

**CHARACTERISATION OF COPPER INDIUM GALLIUM
DISELENIDE SOLAR MODULE IN THE
UGANDAN CLIMATE**

BY

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DECLARATION

I, Zawedde Sarah Kisitu, do hereby declare that this report contains my original work and has not been presented to any University or academic institution for the purpose of an academic award.

Signed:.....Sarah.....

Date:.....23RD - JAN - 2014.....

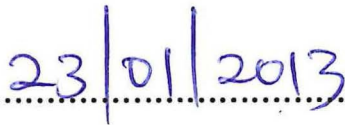
APPROVAL

This is to certify that this research by Ms. Zawedde Sarah Kisitu was carried out under our supervision and is now ready for submission to the Graduate School and the Senate of Kyambogo University with our due approval.

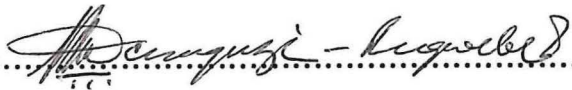


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DEDICATION

I dedicate this report in memory of my dear late father Mr. Dick Kisitu (RIP) and to my dear mother Ms. Annet Namusisi for the good foundation that they laid for me.

ACKNOWLEDGMENT

This research has been a success through the mercy of the Almighty God and through the efforts and encouragements I received from different people.

First and foremost I sincerely thank my supervisors Dr. Willy Okullo and Associate Professor Dr. Eric Mucunguzi for their guidance and encouragement they extended to me throughout the period of carrying out this research.

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ABSTRACT

The photovoltaic solar energy from copper indium gallium diselenide (CIGS) solar module is one of the most promising sources of solar energy for large scale production of clean energy at competitive prices. The focus of the study was to determine the performance of CIGS solar module in terms of its performance parameters in the tropical region. The goal of this dissertation was hence to characterise the performance of CIGS solar modules in the Ugandan climate.

The performance of the CIGS module was assessed when put out doors by measuring the current-voltage (I-V) characteristic of the device. A variable resistor was connected to the CIGS module and was varied from minimum (0Ω) to maximum (100Ω) and the corresponding current and voltage were measured. The electrical performance parameters such as short circuit current, open circuit voltage, maximum power, fill factor and efficiency were then obtained from I-V characteristic curves.

The short circuit current obtained was 1.03A that is 1.9% lower than the rated value. The open circuit voltage obtained was 19.25V that is 35.8% lower than the rated value. The maximum current obtained was 0.71A that is 12.3% lower than the rated value. The maximum voltage obtained was 13.4V that is 37.9% lower than the rated value. The maximum power obtained was 9.5W that is 36.7% lower than the rated value. There was no change in the fill factor. The efficiency obtained was 6.1% that is 24.7% lower than the rated value. The study shows that out of the seven parameters it was only the fill factor which had the same value with the rated value. The short circuit current was close to the rated value while other parameters were significantly lower than the rated value varying between 12.3% and 37.9%.

Basing on the findings of this study, it is recommended that a further study should be done over a longer period of time for example a year in both dry and wet seasons to cross check the reliability of the findings of this study. The results of this study will be useful to compare the performance of this type of module with others in the market to find out if they would give similar values. Current-voltage (I-V) characteristics measurements under the dark should also be considered to determine the performance of the CIGS solar modules. This would determine other electrical parameters such as series resistance, shunt resistance and diode parameters (ideality factor and reverse saturation current).

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

The demand for energy has continued to increase as the population continues to grow and as the number of industries also continues to grow in the different regions of the world. The total energy usage worldwide in 2008 averaged at fifteen terawatts (15TW), where $1\text{TW}=10^{12}\text{W}$ according to the Annual world solar Photovoltaic Market report (2009). One quarter of this energy was noted to have been consumed in the United States of America alone. It is predicted that the energy consumption in 2050 will rise to an estimated value of 30TW according to Shinnar and Citro (2006). In 2005, Uganda's total energy consumption was estimated to be 0.03TW (9.0×10^6 Tonnes of Oil Equivalent Toe) as reported by Mendi information services (2009).

