INVESTIGATING THE EFFECTS OF IRRADIANCE AND TEMPERATURE ON THE PERFORMANCE OF PHOTOVOLTAIC (PV) MODULES OF DIFFERENT TECHNOLOGIES

BY

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A DISSERTATION SUBMITTED TO THE DEPARTMENT OF PHYSICS, BAYERO UNIVERSITY, KANO, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF MASTER OF SCIENCE (M.Sc.) IN PHYSICS

OCTOBER, 2016

DECLARATION

I hereby declare that this project is the result of my research work and to the best of my knowledge no part of the contents had been used in a previous application for higher qualification. All sources of knowledge utilized have been duly acknowledged.

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LUKMAN SULEIMAN　　　　　　　　　　**DATE**

SPS/12/MPY/00050

CERTIFICATION

This is to certify that the research work for this thesis and the succeeding preparation by (Lukman Suleiman) with registration number (SPS/12/MPY/00050) were carried out under my supervision.

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This dissertation has been examined and approved for the award of degree of MASTER OF SCIENCE IN PHYSICS (M.Sc., Physics), Faculty of Science, Bayero University Kano.

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ACKNOWLEDGMENT

In the name of Allah the Most Beneficent the Most Merciful. Praise be to Allah, Lord of the universe. Blessing and peace be upon our Prophet (S. A.W), his household, his companions and all those who follow his teaching till the Day of Judgment. I wish to express my sincere gratitude to my parents for all they have been doing for me, May Allah (S.W.T) reward them with Jannatul Firdaus.

My appreciation and respect goes to my supervisor Dr. F. S. Koki and my internal examiner Dr. M. H. Ali for the great assistance, guidance and support toward the conclusion of this work. Also my appreciation goes to the entire staff of Department of physics Bayero University Kano.

Finally special thanks go to my brothers, sisters, uncles, aunties and friends for their support and encouragement.

DEDICATION

This dissertation is dedicated to my parents.

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ABSTRACT

This Dissertation investigated the effects of irradiance and temperature on the performances of PV module technologies. Since the efficiency of photovoltaic cells vary with the operating condition, there is need to assess the rate of these variations for the different photovoltaic solar cells technologies. Simulations of parameters of the PV modules to evaluate their performances under changing environmental conditions are carried out using MATLAB. The results show that, thin film solar cell technologies; amorphous silicon (a-Si) and copper indium gallium selenide (CIGS), response to variation in both irradiance and temperature more rapidly. However, CIGS's efficiency uniquely decreases with increase in temperature. This fact is in agreement with the experimental results reported.

CHAPTER ONE

INTRODUCTION

1.0 GENERAL INTRODUCTION

The demand of energy is increased due to speedy rise in population and advancement in the technology day-to-day in the entire process of development. Therefore, countries should have high awareness to utilize alternative sources of energy (Tiwari et al., 2015). The entire world is facing a challenge of energy crisis due to the diminishing deposits of non-renewable energy resources such as coal, natural gas, fossil fuels etc and increasing concerns of its effects on global warming, damage to environment and ecosystem. In order to overcome the growing global energy demand alongside the limitation of the fossil fuels reserves and their negative effects on the environment have resulted in a great tendency toward renewable energy sources development (Sabzpooshani & Mohammadi, 2014). Renewable energy sources like wind, geothermal, tidal and solar energy are environmentally friendly, since they have a much lower environmental impact than conventional sources like fossil fuel. Among different kinds of renewable energy sources solar energy is considered as better alternative because of its abundance and sustainability.

Solar energy is a renewable that is inexhaustible and if used in a proper way, it has a capacity to fulfill numerous energy needs of the world (Kachhiya et al., 2011). Solar energy is widely accepted as a key energy source for the future around the world with respect to the environmental issues associated with fossil fuels. The information concerning availability of solar radiation is essential for solar energy devices, such information is also vital for meteorological experts, agriculturalists, air conditioning engineers and energy-conscious designers of buildings (architects) (Li et al., 2012). Solar radiant energy is an important factor that characterizes the energy through the PV (photovoltaic) effect among the renewable energy resources. PVs offer several advantages such as: high reliability, low maintenance cost, no environmental pollution, and absence of noise.

The design and analysis of photovoltaic modules require a tool that can predict the behavior of photovoltaic generators under various weather conditions. Manufacturers usually provide electrical specifications of the PV panels at standard test conditions, namely solar radiation of 1000 W/m^2 and cell temperature of 25 ^0C. To characterize the performance of a photovoltaic module under varying weather conditions, simulation models of PV modules have been developed (Vengatesh & Rajan, 2011). The market for PV systems is growing worldwide. In fact, nowadays, solar energy provides around 4800 GW (Masters, 2004). Between 2004 and 2009, grid connected PV capacity reached 21 GW and was increasing at an annual average rate of 60%. In order to get benefit from the application of PV systems, research activities are being conducted in an attempt to gain further improvement in their cost, efficiency and reliability (Salmi et al., 2012). Photovoltaic solar energy is a clean renewable energy with a long service life and high reliability. Both because of its high cost and low efficiency its energy contribution is less than other energy sources (Ramos-Hernanz et al., 2012). However solar energy is the most ubiquitous and redundant and this makes its study necessary in order to harness it to the fullest human endeavor.

In this work, the effect of irradiance and the ambient temperature on the performance of photovoltaic modules technologies; monocrystalline, polycrystalline and thin film solar cells; amorphous silicon (a-Si) and copper indium gallium selenide (CIGS) were investigated using MATLAB.

1.1 BENEFITS OF CLEAN RENEWABLE ENERGY

There are many advantages resulting from the use of clean energy distributed on fields of environmental, economic and health. The clean energy has benefits include diversity, security, improved quality of life, environment and human health. It also improves economic gains through avoiding medical costs, higher disposable incomes, and more jobs.

1.1.1 Economic Impacts

Technological advancement in the field of renewable energy has become clear in recent years. We note that while the prices of traditional energy sources constantly rise, the costs of Renewable energy decline steadily so the advantages of investment in renewable energy has become increasingly clear, even in areas that traditionally supports fossil fuels. The main reasons that make renewable energy technologies offer an economic advantage are labor intensive, so they generally create more jobs invested than conventional electricity generation technologies, from high-tech manufacturing of photovoltaic components to maintenance jobs at wind power. They also use primarily indigenous resources, so most of the energy dollars can be kept, where the individuals, companies, or communities can reduce their utility bills. For example, schools can cut costs by using wind and electric cooperatives can provide cheaper electricity to members with photovoltaic (Panjeshahi et al., 2008).

1.1.2 Health and Environment Impacts

All energy sources have some impact on our environment and health which varies between long-term and short-term effects. Fossil fuels are more harmful than renewable energy sources. Thus, we need to improve access to low-emission, renewable, and modern energy technologies both at home and at community. They can benefit from long term sustainability. Notably, the inefficient combustion of fossil fuels and biomass for energy purposes is the major cause of climate change. Air pollution, often due to inefficient modes of energy production, distribution, and consumption, is a large and growing cause of environmental health risks (Sawin & Moomaw, 2009), so it is advisable to increase reliance on renewable energy sources, and support clean energy initiatives. This appears through better air quality which enhances local quality of life. Healthier people reduces strain on the health system, using fewer sick days also lower carbon dioxide emissions in the near term may have a large impact on our ability to meet long term climate goals since greenhouse gas (GHGs) accumulate and can remain in the atmosphere for decades, affecting our global climate system and human health for the long term (Sawin & Moomaw, 2009).

1.2 SOURCES OF RENEWABLE ENERGY

The main sources and components used in renewable energy systems included solar, wind, hydropower, biomass, and geothermal resources. In this section a brief is given for each type of these sources.

1.2.1 Biomass and Biofuels

Bioenergy term sometimes used to cover biomass and biofuels together. Bioenergy resources are widely available worldwide and have the largest share of all renewable energy sources. Biomass resource was the first energy source harnessed by humans (Herzog et al., 2001). It comes in many forms. Traditionally, wood, crop residues and animal waste have been used for heating or cooking, but today biomass is also used in many other ways. Municipal solid waste (MSW) can be used for heat or electricity. Landfill gases can be used for heat, electricity or fuels. Biological conversion of MSW using anaerobic digestion can produce electricity, heat or fuel gas. Wood and wood wastes can be used to produce electricity, heat for industrial purposes or domestic space heating.

Recently, the interest in producing liquid fuels from grain and dedicated energy crops are increasing. They are only renewable source of liquid transportation fuels, which can be in the form of ethanol or biodiesel. Moreover, the carbon in biomass is obtained from CO_2in the atmosphere via photosynthesis, and not from fossil sources. When biomass is burnt or digested, the emitted CO_2 is recycled into the atmosphere without adding to atmospheric CO_2concentration over the lifetime of the biomass growth (Herzog et al., 2001).

1.2.2 Wind Power

The extraction of power from the wind with modern turbines and energy conversion systems is an established industry. Machines are manufactured with a capacity from tens of watts to several megawatts, and diameters of about 1m to more than 100m (Herzog et al., 2001).

The power output increases rapidly with an increase in available wind velocity. Small wind speed difference makes a very big difference because the energy contained in the wind increases with the cube of the wind speed. A maximum of about 59 % of the energy can be extracted. For this reason, good wind sites are important (Holm & Arch, 2005).

We must take into account the wind does not blow equally or evenly everywhere on earth. Over open sea or flat stretches of land the wind is stronger than over towns or woods. Modern turbines have already greatly reduced noise pollution, which is less than traffic noise, efficiencies and availabilities have improved and wind farm concept has become popular in addition to that, wind turbines have become larger, combine with solar (Jimenez & Olson, 1998).

1.2.3 Hydropower

The term hydropower is usually restricted to the generation of shaft power from falling water. The power is then used for direct mechanical purposes or, more frequently, for generating electricity. Other sources of water power are waves and tides (Herzog et al., 2001). But Hydroelectric technology is the most mature form of renewable energy and extremely reliable, but it requires very high initial investments, with low maintenance cost. Its design life is more than a century. Natural and pumped storage dams are suitable for peak electricity demand. Hydropower is cheap if calculated in the conventional manner. Worldwide, about 45000 large dams have been built for electricity generation, flood protection, water storage, agricultural irrigation, navigable waterways and recreation. As a result of economies of scale, approximately 97 % of hydroelectric plants have a capacity in excess of 10MW (Holm & Arch, 2005). The main disadvantages of hydro-power are associated with effects other than the generating equipment, particularly for large systems. These include possible adverse environmental impact, effect on fish, silting of dams, corrosion of turbines in certain water conditions, social impact of displacement of people from the reservoir site, loss of potentially productive land (often balanced by the benefits of irrigation on other land) and relatively large capital costs compared with those of fossil power stations.

