listed. When all is said and done, if the price tag can be overcome, the added upfront cost of an MPPT charge controller is usually worth it with the boosts in charging efficiency.

## 3.4 DS-tracer

### 3.4.1 Basic description

The Dayster DS-100C I-V curve tracer is a portable self-contained unit for testing installed photovoltaic systems. It uses a capacitive load to vary the impedance connected to the output terminals of the PV array under test. The voltage and current are sampled as the capacitors in the DS-100C are charged. This data set is transferred to the control computer for the display, analysis and storage using the powerful windows-based IVPC software. The displayed I-V curve includes values of [50]:

- Open Circuit Voltage ( $V_{oc}$ )
- Short Circuit Current ( $I_{sc}$ )
- Peak Power ( $P_{mp}$ )
- Voltage at Peak Power,  $V_{pk}$
- Current at Peak Power,  $I_{pk}$
- Fill Factor (FF)

The DS-100C has two thermocouple inputs,

- a. Two user selectable current ranges (10 and 100 Amperes)
- b. Three automatically selected voltage ranges (600 V, 60 V, 6V)
- c. Two irradiance measurements inputs
- d. Two temperature measurements inputs

The values measured by these sensors are saved as part of the I-V curve data. Apart from those entire attached sensor, for safety the DS-100C is packaged in a rugged non-metallic case. Most

of the DS tracer can be operated continuously for more than ten hours before recharging the battery.

### 3.4.2 Operation of the DS-Tracer

An I-V curve is obtained from the DS-Tracer by varying the electrical impedance that is connected across the PV module output terminals. Usually the impedance is varied from zero to infinity. This action allows the array operating point to change from  $I_{sc}$  to  $V_{oc}$ . The impedance change achieved by the DS-Tracer is obtained by connecting the PV module to a capacitive load. Through the capacitor charging period, the PV module point moves from  $I_{sc}$  to  $V_{oc}$ , and in the process, provides set of current and voltage values. These set of values are then used to form an I-V curve. The collection of data (i.e., the current and voltage values) stops only when the PV module operating point reaches  $V_{oc}$ .

The DS-Tracer employs two high-speed, analog-to-digital converters to sample the current and **voltage. One converter digitizes** the array voltage while the other digitizes the array current. The DS-Tracer analyzes the digitized values, **saves those that show significant change**, and transfers the data set to the control computer. The data set includes the I-V curve data plus values of open-circuit voltage, ( $V_{oc}$ ), and short-circuits current, ( $I_{sc}$ ). Peak-power, voltage at peak-power ( $V_{pk}$ ), current at peak-power ( $I_{pk}$ ), and fill factor are calculated and displayed with the curve [50].

Irradiance and temperature data, and PV module identification may be added to each data set. The irradiance and temperature data are either entered by the operator using IVPC or sampled by the DS-100C. The DS-Tracer sweeps an I-V curve by switching the PV system to a bank of capacitors. As these capacitors charge, the PV system voltage increases until open circuit voltage is reached. While the voltage is increasing, and the current to the capacitors is decreasing from its maximum, short-circuit value, the voltage and current are sampled by high-speed analog-to-digital converters. These data points define the I-V curve.

Before acquiring data, the DS-Tracer reverse charges its capacitive load to approximately -25 V. This negative pre-charge is used to offset any voltage drops created by the test leads and to allow any switching transients to settle before  $I_{sc}$  is reached. This method allows a true short circuit current reading to be made. The DS-Tracer allows 5 seconds for a curve to reach open circuit voltage. At this point the circuitry discharges the capacitors through a resistive load.

The complete cycle actually begins with a discharge of any residual voltage on the capacitors. This discharge is followed by 7 seconds of pre-charge, 5 seconds to take the curve, and finally another 5 seconds for discharge. The initial discharge cycle is not normally needed. However, it ensures that the load capacitors are ready to accept a pre-charge. The initial discharge, if needed, may take up to 5 seconds [50].

The DS-Tracer uses an SCR to close the circuit between the PV system and the load capacitors. SCRs are susceptible to false triggering (turn on) if the voltage across them is increased too rapidly. The DS-Tracer disconnect switch uses two  $1M\Omega$  resistors (one each for the positive and negative leads) across the disconnect switch contacts. These resistors allow the SCR to “see” the PV system voltage before the disconnect switch is closed; thereby preventing the SCR from false triggering when the disconnect switch is closed. Under normal operating conditions, this switch should always be the last switch closed and the first switch opened when making PV system connections. Some PV systems are sensitive to how quickly an I-V curve is taken. The speed of a curve is most easily expressed in volts per second by taking the PV system short circuit current in Amps ( $I_{sc}$ ) and dividing it by the DS-Tracer load capacitance in Farads (F).

### 3.4.3 Connecting the DS-Tracer to the PV System

The DS-Tracer was connected to the PV array or module with the test leads provided. Before connecting a PV module, DS-Tracer power switch was ON and the disconnect switch in the OFF position. The test leads were plugged into the DS-Tracer being sure to match the red and black connectors. The Voltage Sense connector was keyed and can only be inserted in one way.

With the DS-Tracer disconnect switch still OFF, the test leads were attached to the PV module. By making connections with the PV system disconnect switch off, the chance of electric shock is avoided. After connecting the test leads, PV system switch was closed. At this point, PV voltage should be present at the DS-Tracer. The DS-Tracer disconnect switch was turned ON [50].

### 3.5. Experimental set up

#### 3.5.1 Experimental considerations

A small stand alone photovoltaic system was configured at fixed position, fixed azimuthal inclination and fixed direction at Vuwani Science Resource Center at Vuwani region of the Limpopo province, South Africa. The amount of energy received by the panel (solar radiation) and the power output was measured by DS-Tracer. The measurement of module power in the field was made with FLEXmax 60 MPPT Charge Controller and also through the plotting of I-V curves with the DS-Tracer. FLEXmax 60 MPPT Charge Controller was used to record everyday data of maximum voltage. The I-V curve tracer was used to plot I-V curves once every week. One year data of outdoor performance was collected and analyzed in order to determine the maximum voltage of the solar cell.



Figure 3.3. Stand alone PV module installed at the experimental site

Figure 3.3 illustrates the stand alone PV module installed at the Vuwani-University solar research

Before taking a curve, the DS-Tracer was turned on and connected to the PV system. The computer was connected to the DS-Tracer and running IVPC. From the File menu, New I-V Curve was selected. IVPC open a new curve window. This window provides areas to enter curve information identifying the I-V curve. The DS-Tracer takes up to 12 seconds to initialize the tracer hardware. The curve data was entered during the delay.

For example, if not using the Auto feature to read an irradiance or temperature channel, enter a value manually at this time. A status message indicating that the DS-Tracer is pre-charging is displayed in the area normally used to plot the curve.

After initialization, the status message changes and the Take Curve button was enabled. The status message indicates that a curve can be taken by using the mouse to press the Take Curve button or by pressing Alt-T. After Take Curve button was pressed, the DS-Tracer took approximately 6 seconds depending on the speed of the control computer to take the curve and the data was plotted. The data was saved by selecting Save I-V Curve from File menu. The curve was stored in the current directory and the Data Grid was updated [50].

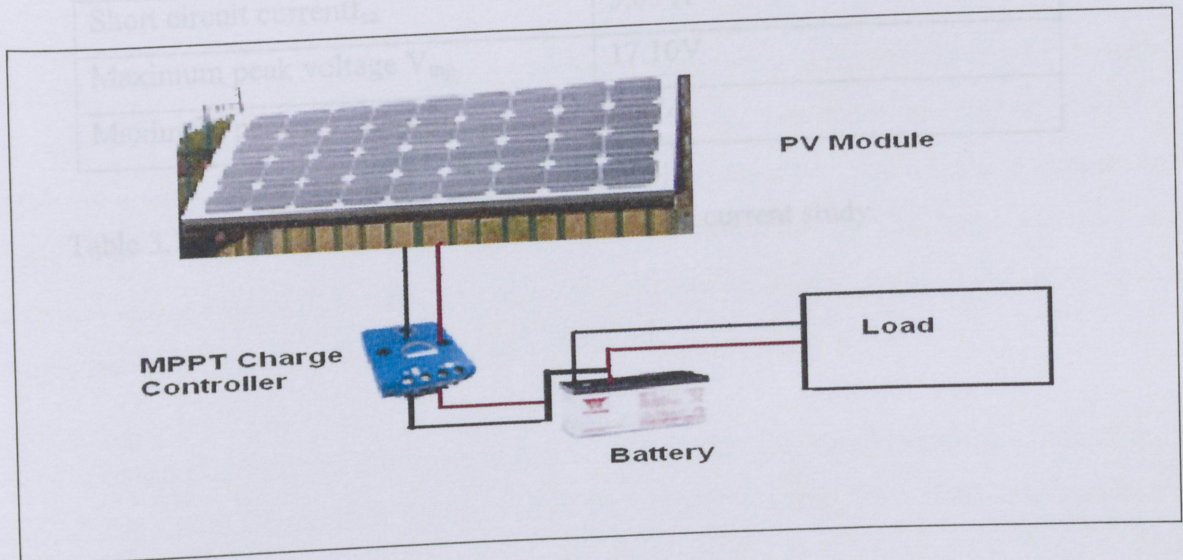


Figure 3.4. Experimental arrangement and setup of the stand alone PV system connected to the MPPT for outdoor performance measurements.