It is estimated that about 90% of the total energy used in the world is from fossil fuels in form of coal, oil and natural gas. Fossil fuel reserves primarily used to produce petroleum fuels are finite and therefore the supply of oil will eventually be depleted since it is spent million times faster than it is formed. Fossil fuel is a non renewable energy resource. It takes millions of years to form from its vegetation form. The heterogeneous distribution of worldwide oil reserves has been observed to create political and economical problems, which may be expected to increase in future as oil reserves run low. Fossil fuels emit many gases such as carbondioxide, sulphurdioxide and nitrousoxide that pollute the environment. Sulphurdioxide and nitrousoxide are the main causes of acid rains and smog. According to research made by Solar energy International (2009), the large emission of carbon dioxide (16 million tons) into the atmosphere is the primary cause of global warming and the main cause of the recent climate changes.

According to a research by Urnec (2012) Uganda's energy mix comprises of 6% petroleum, 2% electricity and 92% biomass. All fossil fuels currently used in Uganda are imported which makes them very costly. This is so because Uganda has not yet started producing any petroleum fuels from the petroleum oil reserves (oil deposits) that have been discovered in the western rift valley area (Albertine basin).

In most of the developing countries, renewable resources of energy which include water power (hydroelectric power), plant materials (biomass), solar energy, geothermal energy and wind energy play an important role. Hydroelectric power is widely used as a major

source of energy for urban areas and industries. The amount of energy obtainable from hydroelectric power stations is however limited by the volume of the water and the conditions of the water flow to run the turbines for the generation of electric energy in particular. Hydro electric power is therefore becoming insufficient to meet the needs of the growing population.

According to Ministry of Energy and Mineral Development report (2012), about 95% of Uganda's population does not have access to electricity and many towns, especially in the Northern part of the country are without electrical power. The total hydroelectric power capacity of the installed stations in Uganda is 683Megawatts (MW). The hydroelectric power stations that generate this power are Bujagali generating 250MW, Nalubale generating 180MW, Kiira generating 200MW and the small mini hydros stations combined generating 53MW). It is estimated that Uganda will require 2,000MW of electricity by the year 2025 to run its industries and homes according to Mendi information service (2009). The electricity distribution network in Uganda at present is known to be poorly maintained therefore the country experiences frequent power cuts.

According to a report from Uganda Bureau of Statistics (2012), electricity transmission by the Uganda Electricity Transmission Company Limited (UETCL) from the main hydro and thermal plants that supply power to the main grid increased by 2.6% from 2,819GWh in 2010 to 2891GWh in 2011. Umeme, Uganda's largest electricity distributor's capital expenditure which includes putting up a distribution network and maintenance increased from shs.51billion in 2010 to shs.78 billion in 2011. This makes electric energy very costly. Uganda charges one of the highest electricity tariffs in East Africa as per research done by Africa Uganda Business Travel Guide (2012) whereby domestic consumers pay sh524 per unit, Street lighting costs sh488.7 per unit, commercial users pay sh458.6 per unit, medium industrial consumers pay sh458.9 per unit and large industries pay sh312.8 per unit. In Kenya, consumers pay an equivalent of Uganda sh38 for the first 50 units. Subsequent units cost between sh166 and sh345 each. Consumers in Tanzania pay only sh52 per unit, while in Rwanda consumers are charged sh389 per unit according to all Africa.com website (2012). The unit cost of electricity in Uganda has thus gone beyond what the majority of Ugandans can afford. Most households only use electricity for lighting and operating their televisions and radios.

Due to the high cost of electricity in Uganda, many households have resorted to the use of biomass in form of firewood or charcoal as a source of energy to provide them with the basic energy requirements especially for domestic use. According to Kiza (2006) and Ministry of energy and Mineral development (2007), biomass demand in Uganda is about 27.7 million tons whereby 92% of Uganda's population use biomass for their energy needs. They however use insufficient technology whereby 72.7% of the households use the three-stone method for cooking; about 14.8% use open charcoal stoves and only 8.7% use improved stoves. The pressure on wood as a source of energy due to population growth and migration is exerting a negative impact on the environment. There is therefore need for alternative and clean sources of energy such as solar energy.