1.2.4 Geothermal

Geothermal activity in the earth‘s crust derives from the hot core of the earth. Where the inner core of the earth reaches a maximum temperature of about 4000°C. Heat passes out through the solid submarine and land surface mostly by conduction and occasionally by active convective currents of molten magma or heated water (Herzog et al., 2001).

Examples of geothermal energy are the natural geysers and hot water sources employed for power generation and space heating or using deep hot dry rock as heat exchangers by pumping water through the natural rock fissures to produce steam for power generation.

1.2.5 Photovoltaic

Solar energy can be used in a number of ways. For electricity generation the most common process is through solar photovoltaic where PV panels convert sunlight directly into DC electricity. PV panels, having no moving parts, require little maintenance, are highly reliable, long lived where the semiconductor materials are encapsulated and sealed hermetically making it lasts for a longer period of more than 25 year. In addition, PV panels are highly modular. Also it is easy to assemble PV panels into an array that can meet any given sized load. With suitable electronics, PV systems can be grid-connected or stand-alone, where they can also be used for water pumping or other mechanical work. PV arrays do not emit vibrations, noises and pollutants during their operation. This means they can be integrated into new and existing buildings, which then become energy exporters instead of consumers. All above advantages make this modern technology increasingly attractive. (Hersch & Zweibel, 1982).

1.3 STATEMENT OF THE PROBLEM

The overall performance of photovoltaic technology varies with varying irradiance and temperature due to the change in time of the day and the power received from the Sun by the PV module also changes. The problem in the performance of photovoltaic technologies can be approached in different perspective; battery efficiency and module efficiency. Since the field tests can be expensive and the performances depend primarily on weather conditions, it is very convenient to have simulation models to enable work at any time. Many mathematical models have been developed (Jitendra & Joshi, 2013), (Taherbaneh, 2011), (Tamrakar & Gupta, 2015). However manufacturer produces PV modules at standard test condition (STC), there is need to investigate its nonlinear behavior under different environmental condition in order to analyze the performance of the PV modules.

1.4 AIM AND OBJECTIVES

1.4.1 Aim

The aim of this Research work is to investigate the effect of irradiance and the ambient temperature on the performance of photovoltaic modules of different technologies.

1.4.2 Objectives

The main objective of this research is to

- To develop a computer code in MATLAB program that will simulate photovoltaic module technologies.
- To investigate the effects of irradiance and temperature on PV module of different technologies.

- To evaluate the performance of each photovoltaic (PV) module technology.
- To compare the simulated result with the measured results.

1.5 SCOPE AND LIMITATION

The main focus of this research work is to investigate the effects of variation due to irradiance and temperature change. To achieve this, a MATLAB program code was developed to simulate mathematical equations relating to diode equivalent circuit photovoltaic (PV) module technologies.

CHAPTER TWO

LITERATURE REVIEW

2.0 INTRODUCTION

In this Chapter, theoretical background of the research and the review of related literatures were presented.

2.1 SEMICONDUCTOR PHYSICS

Semiconductors are characterized by their conductivity properties that lie between those of conductors and insulators. The most common semiconductor is silicon, which is a group IV element in the periodic table of elements. This means that it has four electrons in its outermost shell, i.e., it has four valence electrons, which determines its electrical properties. Other common semiconductors are germanium, gallium and arsenic, cadmium and tellurium and copper, indium and selenide are also used to produce semiconductors. Here semiconductor properties are discussed using the example of silicon. In pure silicon crystal, the four valence electrons of a silicon atom are tied with strong covalent bonds to four adjacent silicon atoms. Therefore at zero temperature silicon is a perfect insulator: there are no free electrons to carry currents as there are in metals, but all the electrons are tied to their nuclei. As the temperature increases, some electrons gain enough energy to escape from the potential field of their nuclei and thus the conductivity of silicon increases. Semiconductors are very sensitive to impurities. This property can be exploited in changing their conductivity in a more favorable direction by adding suitable impurities, which is called doping. Semiconductors can be doped so that there is excess or shortage of electrons, to make N or P-type semiconductors, respectively. When P and N-type materials are brought into contact, a P-N junction is formed. This junction has many favorable properties and is used widely in electronics, including photovoltaic solar cells (Masters, 2004).

2.2 PRINCIPLE OF OPERATION OF PHOTOVOLTAIC (PV) CELL

Ninety-nine percent of today's solar cells are made of silicon (Si) the second most abundant material on earth. However, scarce indium and tellurium are used in some cells (Mcintosh, 2008). PV Cells are basically made up of a PN junction fabricated in a thin wafer or layer of semiconductor. Figure 2.1 shows the photocurrent generation principle of PV cells. In fact, when sunlight hits the cell, the photons are absorbed by the semiconductor atoms, freeing electrons from the negative layer. These free electrons find its path towards the positive layer through an external circuit resulting in an electric current from the positive layer to the negative layer. Typically, a PV cell generates a voltage around 0.5 to 0.8 volts depending on the semiconductor and the built-up technology, this voltage is low enough as it cannot be of use. Therefore, to get benefit from this technology, many of PV cells (involving 36 to 72 cells) are connected in series to form a PV module (Salmi et al., 2012).The photoelectric conversion in the *PN* junction, P-N junction (diode) is a boundary between two differently doped semiconductor layers; one is a P-type layer (excess holes), and the second one is an N-type (excess electrons). At the boundary between the P and the N area, there is a spontaneous electric field, which affects the generated electrons and holes and determines the direction of the current. To obtain the energy by the photoelectric effect, there shall be a directed motion of photoelectrons, i.e. electricity. All charged particles, photoelectrons also, move in a directed motion under the influence of electric field. The electric field in the material itself is located in semiconductors, precisely in the impoverished area of P-N junction (diode). It was pointed out for the semiconductors along with the free electrons in them; there are cavities as charge carriers, which are a sort of a byproduct in the emergence of free electrons. Cavities (holes) occurs whenever the valence electron turns into a free electron, and this process is called the generation, while the reverse process, when the free electron fills the holes, is called recombination. If the electron hole pairs occur away from the impoverished areas it is possible to recombine before they are separated by the electric field. Photoelectrons and holes in semiconductors are accumulated at opposite ends, thereby creating an electromotive force. If a consuming device is connected to such a system, the current will flow and we will get electricity (Green, 1982).

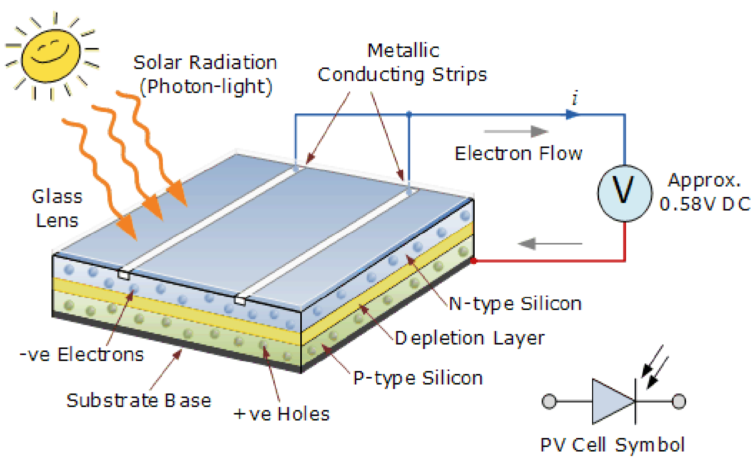


Figure 2.1: Photocurrent Generation Principle.

2.3 PHOTOVOLTAIC MODULE TECHNOLOGIES

There is a wide range of different photovoltaic cell technologies, and they are categorized in many different ways. The major categorization is done according to the thickness of the layer of the photovoltaic material used. In conventional crystalline silicon (c-Si) solar cells, the layer is relatively thick in the order of 200-500µm. Another approach, referred to as thin-film technology, uses layers of only 1-10µm of the photovoltaic material

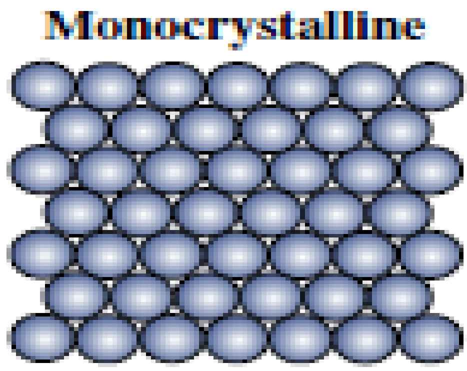
(Masters, 2004). The single junction technology is grouped into two main types; silicon crystalline (Monocrystalline technology and Polycrystalline technology) and thin film technologies. Currently, multi-junction technology is under research and processing, to enhance the PV modules efficiency and to improve the response sensitivity of the sun light spectrum in order to cover the entire incident irradiation wavelength.

2.3.1 Crystalline Silicon (c-Si) Technologies

The basis of a conventional thick c-Si cell is a wafer made of either single or multi-crystalline silicon. The major drawback in this technology is the costly manufacturing process. Though silicon is one of the most abundant elements on the earth, in nature it never exists as pure silicon but as SiO_2 based minerals. The process for purifying the silicon is very energy-intensive, and so are the processes for producing the single- or multicrystalline silicon crystal from the purified silicon. To produce single-crystalline silicon, an ingot composed of a single silicon crystal is formed by growing it from a purified silicon melt using a seed crystal (the Czochralski process). To produce multi-crystalline silicon, the silicon melt is cast into large crucibles. This process is less energy-intensive than the Czochralski process, and it is currently the most common method. An alternative approach is to grow a silicon ribbon from molten silicon. To make wafers, the ingot and the crucible need to be sawed into thin slices, which wastes a lot of silicon as saw dust called kerf; the ribbon on the other hand can be directly cut into rectangular cells, and the kerf losses are avoided (Masters, 2004).Once the wafers have been produced, they are doped to form the P-N junction. The dopants are usually added to the wafers in gaseous form. Furthermore, some surface treatment is required for the cells to minimize reflectance and maximize absorption of light. Finally, the electrical contacts are attached to the cells and the individual cells are wired together, and the whole assembly is encapsulated into an appropriate package. The c-Si solar cells have reached the highest efficiencies among single junction solar cells so far. The theoretical upper limit for the efficiency is almost 50%, and efficiencies of almost 25% have been reached in laboratories. For modules in production, efficiencies of 14-17% have been reached (Masters, 2004).