Figure 3.3 illustrate the stand alone PV module installed at the Vuwani-Univen solar research station. The specification of this module is given on Table 3.1. Figure 3.4 illustrates the experimental arrangement throughout the year. The peak power ( $P_p$ ) and peak voltage ( $V_p$ ) of the module was extracted from the charge controller for the period of a year as shown under the results chapter. The peak voltage produced by the panel was monitored as illustrate on the figure. This was done by taking the peak voltage produced by the panel throughout the day. More of the results obtained are discussed in chapter four.

Commercially available PV module rating and operating parameters are provided with respect to Standard Testing Conditions (STC) [34, 35]. Specification sheets may provide information on operational parameters at a few other set of operating conditions. Table 3.1 shows the electrical specifications of the solar energy module used for the stand alone PV system at the experimental site.

Maximum Power $P_{max}$	75 W
Open circuit voltage $V_{oc}$	21.70 V
Short circuit current $I_{sc}$	5.03 A
Maximum peak voltage $V_{mp}$	17.10V
Maximum peak current $I_{mp}$	4.39A

Table 3.1. Specifications of the PV module of the current study.

## 4.2. Estimation of solar radiation

### CHAPTER 4

## RESULTS, DISCUSSION AND CONCLUSION

### 4.1 Introduction

The main objective of this research work was to determine the outdoor performance of a stand alone PV solar system at Vuwani Region, Limpopo Province in South Africa. In chapter 3 a detailed description of the methods for estimating of the solar radiation was presented, together with the experimental setup to measure the peak power. The estimation of global solar radiation data at Vuwani Science Resource Centre whose coordinates are as follows: Latitude:  $23.1303^{\circ}$  S, Longitude:  $30.4198^{\circ}$  E was performed. As illustrated on chapter 3, the Angstrom-Prescott linear equations were used for the estimation of the global solar radiation. The constants a and b evaluated in ref [55] were used to compute the solar radiation data.

The major aim of measuring the outdoor condition parameters is that photovoltaic modules are sold with their peak power performance (Wp) tested under laboratory conditions at STC [34]. Under real outdoor conditions, this peak power is seldom achieved, since module temperature is usually more in the range of about  $40-50^{\circ}\text{C}$  under illumination. The hours of  $1000\text{ W/m}^2$  irradiation is only about 1 % of total sun hours and the spectral content of the solar spectrum change continuously with varying climatic conditions.

One of the important factors for solar radiation data is that for many locations of the world the solar radiation is available in different forms. Hence before using these data, one should know whether the radiation data is measured or computed, whether they are direct, diffuse or global; whether they are hourly, daily or monthly, mean daily and whether is incident on a horizontal or inclined surface. In addition time or period of measurement and the type of instruments used for measurement should be known.

## 4.2. Estimation of solar radiation

### 4.2.1. Declination angle

The results of solar declination angles computed using Equation 3.3 is presented graphically in Figure 4.1. The variation of solar declination angles depends on the day number. As illustrated in figure 4.1, it can be observed that the solar declination angle is zero in March and as well as in September.

### 4.2.2. Daily sunshine hour angle ( $\omega_s$ )

The daily sunrise hour angles for our current study area, which is Vuwani Science resource centre are computed using Equation 3.4. These results are illustration graphically in figure 4.2. At low solar declination angle, the respective sunrise hour angles are high.

### 4.2.3. Extraterrestrial Solar Radiation ( $I_0$ )

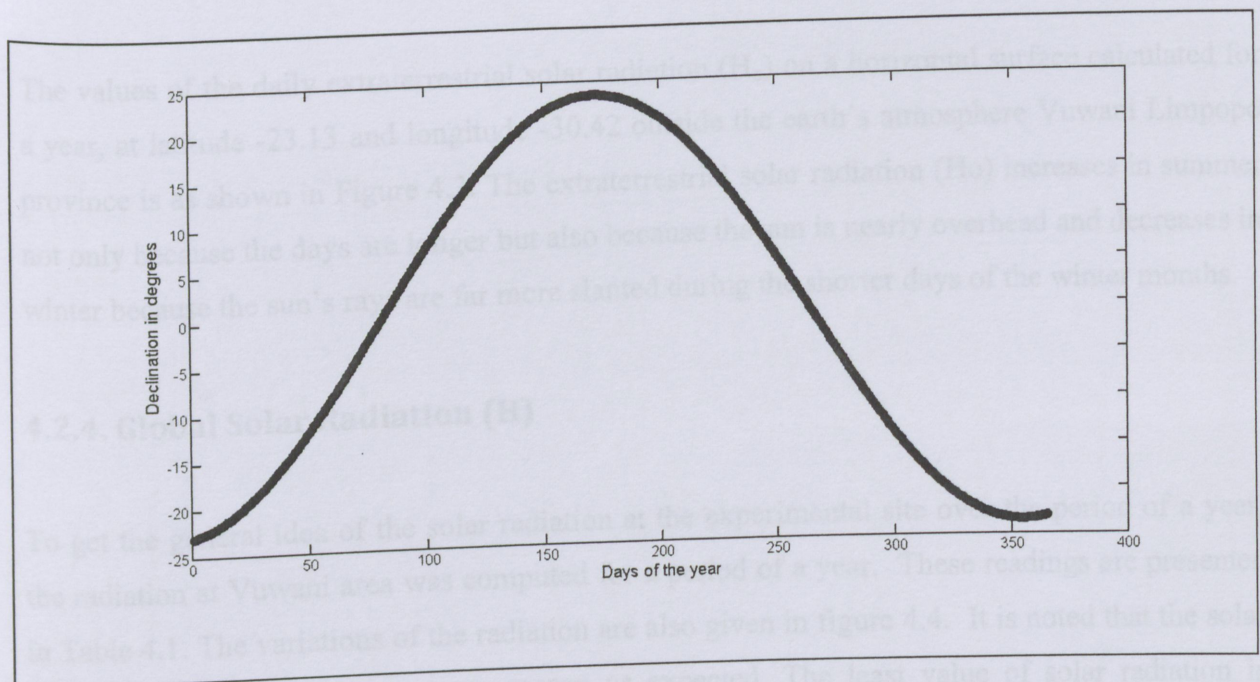


Figure 4.1 Variation of solar declination angles in a year

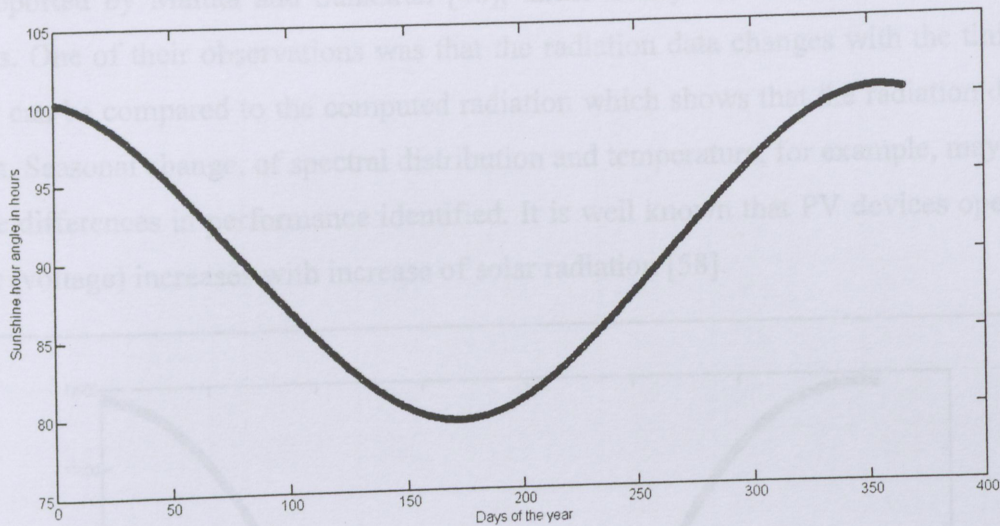


Figure 4.2 Daily sunshine hour angles ( $\omega_s$ )

### 4.2.3. Extraterrestrial Solar Radiation ( $H_0$ )

The values of the daily extraterrestrial solar radiation ( $H_0$ ) on a horizontal surface calculated for a year, at latitude  $-23.13$  and longitude  $-30.42$  outside the earth's atmosphere Vuwani Limpopo province is as shown in Figure 4.3. The extraterrestrial solar radiation ( $H_0$ ) increases in summer not only because the days are longer but also because the sun is nearly overhead and decreases in winter because the sun's rays are far more slanted during the shorter days of the winter months.

### 4.2.4. Global Solar Radiation ( $H$ )

To get the general idea of the solar radiation at the experimental site over the period of a year, the radiation at Vuwani area was computed for a period of a year. These readings are presented in Table 4.1. The variations of the radiation are also given in figure 4.4. It is noted that the solar radiation is higher during summer season as expected. The least value of solar radiation is obtained in winter. This pattern is consistent with the observation made in South Africa for which both theoretical and experimental observations have the same trend. Similar observation

was reported by Maluta and Sankaran [40], under nearly the similar condition of the current studies. One of their observations was that the radiation data changes with the time of the day, which can be compared to the computed radiation which shows that the radiation depend on the season. Seasonal change, of spectral distribution and temperature, for example, may well account for the differences in performance identified. It is well known that PV devices operational peak power (voltage) increases with increase of solar radiation [58].