Solar energy is an environmentally clean source of energy. It is free, abundant, inexhaustible and available in adequate quantities in almost all parts of the world. It is of great importance especially in the tropical African countries where the sun is overhead throughout the year. The energy of sunlight incident on the Earth is 125,000TW according to Zwiebel (2005) and Lewis (2003). This amount of solar energy is about 10,000 times more than the present world energy requirement and much more than the energy produced from all other energy sources in the world. Thus solar energy could supply all the present and future energy needs of the world on a continuous basis for a period of at least 20 years.

The availability of solar energy is dictated by availability of solar technology. Solar cell technology is at present growing rapidly. This is the technology where the energy from the sun can be converted into electrical energy by use of solar cells based on photovoltaic (PV) effect. The photovoltaic cells are unique because they directly convert the incident solar radiation into direct current (DC) electricity. The photovoltaic cells produce no noise, no pollution, require no moving parts, and do not need conventional fuels to run them. This makes them reliable and long lasting. The first type of PV solar cells developed were silicon solar cell in the 1950's at the Bell telephone and Radio Corporation of America (RCA) laboratories. These cells according to Twidell and Weir (2006) were 16% efficient in converting solar energy into electrical energy. The first photovoltaic devices developed were for space applications. Solar cells are still today the main source of power forming space statelites. Photovoltaic use was extended to terrestrial applications about three decades ago and it has continued to grow rapidly.

The growth is inspired by many advantages of solar cells. The primary advantage being its low impact on the environment. Another very important advantage is the more or less homogeneous distribution of solar energy on the Earth, making it accessible to everyone anywhere.

Solar energy as a mode of power generation is said to be a cost effective source of off grid energy as opposed to the conventional generated power where huge capital investments have to be made in putting up transmission and distribution networks. The portability of the solar cells makes them commercially attractive especially for the remote areas. Extending the electricity grids to remote scattered rural areas which usually have lower energy demands compared to the developed urban areas is considered financially unattractive by the electricity providing companies. Basic electricity needs for agricultural enterprises, education and industries for heating and lighting are usually satisfied by use of electrical sources such as rechargeable batteries and small fossil fuel generators. These sources are, however, often very expensive and unreliable. Providing solar powered electricity to remote areas may be one of the very few ecologically and commercially suitable solutions for rural areas. The monthly payments for electricity to electricity generation and distribution companies would be eliminated and instead a one investment in a solar system installation that can last for years before being serviced or replaced to generate electricity needed and is affordable. Most households for example need on average electricity for running about four lights, a television set, a radio and an iron which can be estimated to cost about Shs.50,000 monthly for electricity in Uganda.

Uganda lies across the Equator in the heart of the sub-Saharan Africa. Uganda is endowed with plenty of sunshine throughout the year making it favorable for solar technology applications. Uganda receives 2500-3200 hours of sunshine per year and a solar radiation of about 4-5kWh/m²/day on a horizontal surface according to Urnec (2012) and Mendi international service (2009). The average solar flux in some parts of the country based on 12 hours can be as high as 300W/m² or more.

The government of Uganda abolished import duty on solar equipments in order to make them affordable. There are also fundings from agencies like the World Bank. Solar module price in Uganda has on average fallen from \$10 per wattpeak (WP) to about \$2 per WP. It is estimated that about 600kilowattpeak (KWP)-1megawattpeak (MWP) of solar capacity is imported into Uganda on a monthly average. In Uganda a smallest solar

kit consisting of a one watt panel, lantern and battery can be obtained at shs.39,000. A four lamp solar kit costs shs.341,000, a village kit consisting of four light emitting diode (LED) tubes, two matrices lamps and a security light costs shs.89,000 while a school kit consisting of three LED tubes and a security light costs shs.2million.

Not more than 5% of Ugandan households who are not connected to the national grid have access to solar power despite its clear advantages over the conventional energy sources. This is because PV cells are about three times higher in cost compared to other sources of energy like hydroelectric energy. In order to lower the PV price and increase their usage, the quantity of materials and the energy used to manufacture solar cells need to be minimized.