Monocrystalline technology

Monocrystalline is the oldest, most efficient PV cells technology which is made from silicon wafers after complex fabrication process. Monocrystalline PV cells are designed in many shapes: round shapes, semi-round or square bars, with a thickness between 0.2mm to 0.3mm. Monocrystalline silicon (or single-crystal silicon, single-crystal Si, or just mono-Si) is the base material for silicon chips used in virtually all electronic equipment today. Mono-Si also serves as photovoltaic, light-absorbing material in the manufacture of solar cells. It consists of silicon in which the crystal lattice of the entire solid is continuous, unbroken to its edges, and free of any grain boundaries. Mono-Si can be prepared intrinsic, consisting only of exceedingly pure silicon, or doped, containing very small quantities of other elements added to change its semiconducting properties. Most silicon monocrystallineare grown by the Czochralski process into ingots of up to 2 meters in length and weighing several hundred kilograms. These cylinders are then sliced into thin wafers of a few hundred microns for further processing. Single-crystal silicon is perhaps the most important technological material of the last few decades, the silicon (Siffertan & Krimmel, 2004). Because its availability at an affordable cost has been essential for the development of the electronic devices on which the present day electronic and informatics revolution is based. Monocrystalline silicon differs from other allotropic forms, such as the non-crystalline amorphous silicon used in thin-film solar cells, and polycrystalline silicon, that consists of small crystals, also known as crystallites (Green, 1982).

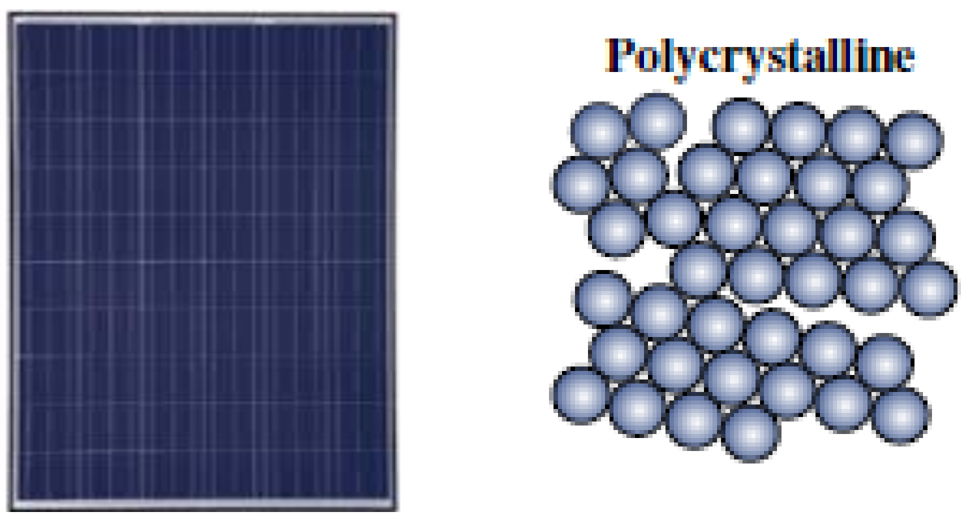


(a) Monocrystalline Module. (b) Allotropic Form of Monocrystalline.

Figure 2.2: Monocrystalline PV Module and Allotropic Forms of Monocrystalline.

<u>Polycrystalline technology</u>

Polycrystalline (or Multicrystalline) cells are effectively a slice cut from a block of silicon, consisting of a large number of crystals. They have a speckled reflective appearance and again you can see the thickness of the slice (Aish, 2015). These cells are slightly less efficient and slightly less expensive than monocrystalline cells. Polycrystalline silicon, also called polysilicon or poly-Si, is a high purity polycrystalline form of silicon, used as a raw material by the solar photovoltaic and electronics industry. Polysilicon is produced from metallurgical grade silicon by a chemical purification process, called Siemens process. This process involves distillation of volatile silicon compounds, and their decomposition into silicon at high temperatures. An emerging, alternative process of refinement uses a fluidized bed reactor. The photovoltaic industry also produces upgraded metallurgical-grade silicon (UMG-Si), using metallurgical instead of chemical purification processes. When produced for the electronics industry, polysilicon contains impurity levels of less than one part per billion (ppb), while polycrystalline solar grade silicon (SoG-Si) is generally less pure. The polysilicon feedstock large rods, usually broken into chunks of specific sizes and packaged in clean rooms before shipment is directly cast into multicrystalline ingots or submitted to a recrystallization process to grow single crystal boules. The products are then sliced into thin silicon wafers and used for the production of solar cells, integrated circuits and other semiconductor devices. Polysilicon consists of small crystals, also known as crystallites, giving the material its typical metal flake effect. While polysilicon and multisilicon are often used as synonyms, multicrystalline usually refers to crystals larger than 1 mm (Myong et al., 2007).



(a) Polycrystalline PV Module. (b) Allotropic Forms of Polycrystalline.

Figure 2.3: Polycrystalline PV Module and Allotropic Forms of Polycrystalline.

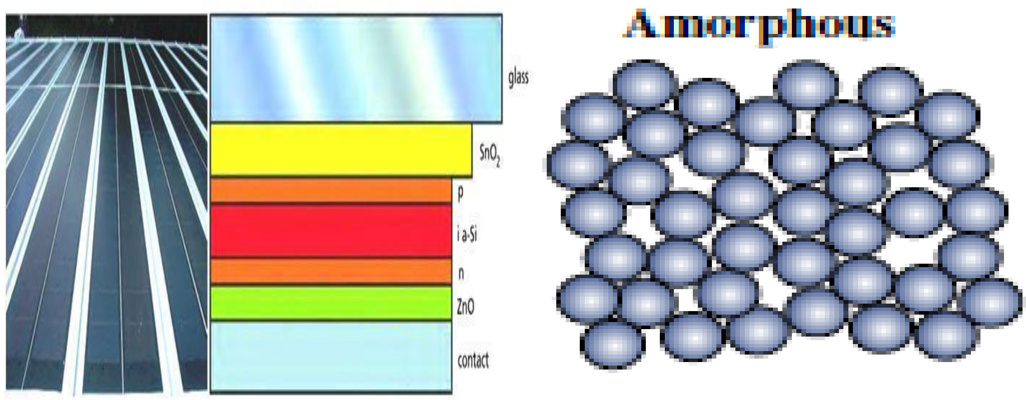
2.3.2 Thin Film Technology

Thin film (TF) technology represents the second PV generation; due to less production materials and less energy consumption, it's cheaper than crystalline technology.

Amorphous silicon, copper Indium Silinum (CIS) and Cadmium Telluride (CdTe) are used as semiconductor materials. Because of the high light absorption of these materials, layer thicknesses of less than 0.001mm are theoretically sufficient for converting incident irradiation (Deutsche, 2008).A thin-film solar cell are made by depositing one or more thin layers, or thin film of photovoltaic material on a substrate, such as glass, plastic or metal. Thin-film solar cells are commercially used in several technologies, including cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and amorphous thin-film silicon (a-Si, TFSi). Film thickness varies from a few nanometers (nm) to tens of micrometers (µm), much thinner than thin-film's rival technology, the conventional, first-generation crystalline silicon solar cell (c-Si) that uses wafers of up to 200µm. This allows thin film cells to be flexible, lower in weight, and have less drag or friction. It is used in building integrated photovoltaic and as semi-transparent photovoltaic glazing material that can be laminated onto windows. Other commercial applications use rigid thin film solar panels (sandwiched between two panes of glass) in some of the world's largest photovoltaic power stations. Thin-film technology has always been cheaper but less efficient than conventional c-Si technology. However, it has significantly improved over the years. The lab cell efficiency for CdTe and CIGS is now beyond 21 percent, outperforming multicrystalline silicon, the dominant material currently used in most solar PV systems (Silverman et al., 2014). Other thin-film technologies that are still in an early stage of ongoing research or with limited commercial availability are often classified as emerging or third generation photovoltaic cells and include organic, dye-sensitized, and polymer solar cells, as well as quantum dot, copper, zinc, tin, sulfide, nanocrystal, micro morph, and perovskite solar cells (Deutsche, 2008).

Amorphous silicon technology (a-Si)

Amorphous silicon (a-Si) is the non-crystalline form of silicon used for solar cells and thin-film transistors in LCD displays. Used as semiconductor material for a-Si solar cells, or thin-film silicon solar cells, it is deposited in thin films onto a variety of flexible substrates, such as glass, metal and plastic. Another disadvantage of a-Si PV cells is light-induced degradation (known as the Staebler-Wronski effect), which reduces the module efficiency during the first 6-12 months of operation before leveling off at a stable value of the nominal output power (Deutsche, 2008). Amorphous silicon cells generally feature low efficiency, but are one of the most environmentally friendly photovoltaic technologies, since they do not use any toxic heavy metals such as cadmium or lead. As a second-generation thin-film solar cell technology, amorphous silicon was once expected to become a major contributor in the fast-growing worldwide photovoltaic market, but has since lost its significance due to strong competition from conventional crystalline silicon cells and other thin-film technologies such as CdTe and CIGS. Amorphous silicon differs from other allotropic variations, such as monocrystalline silicon a single crystal, and polycrystalline silicon, that consists of small grains, also known as crystallites. Some of the varieties of amorphous silicon are amorphous silicon carbide (a-SiC), amorphous silicon germanium (a-SiGe), microcrystalline silicon (μc-Si), and amorphous silicon-nitride (a-SiN) (Parida et al., 2011).