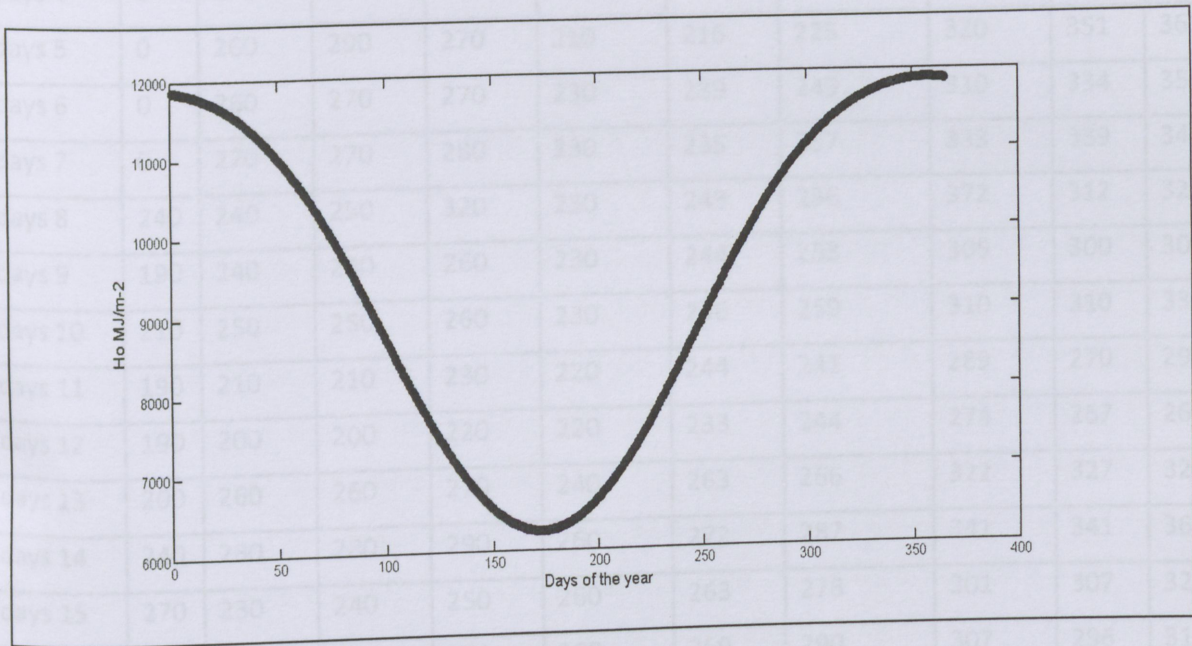


Figure 4.3. Daily extraterrestrial radiation

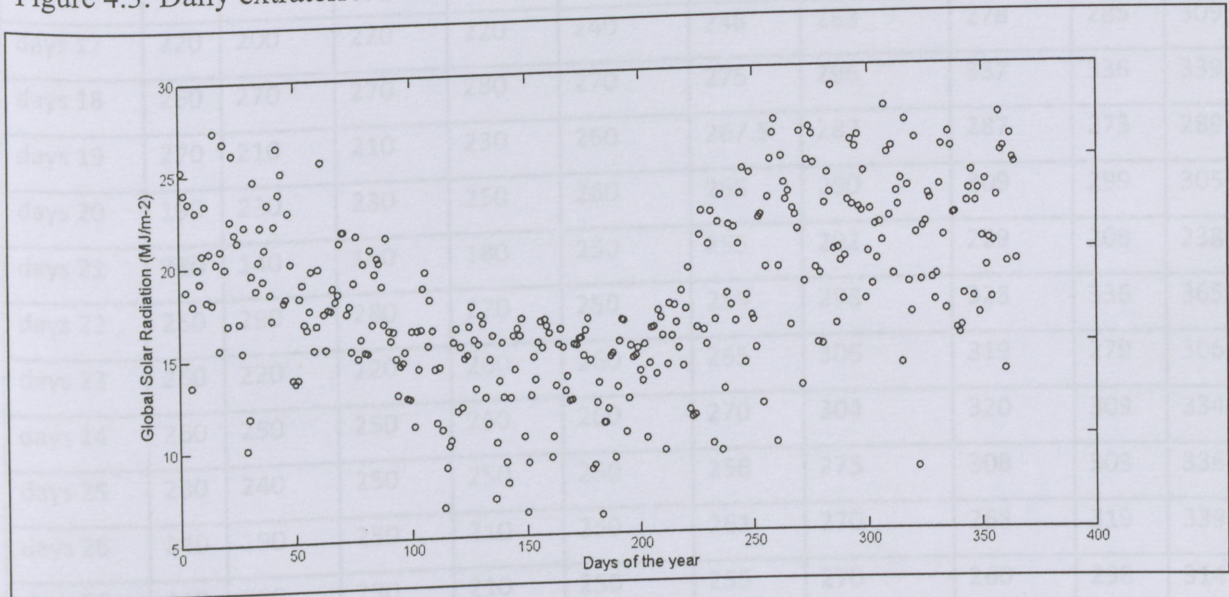


Figure 4.4 Daily Global Solar Radiation

Days	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
days 1	0	250	240	220	230	233	253	271	304	318
days 2	0	200	210	210	190	195	215	267	273	290
days 3	0	260	250	270	230	239	258	325	316	328
days 4	0	270	280	280	220	223	241	337	347	349
days 5	0	260	290	270	210	216	225	320	351	369
days 6	0	260	270	270	230	239	249	310	334	358
days 7	0	270	270	280	230	235	257	333	339	348
days 8	240	240	250	320	230	243	256	372	312	329
days 9	190	240	240	260	230	244	253	305	300	309
days 10	210	250	250	260	230	236	259	310	310	334
days 11	190	210	210	230	220	244	241	289	270	293
days 12	190	200	200	220	220	233	244	274	267	260
days 13	200	260	260	270	240	263	266	322	327	324
days 14	240	280	280	290	260	272	287	341	341	367
days 15	270	230	240	250	260	263	276	301	307	327
days 16	190	230	230	250	260	269	290	307	296	310
days 17	220	200	220	220	240	248	263	278	285	309
days 18	260	270	270	280	270	275	296	337	336	339
days 19	270	210	210	230	260	267.5	287	287	273	289
days 20	190	230	230	250	260	265	290	309	299	305
days 21	280	140	150	180	250	255	292	229	208	238
days 22	260	290	280	270	250	259	298	328	336	365
days 23	260	220	220	260	260	265	306	319	279	306
days 24	260	250	250	260	260	270	304	320	309	334
days 25	230	240	250	250	250	256	275	308	303	336
days 26	240	190	250	210	250	261	270	268	319	339
days 27	240	200	230	210	250	255	270	260	298	314

days 28	250	190	210	210	210	222	234	269	279	296
days 29	0	270	270	250	250	255	289	307	330	357
days 30	0	220	230	210	210	223	259	266	296	318
days 31	0	300	0	270	0	257	278	0	280	0

Table 4.1 Daily extraterrestrial radiation

### 4.3. OUTDOOR MEASUREMENTS AND PV MODULE CHARACTERIZATION

Outdoor measurements have the advantage that actual MPPT behaviour will be observed with the real PV array thus avoiding potentially unrealistic interactions between the MPPT and PV array simulator. Obtaining the necessary range of parameters in the outdoors requires co-operative weather as well as access to a variety of PV technologies. In the present study PV module issued from Solar world was used. The specifications of the PV module are as follows: peak power of 75.00W, open circuit voltage of 21.70V and short circuit current of 5.03A. The module was oriented with latitude tilt of  $45^{\circ}$ , facing South. It was connected to a MPPT which is interfaced with the modules at their maximum power point, and which read PV output power. Apart from the maximum power, the IV curves of the module were also recorded, using the DS tracer. In addition, the average peak voltage ( $V_p$ ) of the module was monitored for a period of a year.

#### 4.3.1. Current -Voltage (I-V) Measurements

Current-voltage characteristics of the module arrays were also taken to supplement the results obtained with the outdoor data monitoring of the module arrays. A DS curve tracer is used for current-voltage measurement of PV module. Standard PV performance parameters such as open circuit voltage, short circuit current, peak power, voltage and current at peak power are obtained from these measurements. The PV module under test receives an electrical performance (I-V),

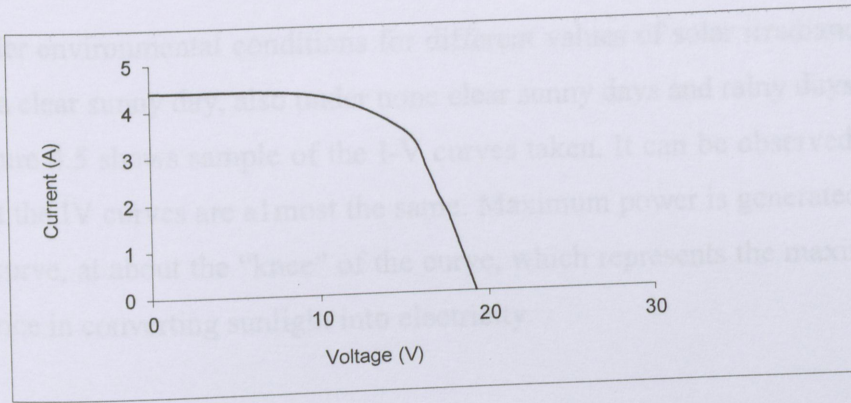


Figure 4.5A: Sample I-V curve 2A1: for c-Si module (Oct)