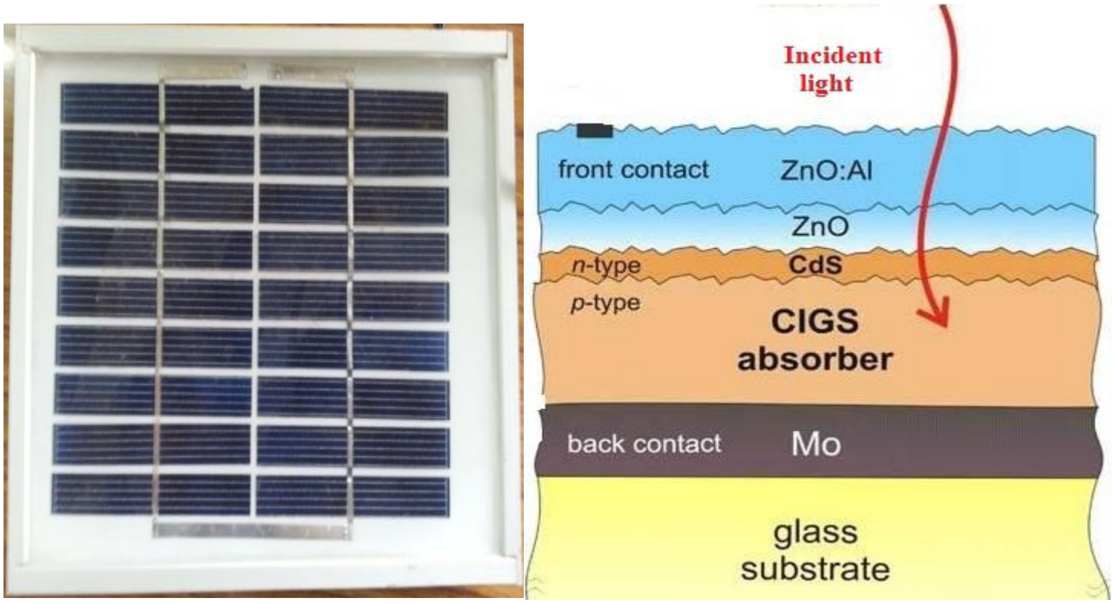


(a) Flexible Module, Layered of a-Si. (b) Allotropic Forms of a-Si.

Figure 2.4: Flexible Module, Layered Structure and Allotropic Forms of an Amorphous Silicon Cell (Deutsche, 2008).

<u>Copper indium gallium selenide solar cells technology (CIGS)</u>

Copper indium gallium diselenide (CIGS) is a semiconductor material composed of copper, indium, gallium, and selenium. The material is a solid solution of copper indium selenide (often abbreviated "CIS") and copper gallium selenide. It has a chemical formula of CuInxGa (1-x)Se2 where the value of x can vary from 1 (pure copper indium selenide) to 0 (pure copper gallium selenide). CIGS is a tetrahedral bonded semiconductor, with the chalcopyrite crystal structure, and a band gap varying continuously with x from about 1.0 eV (for copper indium selenide) to about 1.7 eV (for copper gallium selenide) (Aish, 2015). The thin-film solar cells, such as polycrystalline Cu(In,Ga)Se2 (CIGS) solar cells are promising candidates, since in contrast to conventional wafer-based solar cells these solar cells consume much less semiconductor material and energy during their fabrication. Copper Indium Gallium Selenide (CIGS) solar cells have the highest production among thin film technologies; solar cell based on CIGS has reached conversion efficiencies 18% and 19.5%, a CIGS cell with 21.5% efficiency and an area of 0.1 cm^2 has been fabricated on soda-lime glass (SLG). Laboratory specimens can provide power conversion efficiency as high as 20% (Shamim et al., 2015). CIGS solar cells have a complex multilayer structure. In the modeling of thin-film solar cells one has to take into account to the specific optical and electrical features of the structures. From the optical point of view, thin-film CIGS solar cells are multilayer structures, including thin layers, where the thicknesses are in the range of light wavelengths. The purpose of the front and back contact is to have as good conducting capabilities as possible without disturbing other processes in the cell. Light enters the cell through the Transparent Conductive Oxide layer (TCO), passes through the CdS buffer layer, and enters the absorber. The P-N junction is formed by P- type CIGS layer and N-type buffer layer. The buffer layer is followed by a thin layer of highly resistive ZnO, which may protect the surface from damage in subsequent process steps. Buffer layer is an intermediate layer film between the absorber and window layers with two main objectives, to provide structural stability to the device and to fix the electrostatic conditions inside the absorber layer. Meanwhile, it will have to make good P-N junction with the P-type absorber layer for the electrical conduction and to allow the transmission of photons into the absorber layer to generate electron-hole pair. The absorber layer is the most important layer in the PV device. It is a direct band-gap semiconductor material and has a large absorption coefficient. Most of the incident sunlight is absorbed close to the P-N junction (Shamim et al., 2015).

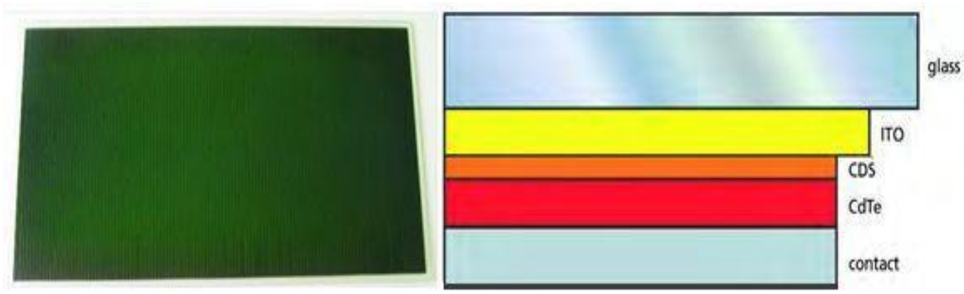


(a) CIGS PV Module. (b) Layered Structure of a CIGS Cell.

Figure 2.5: CIGS Modules and Layered Structure of a CIGS Cell.

Cadmium telluride technology (CdTe)

Cadmium telluride (CdTe) is the predominant thin film technology. With about 5 percent of worldwide PV production, it accounts for more than half of the thin film market. The main advantage of this technology is the lowest production cost among thin film technologies. The back contact is a weak point in CdTe cells since it is responsible for ageing. Modern high-grade CdTe modules do not suffer any initial degradation such as amorphous technology (Fthenakis, 2004). The cell's lab efficiency has also increased significantly in recent years and is on a par with CIGS thin film. Although the toxicity of cadmium may not be that much of an issue and environmental concerns completely resolved with the recycling of CdTe modules at the end of their life time (Fthenakis, 2004).



(a) CdTe PV Module. (b) Layered Structure of a CdTe Cell.
Figure 2.6: CdTe Module and Layered Structure of a CdTe Cell.

<u>Micromorphous tandem technology</u>

Micromorphous silicon module technology combines microcrystalline and amorphous silicon in tandem structure to enhance the performance of the module; they are assembled in the top and bottom of photovoltaic cell. Microcrystalline cells have similar optical properties as the crystalline cells. Also, Micromorphous cell has the ability to response to a broad band of the solar spectrum wave length, and the efficiency could reach to 9.1%. The light-induced degradation is very slight comparing with amorphous cells (Deutsche, 2008).

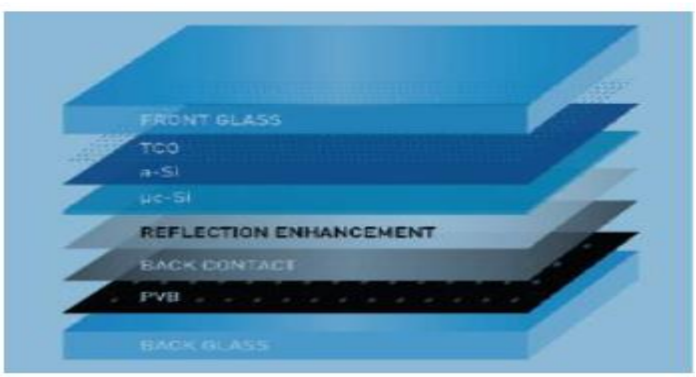


Figure 2.7: Micromorphous Layered Structure.

2.4 ELECTRIC CHARACTERISTICS OF *PV* CELL PERFORMANCE FACTORS

The factors normally taken into account are the sunlight intensity and PV cell temperature where the output power of PV module is dependent on these two parameters. Solar irradiance has direct relation and temperature has reverse relation with output power of PV module. It means increasing the sunlight intensity; the output power rises and increasing the temperature; the power comes down (Rekioua & Matagne, 2012). Photovoltaic module efficiency is affected by many factors during conversion; these factors are mainly climatic conditions, which affect the effective incident irradiation, and the fabrication method of the PV modules.

2.4.1 Irradiation Effect

Photovoltaic output power is affected by incident irradiation. PV module short circuit current (Isc) is linearly proportional to the irradiation, while open circuit voltage (Voc) increases exponentially to the maximum value with increasing the incident irradiation, and it varies slightly with the light intensity (Deutsche, 2008). Figure 2.8 describes the relation between Photovoltaic voltage and current with the incident irradiation.

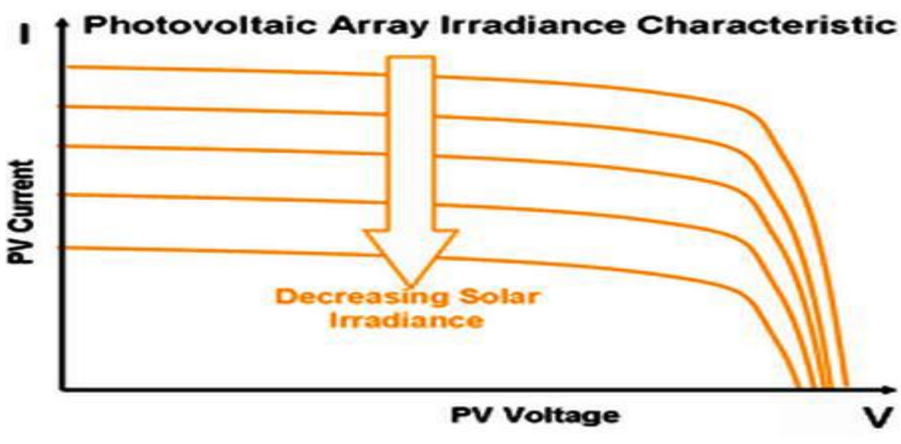


Figure 2.8: Effects of the Incident Irradiation on Module Voltage and Current.

2.4.2 Temperature Effect

Module temperature is highly affected by ambient temperature. Short circuit current increases slightly when the PV module temperature increases more than the Standard Test Condition (STC) temperature, which is 25^0C. However, open circuit voltage is enormously affected when the module temperature exceeds 25^0C. In other words the increasing current is proportionally lower than the decreasing voltage. Therefore, the output power of the PV module is reduced (Deutsche, 2008). Figure 2.9 explains the relation between module temperature with voltage and current.