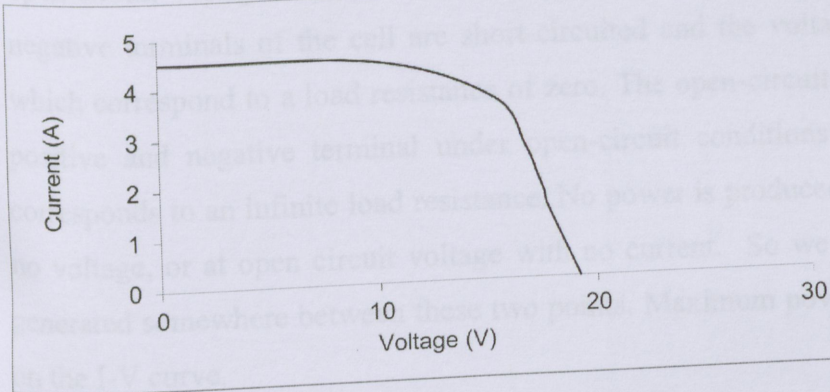


Figure 4.5B: Sample I-V curve November

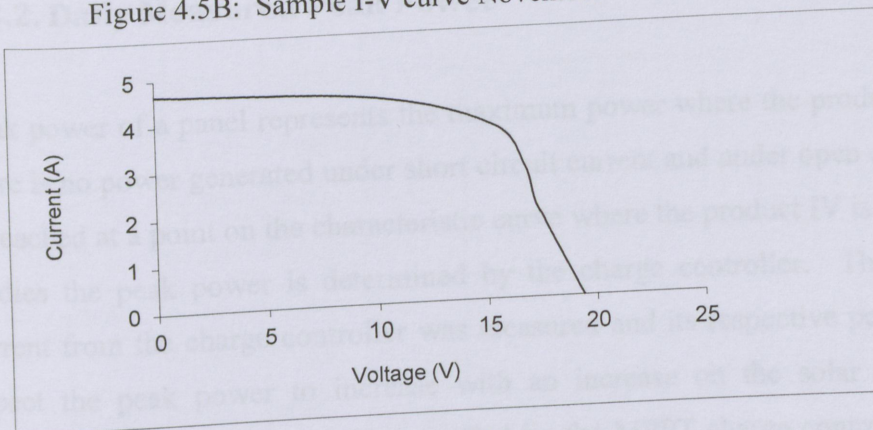


Figure 4.5C: Sample I-V curve December

Figure 4.5: Sample I-V curves for Modules under study for the months of October, November and December 2011.

under environmental conditions for different values of solar irradiance and ambient temperature on a clear sunny day, also under none clear sunny days and rainy days.

Figure 4.5 shows sample of the I-V curves taken. It can be observed as illustrated on the figure that the IV curves are almost the same. Maximum power is generated at only one point on the I-V curve, at about the “knee” of the curve, which represents the maximum efficiency of the solar device in converting sunlight into electricity.

The actual I-V curve typically passes through two significant points, the short circuit current and open-circuit voltage. The short-circuit current is the current produced when the positive and negative terminals of the cell are short-circuited and the voltage between the terminal is zero which correspond to a load resistance of zero. The open-circuit voltage is the voltage across the positive and negative terminal under open-circuit conditions and the current is zero which corresponds to an infinite load resistance. No power is produced at the short-circuit current with no voltage, or at open circuit voltage with no current. So we expect to find maximum power generated somewhere between these two points. Maximum power is generated at only one point on the I-V curve.

#### 4.3.2. Daily Measured Peak Power

Peak power of a panel represents the maximum power where the product  $IV$  is maximum, since there is no power generated under short circuit current and under open circuit voltage. Hence this is reached at a point on the characteristic curve where the product  $IV$  is maximum. In the current studies the peak power is determined by the charge controller. The peak voltage and peak current from the charge controller was measured and its respective peak power. In general we expect the peak power to increase with an increase on the solar radiation. In our current investigation the peak power is controlled by the MPPT charge controller. We hope that this is because the charge controller controls the current entering the battery and when the battery is full, there is no current supplied to the battery until the battery is losing the current when is in use. The other important factor which can be noted about charging the battery using the MPPT charge controller is that the battery temperature is influenced by two factors: the temperature in

the battery room and the fact that charging batteries is an exothermic process. These two factors were reported by Woodworth et.al. [56], they have shown how the battery temperature varies with the time of the day.

The peak power of the module are presented in table 4.2 and also illustrated by figures 4.5 -4.16. The peak power of the panel was monitored for a period of a year as illustrated in the above mentioned table and figures.

Jan	Feb	March	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
67.80	64.41	47.46	30.51	33.9	64.41	64.41	64.41	64.41	64.41	67.80	67.80
64.41	64.41	47.46	30.51	64.41	64.41	67.80	71.19	64.41	64.41	64.41	67.80
67.80	57.63	50.85	30.51	67.80	64.41	67.80	67.80	64.41	64.41	67.80	64.41
67.80	67.80	50.85	33.90	67.8	64.41	67.80	71.19	67.80	67.80	64.41	64.41
67.80	64.41	50.85	37.29	64.41	64.41	67.80	64.41	67.80	67.80	64.41	64.41
67.80	54.24	50.85	64.41	64.41	61.02	64.41	64.41	64.41	64.41	64.41	64.41
67.80	54.24	50.85	64.41	64.41	64.41	67.80	74.58	64.41	67.80	67.80	67.80
67.80	54.24	50.85	64.41	64.41	64.41	67.80	64.41	67.80	67.80	64.41	67.80
64.41	54.24	50.85	64.41	64.41	64.41	67.80	67.80	67.80	64.41	64.41	67.80
67.80	54.24	50.85	64.41	64.41	64.41	67.80	67.80	64.41	64.41	67.80	64.41
67.80	50.85	50.85	67.80	64.41	61.02	71.19	71.19	67.80	61.02	64.41	71.19
64.41	47.46	50.85	64.41	64.41	61.02	67.80	71.19	64.41	67.80	67.80	67.80
67.80	47.46	50.85	64.41	64.41	61.02	67.80	71.19	67.80	67.80	64.41	67.80
64.41	50.85	57.63	64.41	64.41	64.41	64.41	67.8	64.41	67.80	64.41	67.80
67.80	50.85	57.63	64.41	64.41	64.41	71.19	67.80	64.41	61.02	64.41	67.80
64.41	47.46	47.46	64.41	64.41	64.41	67.80	67.80	64.41	67.80	67.80	64.41
67.80	47.46	50.85	64.41	64.41	64.41	67.80	71.19	67.80	67.80	64.41	64.41
67.80	47.46	50.85	64.41	64.41	64.41	71.19	67.80	64.41	64.41	64.41	64.41
64.41	47.46	61.02	64.41	64.41	64.41	71.19	64.41	64.41	64.41	71.19	67.80
67.80	47.46	54.24	64.41	61.02	64.41	71.19	61.02	64.41	64.41	64.41	67.80
64.41	37.29	67.80	64.41	64.41	64.41	71.19	64.41	64.41	64.41	64.41	67.80
67.80	37.29	64.41	64.41	64.41	64.41	71.19	67.80	64.41	64.41	67.80	64.41

64.41	33.90	64.41	64.41	64.41	64.41	67.80	64.41	64.41	64.41	67.80	64.41
67.80	33.90	64.41	64.41	64.41	64.41	67.80	61.02	64.41	64.41	64.41	64.41
64.41	33.90	64.41	64.41	64.41	64.41	67.80	71.19	64.41	67.8	64.41	64.41
64.41	37.29	64.41	64.41	64.41	64.41	71.19	71.19	64.41	64.41	64.41	67.80
64.41	33.90	50.85	64.41	64.41	64.41	64.41	64.41	64.41	64.41	67.80	67.80
64.41	33.9	30.51	33.90	64.41	64.41	71.19	64.41	61.02	64.41	64.41	64.41
64.41	-	30.51	67.80	64.41	64.41	64.41	64.41	71.19	67.80	64.41	67.80
64.41	-	30.51	64.41	61.02	67.80	67.80	67.80	64.41	64.41	67.80	67.80
64.41	-	30.51	-	64.41	-	67.80	67.80	-	67.80	-	64.41

Table 4.2 Illustration of measured peak power for the period of a year

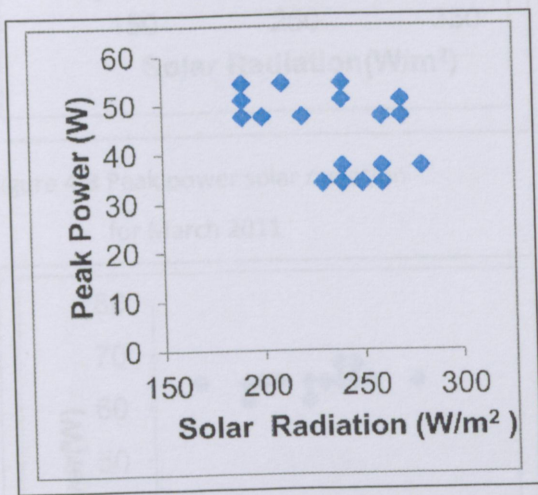


Figure 4.6 Peak power solar radiation for January 2011

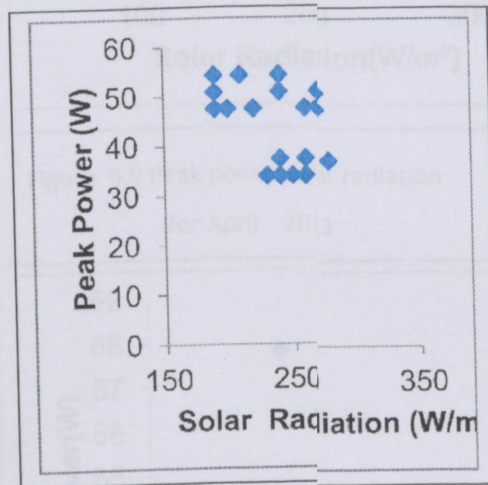


Figure 4.7 Peak power solar radiation for February 2011

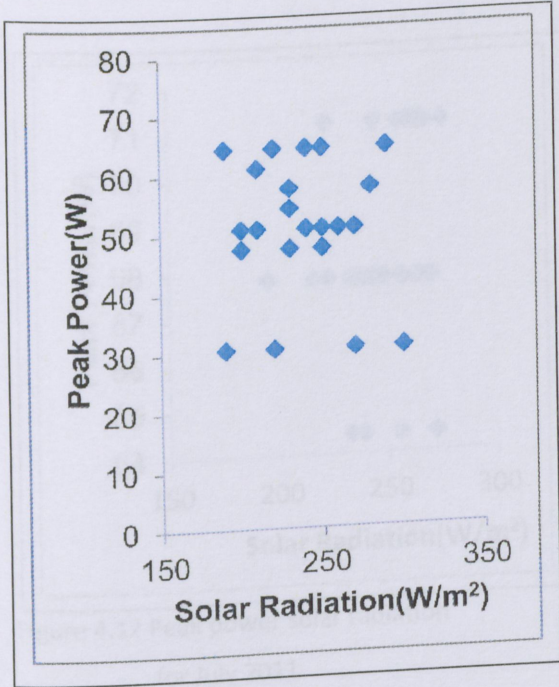


Figure 4.8 Peak power solar radiation for March 2011

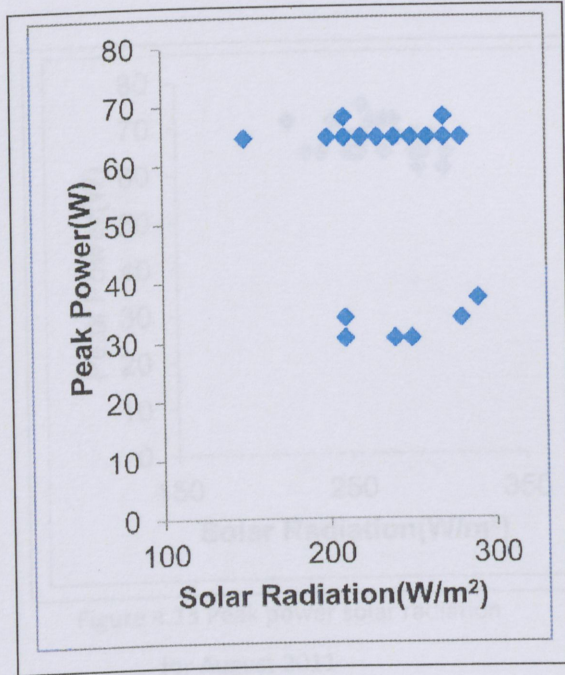


Figure 4.9 Peak power solar radiation for April 2011

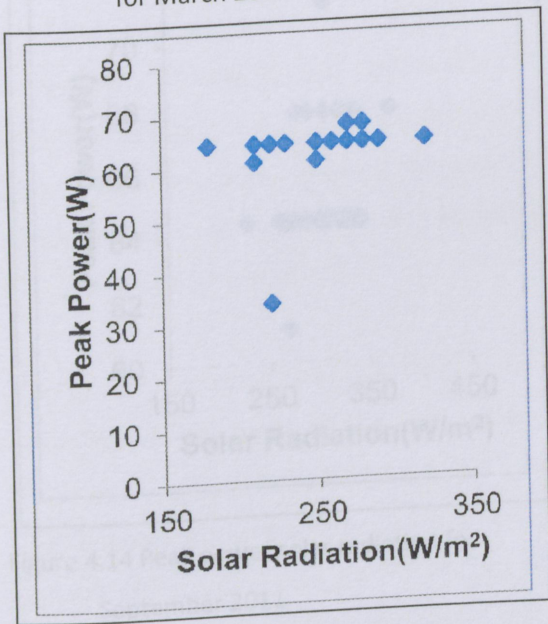


Figure 4.10 Peak power solar radiation for May 2011

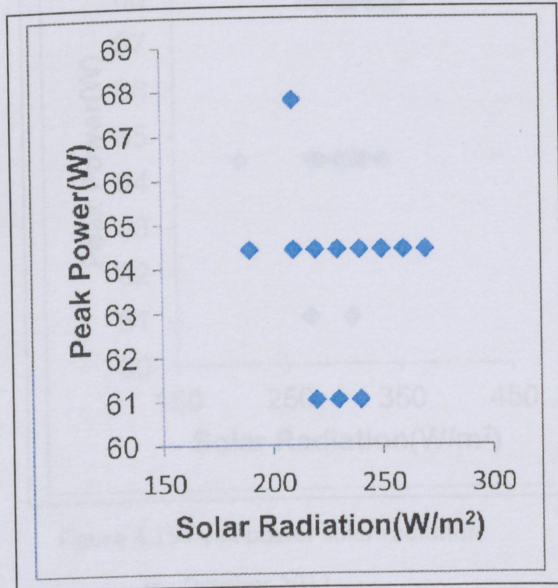


Figure 4.11 Peak power solar radiations for June 2011

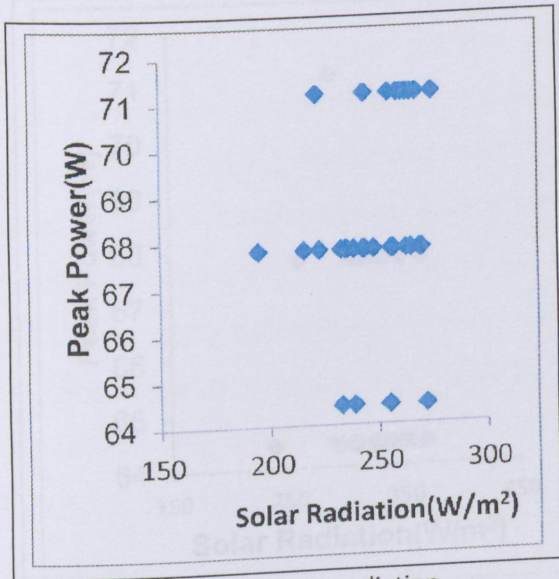


Figure 4.12 Peak power solar radiation for July 2011

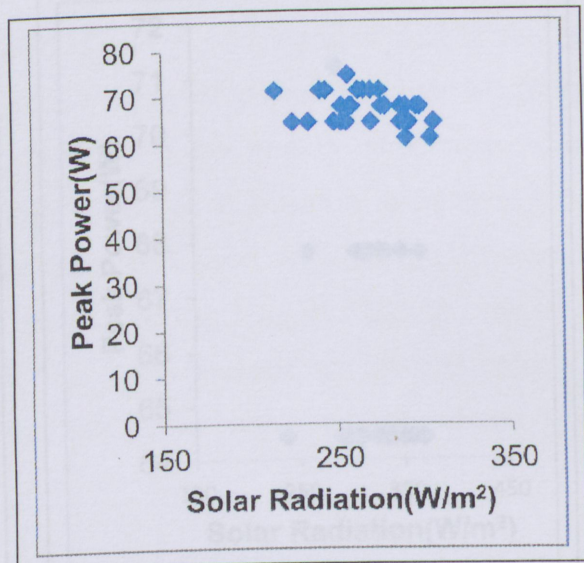


Figure 4.13 Peak power solar radiation for August 2011

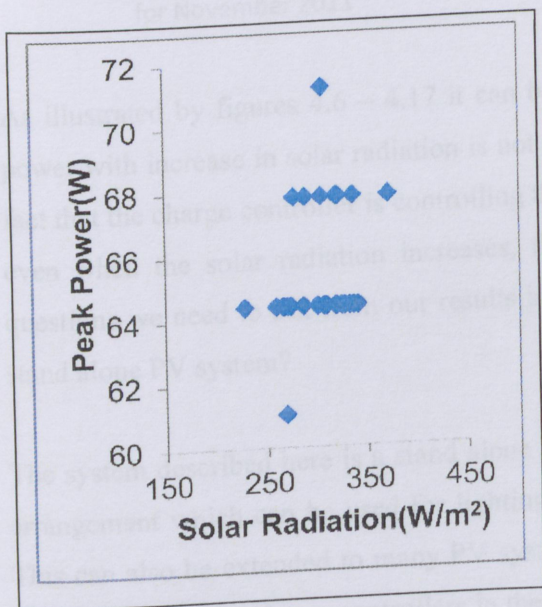


Figure 4.14 Peak power solar radiation for September 2011

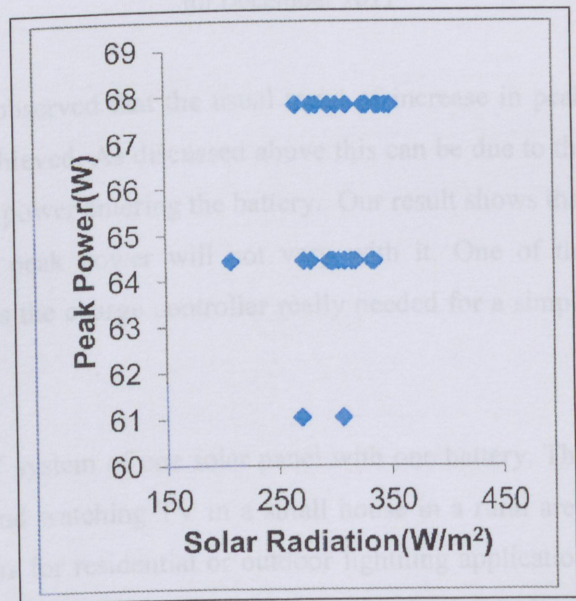


Figure 4.15 Peak power solar radiation for October 2011

### 4.3.3. Average monthly peak power

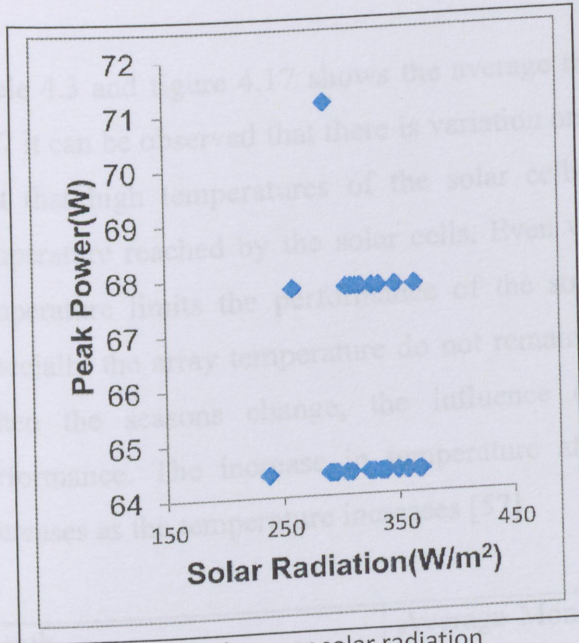


Figure 4.16 Peak power solar radiation for November 2011

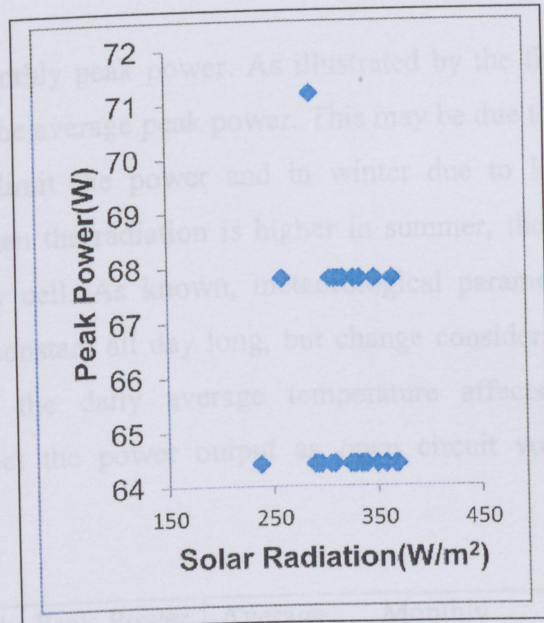


Figure 4.17 Peak power solar radiation for December 2011

As illustrated by figures 4.6 – 4.17 it can be observed that the usual trend of increase in peak power with increase in solar radiation is not achieved. As discussed above this can be due to the fact that the charge controller is controlling the power entering the battery. Our result shows that even when the solar radiation increases, the peak power will not vary with it. One of the questions we need to ask from our results is: is the charge controller really needed for a simple stand alone PV system?

The system described here is a stand alone PV system of one solar panel with one battery. This arrangement which can be used for lighting and watching TV in a small house in a rural area. This can also be extended to many PV systems for residential or outdoor lightning application. The function of the charge controllers in these systems is to protect the batteries