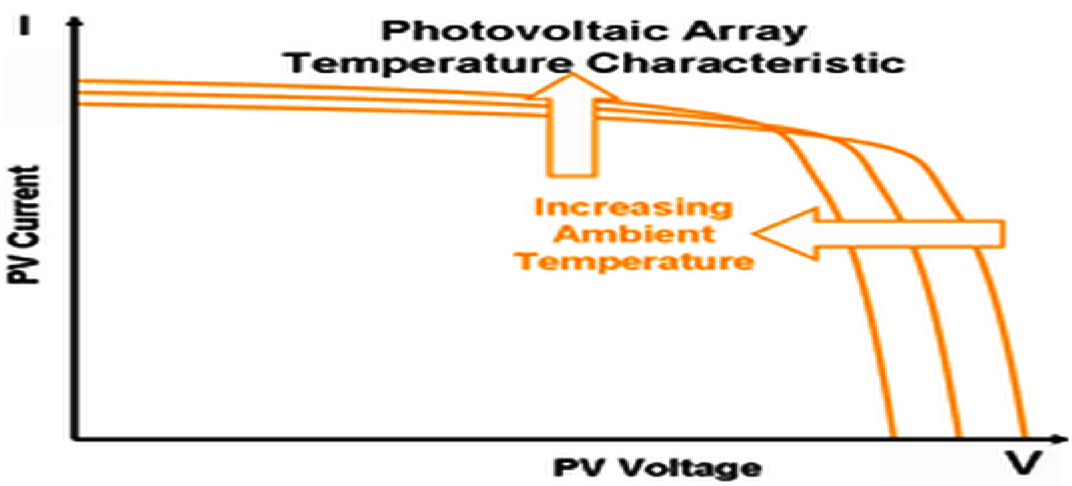


Figure 2.9: Effect of Ambient Temperature on Module Voltage and Current.

2.4.3 Thermal Effect

Thermal response of the PV module is the main factor which affects the electrical power output. The PV module receives the incident irradiation; a portion of it is converted to electricity in proportional with the module efficiency. The rest of the incident irradiation heats the PV module and increases its operating temperature in relation to the PV material heat capacity. In the same time, a portion of the absorbed heat is dissipated into surrounding; this is occurred through conduction, convection and the radiation exchange heat transfer between the module and the surrounding.

2.4.4 Fabrication Effect

The Czochralski process (crucible drawing process) has become established in the production of single-crystal silicon for terrestrial applications. In this process, the polycrystalline starting material (polysilicon) is melted in a quartz crucible at around 1420°C. A seed crystal with a defined orientation is dipped into the silicon melt and slowly drawn upwards out of the melt. During this process the crystal grows into a cylindrical mono-crystal up to 30cm in diameter and several meters in length. These cylindrical mono-crystals are cut to form semi-round or square bars, which are then cut with wire saws into slices (wafers) with a thickness of around 0.3mm. When cutting the mono-crystals and sawing the wafers, a large percentage of the silicon is lost as sawdust and needs to be re-melted, as do the conical ends of the rods. The wafers are chemically wet cleaned in etching and rinsing baths to remove sawing residues and marks. This cleaning process etches away approximately 0.01mm of the wafer on both sides. Starting from the raw wafers that have already been p-doped with boron, the thin n-doped layer is created through phosphorus diffusion. Phosphorus gas is diffused into a diffusion furnace at temperatures of between 800°C and 900°C, and the upper surface is doped. The heart of the solar cell, the p-n junction, is created. After applying the anti-reflective (AR) coating, the current collector lines are printed on the front, while the contacts appear on the back, in a screen printing process. The contacts have to be baked to contact the front side through the anti-reflective coating. Finally, the solar cells are etched at the edges to create a clean division between the p-layer and n-layer and to prevent a short circuit at the sides (Deutsche, 2008).

2.5 CURRENT VOLTAGE (I-V) AND POWER VOLTAGE (P-V) CHARACTERISTICS OF SOLAR CELL

PV system naturally exhibits a nonlinear I-V and P-V characteristics which vary with the radiant intensity and cell temperature. The typical I-V and P-V characteristics of solar cell are shown in Figure. 2.10. The fundamental parameters related to solar cell characteristics are Short circuit current (I_{SC}), Open circuit voltage (V_{OC}), Maximum power point (MPP) and Fill factor (Islam et al., 2014).

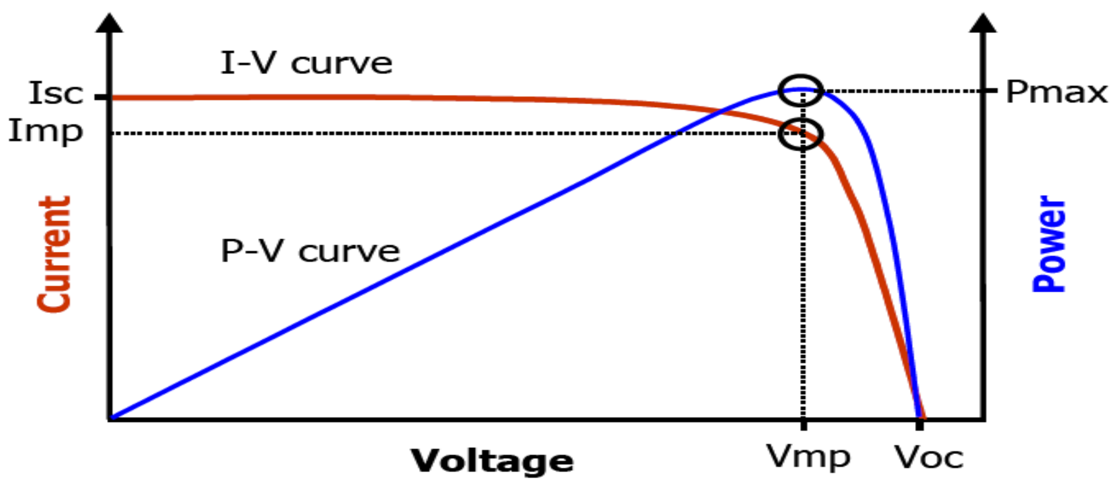


Figure 2.10: Typical I-V and P-V Characteristics of Solar Cell.

2.5.1 Maximum Power Point (P_{MPP})

Maximum electrical power of the PV module is equal to the current at maximum power point (IMP) multiplied by the voltage at maximum power point (VMP), which is the maximum possible power at Standard Test Condition (STC). Referring to Figure 2.10, the "knee" of the I-V curve represents the maximum power point (PMPP) of the PV module/system. At this point the maximum electrical power is generated at STC. The usable electrical output power depends on the PV module efficiency which is related to the module technology and manufacture.

2.5.2 Fill Factor (FF)

The PV cell/module or arrays are often characterized by a parameter known as fill factor (FF). FF actually measures the quality of the PV array. It is the ratio of the power at the maximum power point (actual) to the product of V_{OC} and I_{SC} (theoretical), FF can be expressed as:

$$FF = \frac{I_{MP}*V_{MP}}{I_{SC}*V_{OC}} \qquad (2.1)$$

And it can be interpreted graphically as the ratio of the rectangular areas defined by the I-V curve as illustrated in Figure: 2.11 (Chen, 2011).

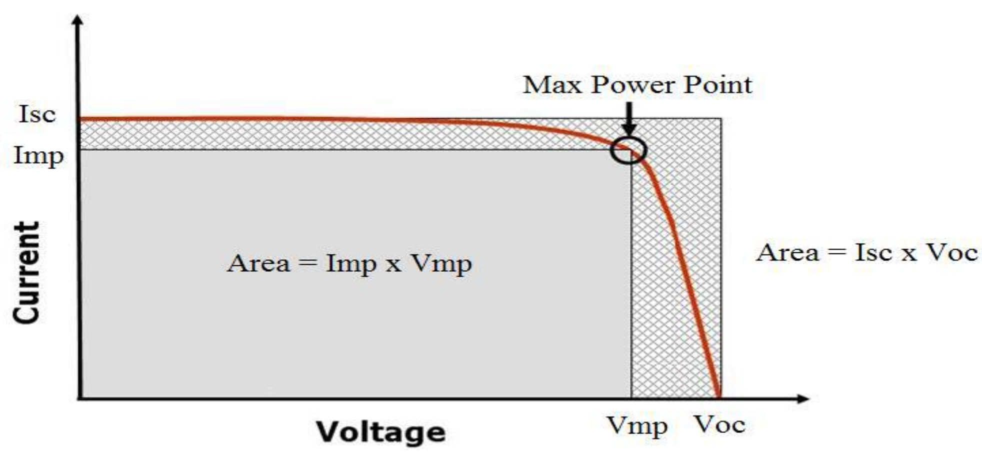


Figure 2.11: Fill Factor.

High performance cell are designed with a low series resistance values and high parallel resistance values, to reach ideal situation where the current held right up to the short circuit value, then reduced suddenly to zero at the MPP, and have a FF of unity. Needless to say, practical cells do not achieve this value where they depend on PV arrays types. The importance of FF is to indicate the power achieved. The array with higher FF will produce more power; e.g., in case of two individual PV modules having the same values Of I_{SC} and V_{OC}. Also, any impairment that reduces the FF will reduce the output power. The ideal FF value is 1 which means that the two rectangles are identical (Chen, 2011).

2.5.3 The Short-Circuit Current (I_{SC}) and the Open-Circuit Voltage (V_{OC})

There are two conditions of particular interest for the actual PV cell and for its equivalent circuit. As shown in Figure 2.12, the current that flows when the terminals are shorted together which called the short circuit current $I_{SC,}$ and the voltage across the terminals when the leads are left open which called the open circuit voltage V_{OC}. When the leads of the equivalent circuit for the PV cell are shorted together, no current flows in the (real) diode since $V_d = 0$, so all of the current from the ideal source flows through the shorted leads. The shunt resistance R_{SH} is neglected In both cases, since power is the product of current and voltage, no power is delivered by the module and no power is received by the load (Masters, 2004).

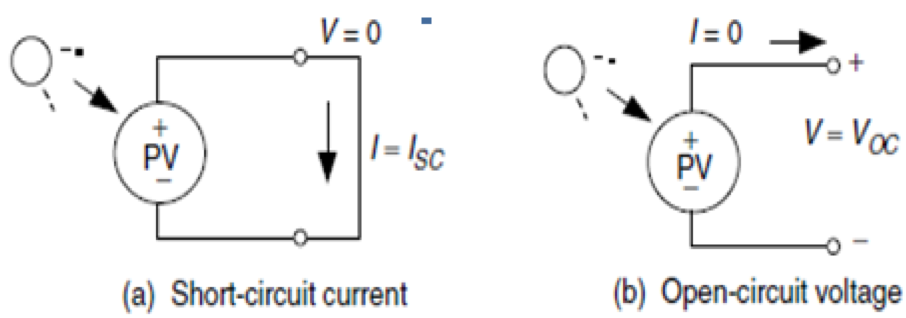


Figure 2.12: The Short Circuit Current I_{SC} and the Open-Circuit Voltage V_{OC}

2.5.4 Efficiency

The PV cell/module efficiency is the ability to convert sunlight to electricity. The efficiency of a solar cell is defined as the ratio of the output electric power over the input solar radiation power under standard illumination conditions at the maximum power point (Chen, 2011). The maximum efficiency of the PV module is given by:

$$\eta = \frac{P_{out}}{G*A} * 100\% \quad (2.2)$$

Where *G* is global radiation and considered to be 1000 W/m^2 at (STC) and *A* is the Area of the PV module (input power of the solar panelP_{in}).

2.6 ONE DIODE PHOTOVOLTAIC (PV) CELL & CHARACTERISTIC EQUATIONS

A general mathematical description of I-V output characteristics for a PV cell has been studied for over the past four decades. Such an equivalent circuit-based model is mainly used for the MPPT technologies (El-Basit, 2013)

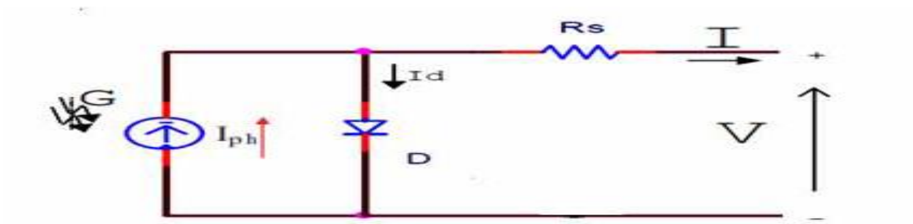


Figure 2.13: A one Diode Equivalent Circuit PV Cell.

WhereI_{ph}, is the photocurrent generator, D is a single parallel-connected diode, Rs is a series resistor, I_d is the normal diode current and I is the output current. From Figure 1, it can be seen that (Vengatesh & Rajan, 2011)

$$I = I_{ph} - I_d \quad (2.3)$$

And the normal diode current I_d is

$$I_d = I_S \left[exp\left(\frac{q(V+IR_S)}{KAT_C}\right) - 1\right] \quad (2.4)$$

Substituting Eq. (2.4) into Eq. (2.3) yields

$$I = I_{ph} - I_S \left[exp \left(\frac{q(V+IR_S)}{KAT_C} \right) - 1 \right] \quad (2.5)$$

Where I_S is the cell saturation dark current, q (= 1.6×10^{-19}C) is an electronic charge, k (= 1.38 $\times10^{-23}$J/K) is a Boltzmann's constant, T_C is the cell's working temperature, A is the ideality factor. The photocurrent I_{ph} mainly depends on the solar insolation and cell's working temperature, which is described as (Islam et al., 2014)

$$I_{ph} = \left[I_{SC} + K_I (T_C - T_{Ref}) \right] N \quad (2.6)$$

Where I_{SC} is the cell's short-circuit current at 25^0C and 1000W/m^2, K_I is the short-circuit temperature coefficient, T_{Ref} is the cell's reference temperature, N is the solar insolation in W/m^2. Since normally $I_{ph} \gg I_S$ and ignoring the small diode current I_d and ground-leakage currents under zero-terminal voltage, the short-circuit current is approximately equal to the photocurrent I_{ph} (Kachhiya et al., 2011)

$$I_{ph} = I_{SC} \quad (2.7)$$

Therefore the short-circuit current I_{SC} can be obtained as:

$$I_{SC} = I = I_{ph} - I_S \left[exp \left(\frac{q(I_{ph} R_S)}{KAT_C} \right) - 1 \right] \quad (2.8)$$

The cell's or diode saturation current varies with the cell temperature, which is described as:

$$I_S = I_{RS}\left(\frac{T_C}{T_{Ref}}\right)^3 exp\left[\frac{qE_G}{kA}\left(\frac{1}{T_{Ref}} - \frac{1}{T_C}\right)\right] \quad (2.9)$$

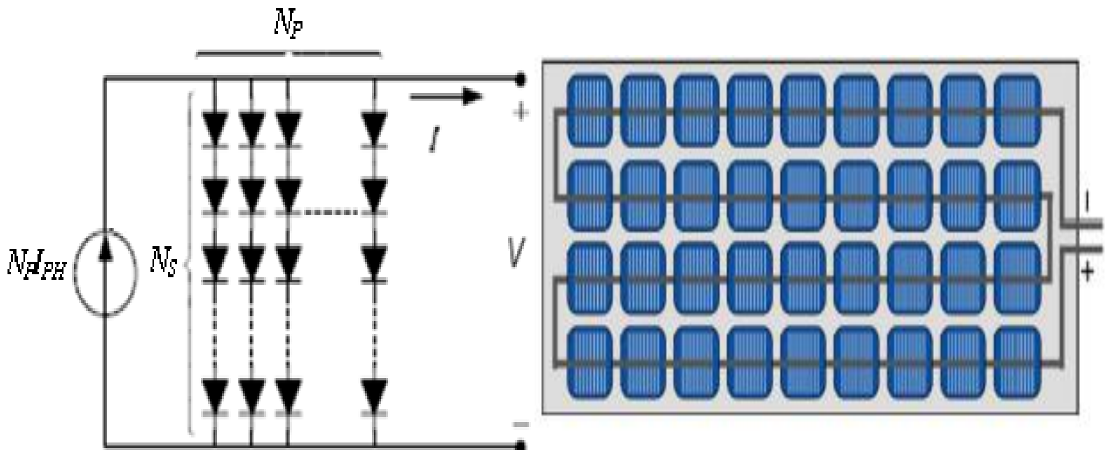
WhereI_{RS}, is the cell's reverse saturation current at a reference temperature of a solar radiation, E_G is the bang-gap energy of the semiconductor used in the cell. The reverse saturation current at reference temperature can be approximately obtained as (Vajpai & Khyani, 2013)

$$I_{RS} = \frac{I_{SC}}{\left[exp\left(\frac{qV_{OC}}{N_S T_C KA}\right) - 1\right]} \quad (2.10)$$

Where V_{OC} is an open circuit voltage obtained when the diode is not conducting. V_{OC} is found to be given as (Rodrigues et al., 2011)

$$V_{OC} = \frac{AKT}{q} ln\left(1 + \frac{I_{SC}}{I_s}\right) \quad (2.11)$$

Since a typical PV cell produces less than 2W at 0.5V approximately, the cells must be connected in series and parallel configurations on a given module to produce enough high power (Seifi et al., 2013). A PV array is a group of several PV modules which are electrically connected in series and parallel circuits to generate the required current and voltage. The terminal equation for the current and voltage of the array becomes as follows (Vajpai & Khyani, 2013)(Rizi & Abadi, 2016) .



(a) Ideal Model of PV Module. (b) PV Cells Connected in Series.
Figure 2.14: Ideal Model of PV Module and a Typical PV Cells Connected in Series.

$$I = N_P I_{ph} - N_P I_S \left[exp \frac{q}{kAT_c} \left(\frac{V + IR_S}{N_S} \right) - 1 \right] \quad (2.12)$$

The output power can be obtained by:

$$P = V \left[N_P I_{ph} - N_P I_S \left[exp \frac{q}{kAT_c} \left(\frac{V + IR_S}{N_S} \right) - 1 \right] \right] \quad (2.13)$$

In this Chapter, related literatures and theoretical background of the research work has been carried out. In the proceeding Chapter the materials and the method used in carrying the research will be discuss.

CHAPTER THREE

MATERIALS AND METHOD

3.0 INTRODUCTION

In this Chapter, method and the detail of the procedure that lead to the successful execution of this work is presented. Current-Voltage and Power-Voltage equations were simulated. Data sheets of four different modules technologies rated at 200W and 220W were acquired.

3.1 SIMULATION METHOD

The method adopted in this work is the simulation using MATLAB program. We consider PV modules rated at 200W and 220W from the three photovoltaic modules technologies as shown in (Table3.1). We wrote MATLAB scripts that can simulate equations (2.10) and (2.11) in chapter two. First we set the module at constant ambient temperature of 25^0C and vary the irradiance as 100W/m^2, 200W/m^2, 300W/m^2, 400W/m^2, 500W/m^2, 600W/m^2……1200W/m^2. Secondly the irradiance is maintained constant at value of 1000W/m^2 and the temperature varied as 10^0C, 25^0C, 35^0C, 45^0C, 55^0C, 65^0C, and 750C. From the scripts, we evaluated the performances (efficiency) of the modules from equation (2.12) given.

The essential input parameters such as Voc, Isc, Ns, K_I, Tc and G are taken from the manufacturers datasheet for the typical 220W and 200W modules selected under test at standard test condition (STC) as shown in Table:3.1. The 220W and 200W datasheets where selected because they are the once available for all the three technologies.

Table3.1: Major specifications for the PV Modules

S/N	Module Number	Technology	P_{max} (W)	I_{mp} (A)	I_{sc} (A)	V_{mp} (V)	V_{oc} (V)	Temp Coeff I_{sc} (%/^{0}C)	Area (M^2)
1	SR-M654220	Monocrystalline	220	8.15	8.80	27.00	33.21	0.05	1.47
2	CS5A-200	Monocrystalline	200	5.35	5.71	37.40	45.30	0.06	1.28
3	CS6P-220	Polycrystalline	220	7.52	8.09	29.30	36.30	0.06	1.61
4	SR-P654200	Polycrystalline	200	7.34	7.90	27.25	33.79	0.046	1.47
5	FLEX-01 220	CIGS. Thin film	220	9.86	11.13	22.60	28.20	-0.003	1.71
6	BIPV-200	CIGS. Thin film	200	5.50	6.40	32.20	46.40	-0.03	1.92
7	HIP-220HDE1	a.Si. Thin film	220	6.57	7.07	33.50	41.40	0.0299	1.39
8	HIP-200BA3	a.Si. The film	200	3.59	3.83	55.80	68.70	0.0229	1.18

Table 3.2: Ideality Factor (A) for PV Technologies.

S/N	Technology	Ideality Factor
1	Monocrystalline	1.2
2	Polycrystalline	1.3
3	a-Si:H (amorphous silicon)	1.8
4	a-Si:Htadem	3.3
5	a-Si:H triple	5
6	CIGS (Copper indium gallium Selenide)	1.5
7	CdTe (Cadmium Telluride)	1.5
8	AsGa (gallium arsenide)	1.3

In this Chapter, the materials used in the research where listed and the method adopted was discuss. The following Chapter will show the results and discussion of the simulations.