from overcharge or overdischarged. There are PV designs which operate satisfactorily without charge controllers. In a system described in our current studies, there is a need to use the charge controller to prevent overcharging of the battery due to some extreme hot days. But when load requirements are much higher than in the systems described here, it is often economical to omit the charge controller entirely and use a battery with capacity of a load requirement.

### 4.3.3. Average monthly peak power

Table 4.3 and figure 4.17 shows the average monthly peak power. As illustrated by the figure 4.17 it can be observed that there is variation on the average peak power. This may be due to the fact that high temperatures of the solar cells limit the power and in winter due to lower temperature reached by the solar cells. Even when the radiation is higher in summer, the cell temperature limits the performance of the solar cell. As known, meteorological parameters, especially the array temperature do not remain constant all day long, but change considerably. When the seasons change, the influence of the daily average temperature affects the performance. The increase in temperature affect the power output as open circuit voltage decreases as the temperature increases [57].

Month	Average Monthly Peak Power (W)	Average Monthly Solar Radiation (W/m <sup>2</sup> )
January 2011	66.16	
February 2011	44.23	232.381
March 2011	51.51	236.4516
April 2011	58.31	241.3333
May 2011	63.43	248.7097
June 2011	67.07	238.6667
July 2011	68.24	247.7581
August 2011	67.36	267.129
September 2011	65.31	302.3
October 2011	65.5	304
November 2011	65.77	321.933
December 2011	66.38	

Table 4.3 Average monthly peak power and solar radiation

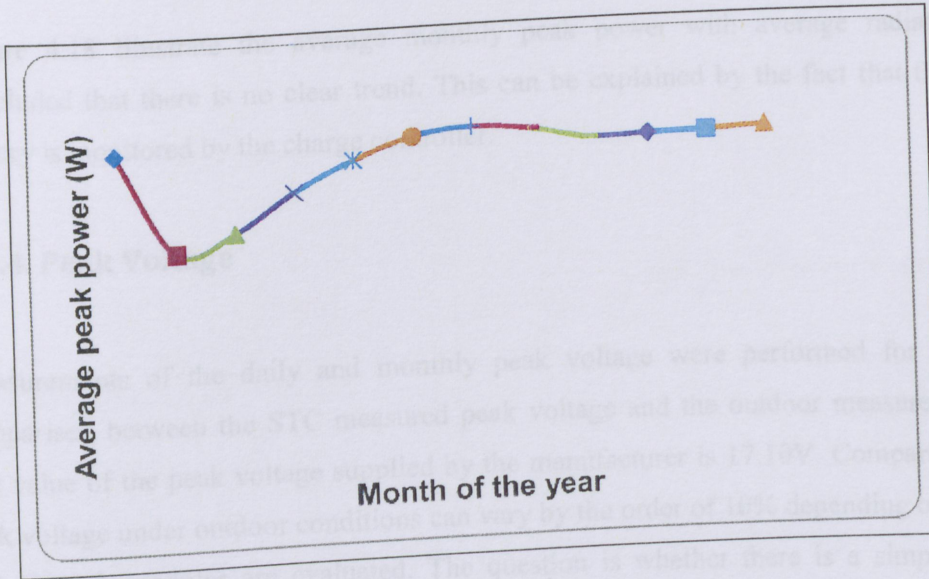


Figure 4.17 Illustrating the average monthly peak power

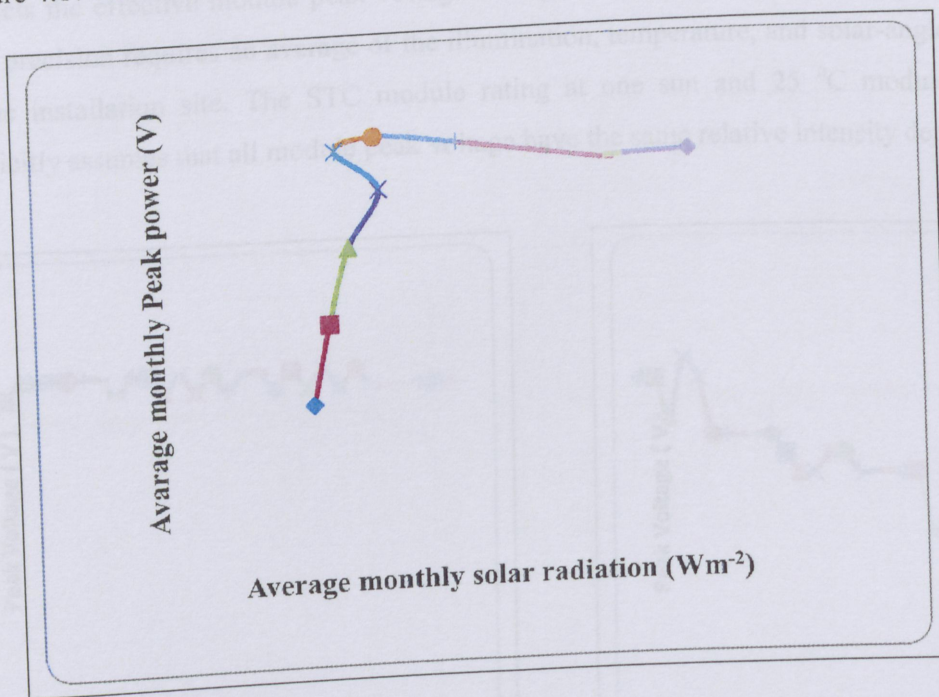


Figure 4.18 Average monthly peak power with monthly radiation

Figure 4.18 illustrate the average monthly peak power with average radiation, it can be concluded that there is no clear trend. This can be explained by the fact that the power to the battery is monitored by the charge controller.