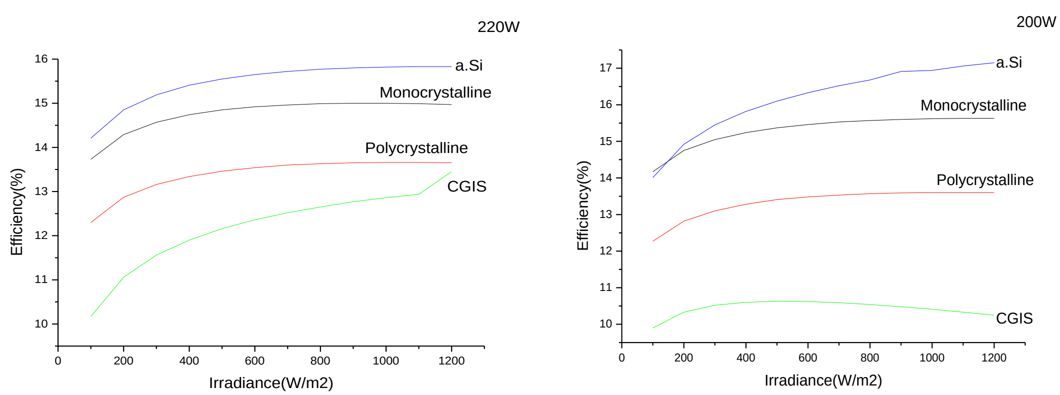
CHAPTER FOUR

RESULTS AND DISCUSSION

4.0 INTRODUCTION

This Chapter presents the results and discussion of the simulation carried out as defined in Chapter three. By simulating the equations (2.10) and (2.11), we are able to develop the graphs indicating the variation of the performances of each module technology with solar intensity and ambient temperature. Results of the simulation are given in proceeding section and described in 4.1.

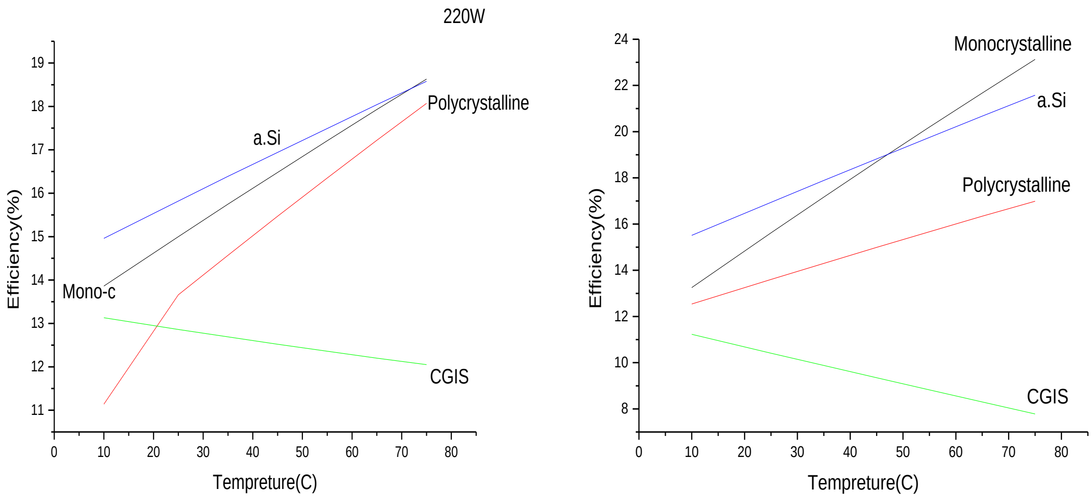
4.1 GENERAL RESULTS AND DISCUSSION



(a) Graph of 220W PV modules (b) Graph of 200W PV modules

Figure 4.1: Variation of Efficiency with Irradiance at Fixed Temperature (25^0C) for the three PV Module Technologies rated at 220W and 200W.

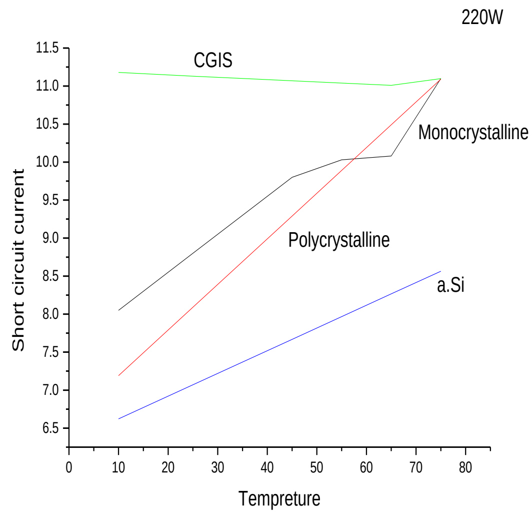
It was observed that efficiency is improved upon with increase in irradiance for both mono-crystalline, poly-crystalline, amorphous silicon (a-Si) and CIGS technology which is in agreement with other work reported (Islam et al., 2014).

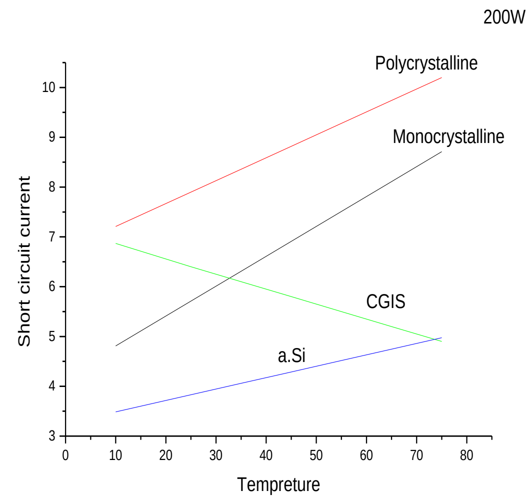


(a) Graph of 220W PV modules (b) Graph of 200W PV modules

Figure 4.2: Variation of Efficiency with Temperature at Fixed Irradiance (1000W/m^2) for the three PV Module Technologies rated at 220W and 200W.

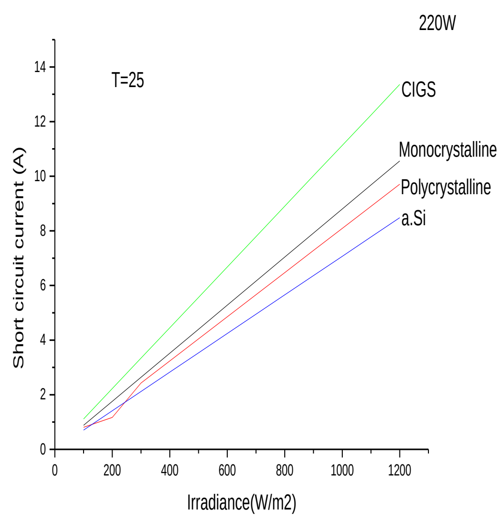
It can be seen that from the simulated result and graphs plotted the temperature has effect on the performance of monocrystalline, polycrystalline, amorphous silicon (a.Si) and CIGS. The efficiency increases with increase in temperature in mono-crystalline, poly-crystalline and amorphous silicon (a.Si) technology while the efficiency decreases with increase in temperature in cupper indium gallium diselenide (CIGS) technology which is in agreement with the measured (experimental) work reported (Aish, 2015).

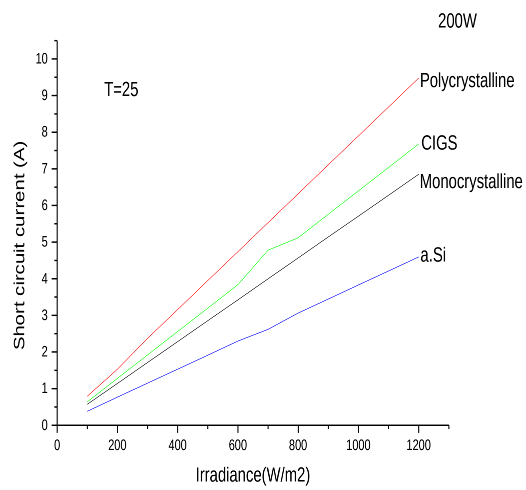




(a) Graph of 220W PV modules (b) Graph of 200W PV modules

Figure 4.3: Variation of Short Circuit Current with Temperature at Fixed Irradiance ($1000W/m^2$) for the three PV Module Technologies rated at 220W and 200W.





(a) Graph of 220W PV modules (b) Graph of 200W PV modules

Figure 4.4: Variation of Short Circuit Current with Irradiance at Fixed Temperature (25^0C) for the three PV Module Technologies rated at 220W and 200W.

It can be seen that from the graph of figure 4.4 variation of the short circuit current with irradiance for all the technologies is pure linear with positive slope.

The results of this research were discuss in this Chapter. In Chapter five the Summery Conclusion and Recommendation of the entire research will be given.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.0 SUMMARY

Renewable energy is an energy that is environmentally friendly and if managed in a proper way it can mate the high demand of the energy of the world. Solar radiation distribution at a particular geographical location is of vital importance for the developments of many solar devices. Photovoltaic (PV) modules are devices that convert solar irradiance into electricity. PV parameters were simulated to assess the performances of different technologies due to the changes in solar insolation and temperature. It was found that both increases in irradiance and temperature increase the performance of photovoltaic solar cells, where CIGS it performances decreases with increase in temperature.

5.1 CONCLUSION

It was found that the response of thin film technologies to variations of solar irradiance and ambient temperature is faster than those of monocrystalline and polycrystalline solar cells. It is also found that the performance of one of the thin film solar cells, CIGS, decreases with increase in temperature. Since thin film has fast response to variations in operating conditions, this makes it very advantageous. However the decrease in efficiency of some thin film solar cells with increase in temperature is a drawback. As such it is recommendable to make use of a combination of thin film and monocrystalline or polycrystalline solar cells where there is need for more than one PV cells. This would improve the overall performance of the entire system and thus maximizes the utilization of the solar energy.

5.2 RECOMMENDATIONS

- In order to improve the performance of CIGS with increase in temperature it is recommended to combine CIGS with monocrystalline or polycrystalline solar module where there is need for more than one PV modules.
- It is recommended to integrate the solar cells with thermoelectric device that will cool the solar cells to eliminate the effects of rise in temperature.