#### 4.3.4. Peak Voltage

Measurements of the daily and monthly peak voltage were performed for the purpose of comparison between the STC measured peak voltage and the outdoor measured peak voltage. The value of the peak voltage supplied by the manufacturer is 17.10V. Comparisons of module peak voltage under outdoor conditions can vary by the order of 10% depending on the conditions under which modules are evaluated. The question is whether there is a simple protocol that predicts the effective module peak voltage averaged over a typical year of operation. To do so with precision requires an average of the illumination, temperature, and solar-angle distributions at the installation site. The STC module rating at one sun and 25 °C module temperature implicitly assumes that all module peak voltage have the same relative intensity dependence.

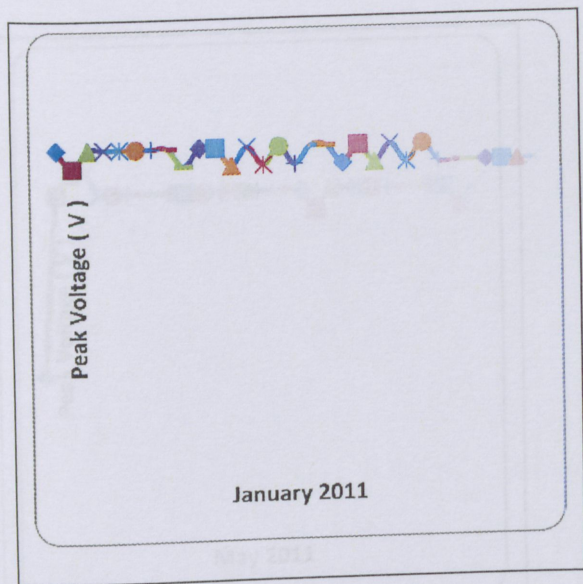


Figure 4.19 Peak voltage for January 2011



Figure 4.20 Peak voltage for February 2011

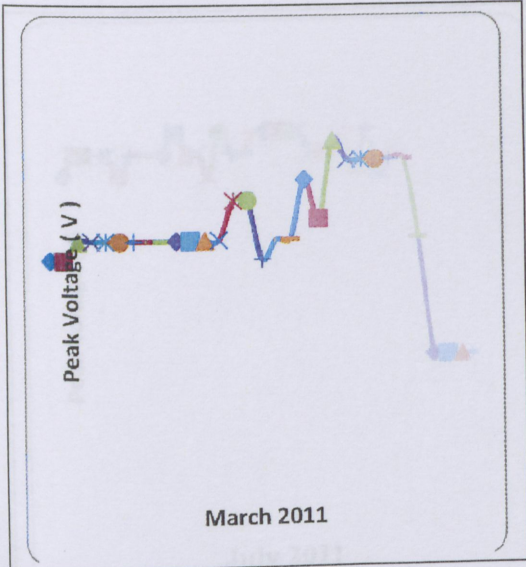


Figure 4.21 Peak voltage for March 2011



Figure 4.22 Peak voltage for April 2011

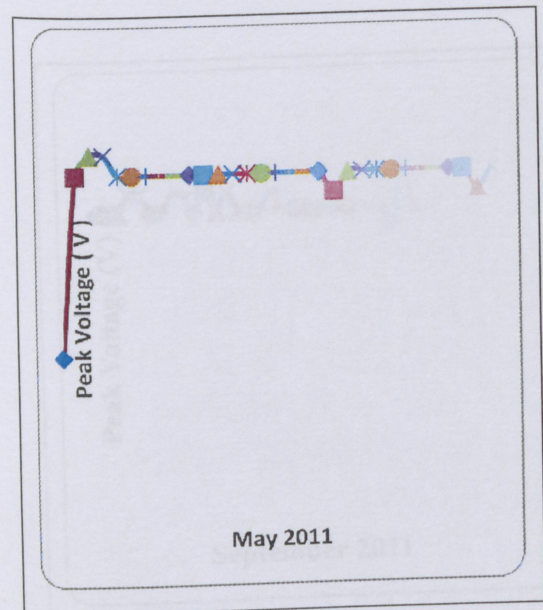


Figure 4.23 Peak voltage for May 2011



Figure 4.24 Peak voltage for June 2011

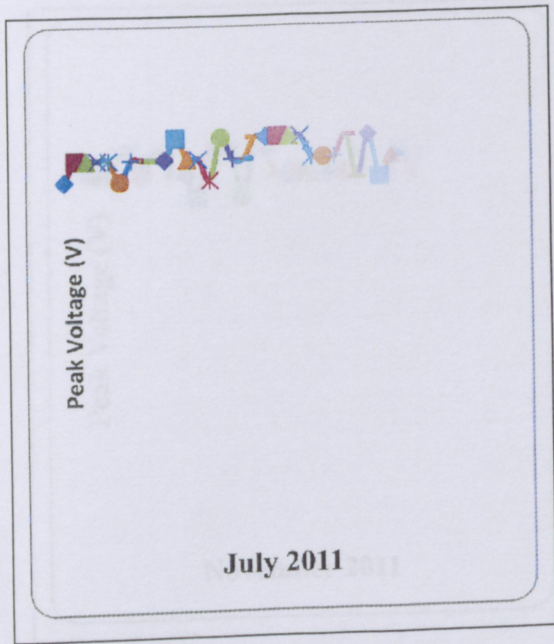


Figure 4.25 Peak voltage for July 2011

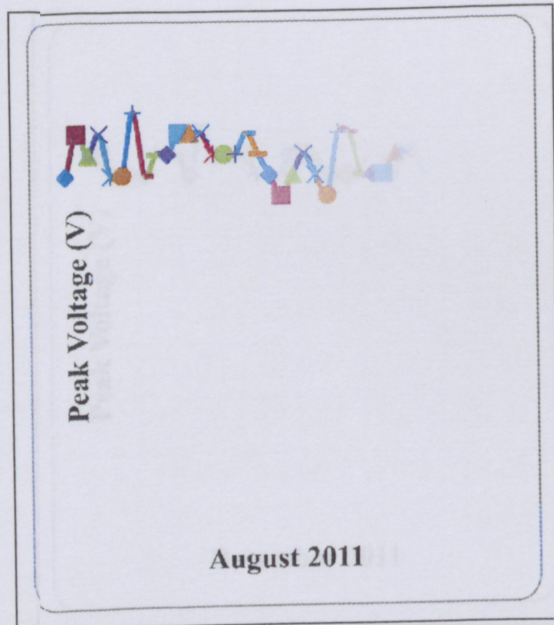


Figure 4.26 Peak voltage for August 2011

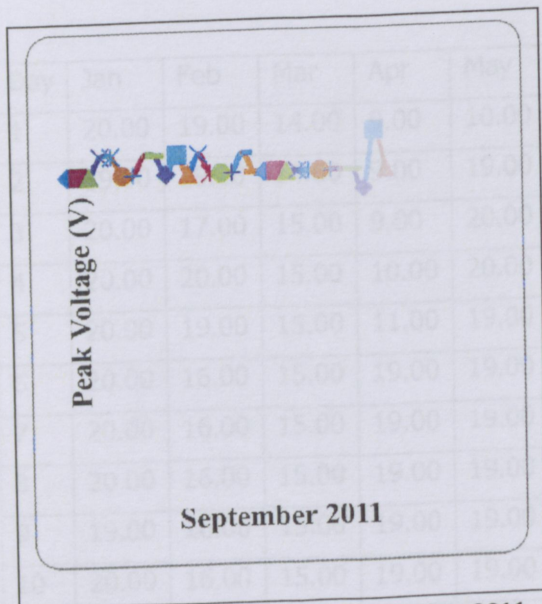


Figure 4.27 Peak voltage for September 2011

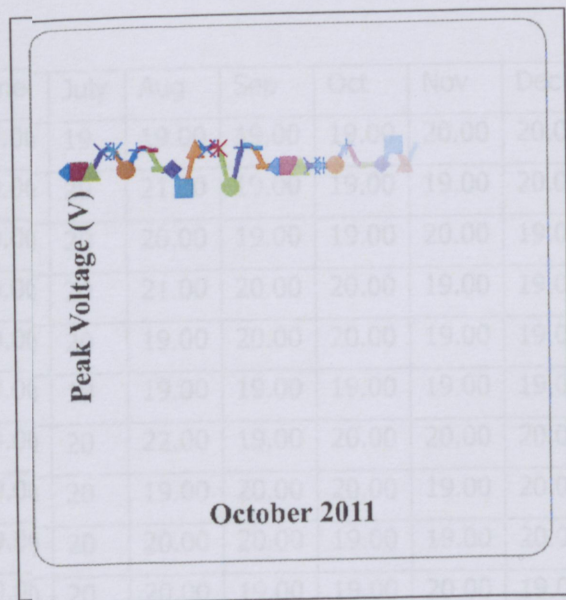


Figure 4.28 Peak voltage for October 2011

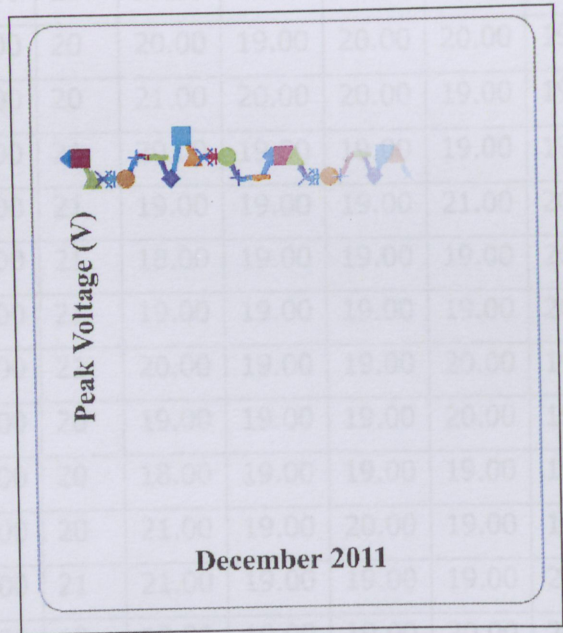
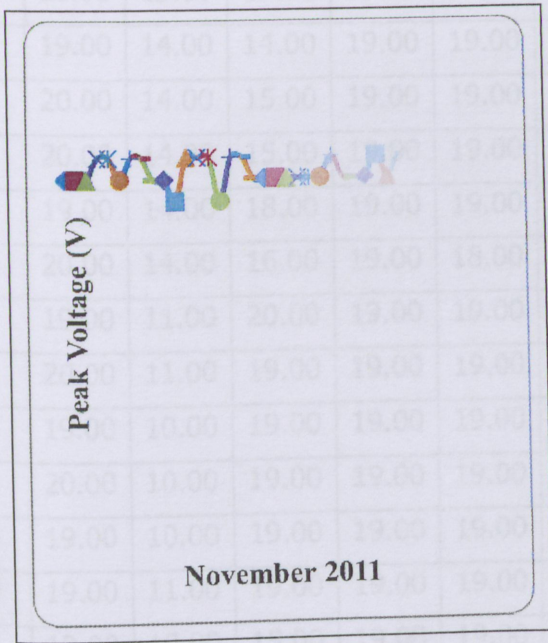


Figure 4.29 Peak voltage for November 2011

Figure 4.30 Peak voltage for December 2011

Day	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
1	20.00	19.00	14.00	9.00	10.00	19.00	19	19.00	19.00	19.00	20.00	20.00
2	19.00	19.00	14.00	9.00	19.00	19.00	20	21.00	19.00	19.00	19.00	20.00
3	20.00	17.00	15.00	9.00	20.00	19.00	20	20.00	19.00	19.00	20.00	19.00
4	20.00	20.00	15.00	10.00	20.00	19.00	20	21.00	20.00	20.00	19.00	19.00
5	20.00	19.00	15.00	11.00	19.00	19.00	20	19.00	20.00	20.00	19.00	19.00
6	20.00	16.00	15.00	19.00	19.00	18.00	19	19.00	19.00	19.00	19.00	19.00
7	20.00	16.00	15.00	19.00	19.00	19.00	20	22.00	19.00	20.00	20.00	20.00
8	20.00	16.00	15.00	19.00	19.00	19.00	20	19.00	20.00	20.00	19.00	20.00
9	19.00	16.00	15.00	19.00	19.00	19.00	20	20.00	20.00	19.00	19.00	20.00
10	20.00	16.00	15.00	19.00	19.00	19.00	20	20.00	19.00	19.00	20.00	19.00
11	20.00	15.00	15.00	20.00	19.00	18.00	21	21.00	20.00	18.00	19.00	21.00

12	19.00	14.00	15.00	19.00	19.00	18.00	20	21.00	19.00	20.00	20.00	20.00
13	20.00	14.00	15.00	19.00	19.00	18.00	20	21.00	20.00	20.00	19.00	20.00
14	19.00	15.00	17.00	19.00	19.00	19.00	19	20.00	19.00	20.00	19.00	20.00
15	20.00	15.00	17.00	19.00	19.00	19.00	21	20.00	19.00	18.00	19.00	20.00
16	19.00	14.00	14.00	19.00	19.00	19.00	20	20.00	19.00	20.00	20.00	19.00
17	20.00	14.00	15.00	19.00	19.00	19.00	20	21.00	20.00	20.00	19.00	19.00
18	20.00	14.00	15.00	19.00	19.00	19.00	21	20.00	19.00	19.00	19.00	19.00
19	19.00	14.00	18.00	19.00	19.00	19.00	21	19.00	19.00	19.00	21.00	20.00
20	20.00	14.00	16.00	19.00	18.00	19.00	21	18.00	19.00	19.00	19.00	20.00
21	19.00	11.00	20.00	19.00	19.00	19.00	21	19.00	19.00	19.00	19.00	20.00
22	20.00	11.00	19.00	19.00	19.00	19.00	21	20.00	19.00	19.00	20.00	19.00
23	19.00	10.00	19.00	19.00	19.00	19.00	20	19.00	19.00	19.00	20.00	19.00
24	20.00	10.00	19.00	19.00	19.00	19.00	20	18.00	19.00	19.00	19.00	19.00
25	19.00	10.00	19.00	19.00	19.00	19.00	20	21.00	19.00	20.00	19.00	19.00