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APPENDIX A

Simulated result of monocrystalline PV module ratted 220W for different irradiance at constant temperature of 25^0C.

G(W/m2)	Pmax(W)	Isc(A)	Pin(W)	η(%)
100	20.19	0.88	147	13.73
200	42.02	1.76	294	14.29
300	64.27	2.64	441	14.57
400	86.69	3.52	588	14.74
500	109.18	4.4	735	14.85
600	131.65	5.28	882	14.92
700	154.04	6.16	1029	14.96
800	176.34	7.04	1176	14.99
900	198.52	7.92	1323	15
1000	220.54	8.8	1470	15
1100	242.43	9.68	1617	14.99
1200	264.14	10.56	1764	14.97

Simulated result of polycrystalline PV module ratted 220W for different irradiance at constant temperature of 25^0C.

G(W/m2)	Pmax(W)	Isc(A)	Pin(W)	η(%)
100	19.81	0.809	161	12.3
200	41.45	1.168	322	12.87
300	63.59	2.427	483	13.16
400	85.96	3.236	644	13.34
500	108.41	4.045	805	13.46
600	130.88	4.854	966	13.54
700	153.3	5.663	1127	13.6
800	175.66	6.472	1288	13.63
900	197.9	7.281	1449	13.65
1000	220.02	8.09	1610	13.66
1100	240	8.899	1771	13.66
1200	263.82	9.708	1932	13.65

Simulated result of CIGS PV module ratted 220W for different irradiance at constant temperature of 25^0C.

G(W/m2)	Pmax(W)	Isc(A)	Pin(W)	η(%)
100	17.4	1.113	171	10.17
200	37.84	2.226	342	11.06
300	59.33	3.339	513	11.56
400	81.46	4.452	684	11.9
500	104.01	5.565	855	12.16
600	126.86	6.678	1026	12.36
700	149.94	7.791	1197	12.52
800	173.18	8.904	1368	12.65
900	196.55	10.02	1539	12.77
1000	220	11.13	1710	12.86
1100	243.53	12.24	1881	12.94
1200	267.1	13.36	2052	13.45

Simulated result of amorphous silicon (a-Si) PV module ratted 220W for different irradiance at constant temperature of 25^0C.

G(W/m2)	Pmax(W)	Isc(A)	Pin(W)	η(%)
100	19.76	0.707	139	14.21
200	41.31	1.414	278	14.85
300	63.38	2.121	417	15.19
400	85.69	2.828	556	15.41
500	108.12	3.535	695	15.55
600	130.58	4.242	834	15.65
700	153.04	4.949	973	15.72
800	175.44	5.656	1112	15.77
900	197.77	6.363	1251	15.8
1000	220	7.07	1390	15.82
1100	242.12	7.777	1529	15.83
1200	264.12	8.484	1668	15.83

Simulated result of monocrystalline PV module ratted 220W for different temperature at constant irradiance of 1000W/m^2.

Temp.	Pmax(W)	Isc(A)	Pin(W)	η(%)
10	203.75	8.05	1470	13.86
25	220.54	8.8	1470	15
35	231.55	9.3	1470	15.75
45	242.39	9.8	1470	16.48
55	253.07	10.03	1470	17.21
65	263.59	10.08	1470	17.93
75	273.96	11.1	1470	18.63

Simulated result of polycrystalline PV module ratted 220W for different temperature at constant irradiance of 1000W/m^2.

Temp.	Pmax(W)	Isc(A)	Pin(W)	η(%)
10	179.51	7.19	1610	11.14
25	220.02	8.09	1610	13.66
35	234.71	8.69	1610	14.57
45	249.15	9.29	1610	15.47
55	263.34	9.89	1610	16.35
65	277.29	10.49	1610	17.22
75	290.99	11.09	1610	18.07

Simulated result of CIGS PV module ratted 220W for different temperature at constant irradiance of 1000W/m^2.

Temp.	Pmax(W)	Isc(A)	Pin(W)	η(%)
10	224.61	11.18	1710	13.13
25	220	11.13	1710	12.86
35	217.06	11.1	1710	12.69
45	24.2	11.07	1710	12.52
55	211.42	11.04	1710	12.36
65	208.72	11.01	1710	12.2
75	206.1	11.098	1710	12.05

Simulated result of amorphous silicon (a-Si) PV module ratted 220W for different temperature at constant irradiance of 1000W/m^2.

Temp.	Pmax(W)	Isc(A)	Pin(W)	η(%)
10	208.06	6.621	1390	14.96
25	220	7.07	1390	15.82
35	227.84	7.369	1390	16.39
45	235.59	7.668	1390	16.94
55	243.24	7.967	1390	17.49
65	250.81	8.266	1390	18.04
75	258.29	8.565	1390	18.58

Simulated result of monocrystalline PV module ratted 200W for different irradiance at constant temperature of 25^0C.

G(W/m2)	Pmax(W)	Isc(A)	Pin(W)	η(%)
100	18.15	0.571	128	14.17
200	37.76	1.142	256	14.75
300	57.8	1.713	384	15.05
400	78.05	2.284	512	15.24
500	98.39	2.855	640	15.37
600	118.77	3.426	768	15.46
700	139.15	3.997	896	15.53
800	159.5	4.568	1024	15.57
900	170.79	5.139	1152	15.6
1000	200	5.71	1280	15.62
1100	220.14	6.281	1408	15.63
1200	240.18	6.852	1536	15.63

Simulated result of polycrystalline PV module ratted 200W for different irradiance at constant temperature of 25^0C.

G(W/m2)	Pmax(W)	Isc(A)	Pin(W)	η(%)
100	18.04	0.79	147	12.27
200	37.7	1.53	294	12.82
300	57.8	2.37	441	13.1
400	78.12	3.16	588	13.28
500	95.52	3.95	735	13.41
600	118.93	4.74	882	13.48
700	139.32	5.53	1029	13.53
800	159.65	6.32	1176	13.57
900	179.9	7.11	1323	13.59
1000	200.04	7.9	1470	13.6
1100	220.06	8.69	1617	13.6
1200	239.95	9.48	1764	13.6

Simulated result of CIGS PV module ratted 220W for different irradiance at constant temperature of 25^0C.

G(W/m2)	Pmax(W)	Isc(A)	Pin(W)	η(%)
100	19.02	0.64	192	9.9
200	39.7	1.28	384	10.33
300	60.62	1.92	576	10.52
400	81.47	2.56	768	10.6
500	102.1	3.2	960	10.63
600	122.44	3.84	1152	10.62
700	142.44	4.78	1344	10.59
800	162.04	5.12	1536	10.54
900	181.24	5.76	1728	10.48
1000	200	6.4	1920	10.41
1100	218.32	7.04	2112	10.33
1200	236.18	7.68	2304	10.25

Simulated result of amorphous silicon (a-Si) PV module ratted 200W for different irradiance at constant temperature of 25^0C.

G(W/m2)	Pmax(W)	Isc(A)	Pin(W)	η(%)
100	16.54	0.383	118	14.01
200	35.23	0.766	236	14.92
300	54.71	1.149	354	15.45
400	74.69	1.532	472	15.82
500	95.03	1.915	590	16.1
600	115.64	2.298	708	16.33
700	136.48	2.618	826	16.52
800	157.5	3.064	944	16.68
900	179.69	3.447	1062	16.91
1000	200	3.83	1180	16.94
1100	221.44	4.213	1298	17.06
1200	242.97	4.596	1416	17.15

Simulated result of monocrystalline PV module ratted 200W for different temperature at constant irradiance of $1000W/m^2$.

Temp.	Pmax(W)	Isc(A)	Pin(W)	η(%)
10	169.68	4.81	1280	13.25
25	200	5.71	1280	15.62
35	219.84	6.31	1280	17.17
45	239.37	6.91	1280	18.7
55	258.58	7.51	1280	20.2
65	277.49	8.11	1280	21.67
75	296.08	8.711	1280	23.13

Simulated result of polycrystalline PV module ratted 200W for different temperature at constant irradiance of 1000W/m^2.

Temp.	Pmax(W)	Isc(A)	Pin(W)	η(%)
10	184.35	7.21	1470	12.54
25	200.04	7.9	1470	13.6
35	210.3	8.36	1470	14.3
45	220.42	8.82	1470	14.99
55	230.38	9.28	1470	15.67
65	240.21	9.74	1470	16.34
75	249.89	10.2	1470	16.99

Simulated result of CIGS PV module ratted 200W for different temperature at constant irradiance of 1000W/m^2.

Temp.	Pmax(W)	Isc(A)	Pin(W)	η(%)
10	215.64	6.87	1920	11.23
25	200	6.4	1920	10.41
35	189.71	6.1	1920	9.88
45	179.52	5.8	1920	9.35
55	169.43	5.5	1920	8.82
65	169.42	5.2	1920	8.3
75	149.49	4.9	1920	7.78

Simulated result of amorphous silicon (a-Si) PV module ratted 200W for different temperature at constant irradiance of 1000W/m^2.

Temp.	Pmax(W)	Isc(A)	Pin(W)	η(%)
10	183.13	3.486	1180	15.51
25	200	3.83	1180	16.94
35	211.13	4.059	1180	17.89
45	222.17	4.288	1180	18.82
55	233.12	4.517	1180	19.75
65	243.98	4.746	1180	20.67
75	254.75	4.975	1180	21.58

APPENDIX B

MATLAB CODE

```
function [u P PMAX]=photocurrent(T,G)
i=[];Tc=25+273;u=[];v=[];P=[];
T=T+273;
Isc=1.87; %Isc and mu;the Temperature coefficient of the short circuit current; in
datasheet;
mu=0.06;
DT=T-Tc;
Iph=0.001*G*(Isc+mu*DT);
%Io expression
Voc=21.20;
Rs=0.39;
Ns=36;
k=1.38*exp(-23);
eg=1.12*1.6*exp(-19);
A=1.3;
q=1.6*exp(-19);
a=0.026*A*Ns;
Io=Isc*(exp(-Voc/a)).*(T/Tc).^3.*exp((q*eg/A*k).*((T-Tc)/(T*Tc)));
%Initialize I
I=0;
for V=0:0.1:Voc
   I= Iph-Io*(exp((V+I*Rs)/a)-1);

u=[u I];
p=V*I;
P=[P p];
v=[v V];
end
u(u<=0)=0;
P(P<=0)=0;
u=u';
P=P';
v=v';
d=horzcat(u,P,v);
plotyy(v,u,v,P)
plot(v,P)
PMAX=max(P)
end
```