26	19.00	11.00	19.00	19.00	19.00	19.00	21	21.00	19.00	19.00	19.00	20.00
27	19.00	10.00	15.00	19.00	19.00	19.00	19	19.00	19.00	19.00	20.00	20.00
28	19.00	10.00	9.00	10.00	19.00	19.00	21	19.00	18.00	19.00	19.00	19.00
29	19.00		9.00	20.00	19.00	19.00	19	19.00	21.00	20.00	19.00	20.00
30	19.00		9.00	19.00	18.00	20.00	20	20.00	19.00	19.00	20.00	20.00
31	19.00		9.00		19.00		20	20.00		20.00		19.00

Table 4.4 Daily and monthly measured peak voltage for a year

In our current study we recorded the peak voltage of the module for the period of a year as illustrated in table 4.4 and figures 4.19 – 4.30. It can be observed that the peak voltage does not vary much during some of the months, but vary a little in other months. For example during the months of February and March we can observe the variation in peak voltage. This may be due to rain in our region during this month and the variation is due to the weather conditions which differ daily.

### 4.3.5. Average Monthly Peak Voltage

Table 4.5 and figure 4.31 show the average monthly peak voltage measured for a period of a year. As mentioned above the charge controller only controls the current entering the battery not the voltage. In the case of the peak voltage the MPPT charge controller allows us to measure the peak voltage produced by the PV module.

The variations observed in the peak power may be due to weather conditions such as rainy, cloudy, partially cloudy, clear sky, etc. These conditions can influence variation at the peak power.

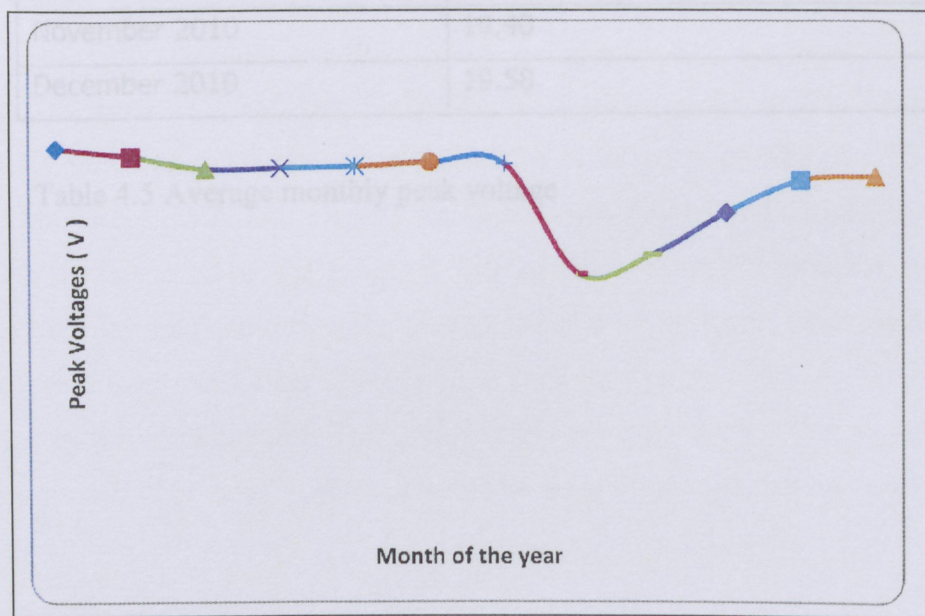


Figure 4.31 Illustrating the average monthly peak voltage

Date	Average monthly peak voltage
January 2010	19.52
February 2010	14.29
March 2010	15.19
April 2010	17.20
May 2010	18.71
June 2010	18.90
July 2010	20.25
August 2010	19.87
September 2010	19.27
October 2010	19.32
November 2010	19.40
December 2010	19.58

Table 4.5 Average monthly peak voltage

#### 4.4. CONCLUSION

In the present investigation a small stand alone photovoltaic system was tested under outdoor conditions. Its performance was monitored for a period of one year. It was found that the system was performing close to the manufacturer's specifications. The peak power was recorded for one year using a MMPT monitor. The solar radiation was also computed for this period. The peak power performance of the panel reveals that it can provide sufficient power to charge the batteries and hence the stored energy can be used for using small electrical appliances. Some of the additional measurement with the IV tracer also confirmed our results on solar radiation and peak power measurements. In addition to that the short circuit currents and open circuit voltages results obtained in the study closely correspond to the manufacturer data.

Hence it can be concluded that the solar panel used in the present investigation can be successfully used for small electricity generation in this area so that the rural community can benefit from such installation. Though the high temperatures in this region during summer may reduce the performance of the panel, it will be still within a reasonable margin so that the performance may not be affected. Our present investigations were made under outdoor conditions and they can be taken as the true performance on a day to day basis than what is mentioned by the manufacturer. This study can be extended to the other regions in the province to make a comparative study so that we can map the performances for the entire province.

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