Solar cells may be in the form of crystalline silicon (Monocrystalline, c-Si or multicrystalline mc-Si). They can also be in form of Polycrystalline (thin film) solar cells. Majority of the solar cells are made of crystalline silicon because silicon is available in large quantities, very stable and produces devices with an efficiency of 24.7% according to Green et al. (2007). However silicon is fragile, and is an indirect semiconductor material with a low band gap of 1.1eV at room temperature making it possess a low optical absorption coefficient. Silicon therefore requires manufacture of relatively thick cells in order to absorb most of the incident photons. A typical silicon cell thickness is approximately 300 μ m which is 100 times more than the thickness of a typical polycrystalline thin film cell. This makes crystalline silicon cells require an expensive production process which makes them very expensive therefore their technology is not expected to become a low cost alternative energy resource.

Thin film solar cell technology is one of the most promising ways to achieve economical competitiveness of photovoltaic and is a better alternative to silicon solar cell technology. According to research made by sustainable energy (2006), the market for thin film PV cells grew at a 60% annual rate from 2002 to 2007 and is still growing rapidly. Thin film solar cell technologies have substantial cost advantages over traditional silicon photovoltaic cells because of the reduced amount of semiconductor material necessary for the construction of the device. They usually utilize a semi conductor material of approximately 10 μ m or less in thickness. The primary commercial technologies for thin film devices are based on amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) semi conductors. Copper indium gallium diselenide

solar cells have emerged as one of the most promising thin film solar cells among all other thin film solar cells in terms of cost effectiveness. The first CIGS module was released in 1998 by Siemens Solar Industries according to Wieting (1999). The main advantage of CIGS thin film solar cells over the crystalline silicon solar cells is that they are substantially cheaper due to less material and thermal energy usage during the fabrication process which lowers their production cost. The copper indium gallium diselenide is known to be a very strong light absorption material since it is a direct band gap material compared to crystalline silicon which is an indirect band gap material. Only 1-2 μ m of CIGS is enough to absorb most of the sunlight incident on it yet a much greater thickness of crystalline silicon is required for the same absorption.

1.2 Statement of the Problem of the Study

The copper indium gallium diselenide (CIGS) photovoltaic solar cells among other solar cells produce clean energy which is environmentally friendly with competitive prices and are easy to manufacture. The CIGS would hence be preferred but there is no available data so far on the performance of CIGS done in Uganda. Consumers therefore only rely on the power ratings of the modules provided by the manufacturers.

1.3 Purpose of the Study

The purpose of the study is to determine the characteristics that can be used to evaluate the performance of CIGS solar module in the Ugandan climate.

1.4 Objectives of the Study

The study is guided by the following objectives:

- i. To determine the electrical performance parameters of CIGS solar module.
- ii. To investigate the effect of temperature on the performance parameters of CIGS solar module.
- iii. To investigate the effect of irradiance on the performance parameters of CIGS solar module.
- iv. To determine the effect of shading on the performance parameters of CIGS solar module.
- v. To determine the effect of dusting on the performance parameters of CIGS solar module.

1.5 Scope of the Study

The study was limited to the five objectives above. The study was focused on CIGS solar module which was available on market in the country. The module's cells were manufactured in the United States of America and then assembled in India. It had an area of 62cmx30cm and a power rating of 15W. Measurements were taken at Kyambogo University for two weeks.

1.6 Significance of the Study

The study was to generate the I-V characteristic curve for CIGS when used in the Ugandan climate. The I-V characteristic measurements generated in this study for the CIGS module can be used as a basis for quality control of CIGS modules in Uganda as against the rated values. The values of the parameters obtained in this study can give feedback to the manufacturers of solar modules about the outdoor performance of CIGS modules in the equatorial climate which would widen on their knowledge about the CIGS performance in the region. In Uganda this study has provided available data and information on CIGS modules which researchers and even policy makers in government, engineers, designers, scientists, and the general public at large who are potential users (such as vendors and consumers) can use. The results provide baseline data for research to improve the performance of solar modules.

CHAPTER TWO: REVIEW OF RELATED LITERATURE

2.1 Introduction

This chapter has discussed the theory and covered the literature related to the copper indium gallium diselenide (CIGS) solar modules. It has considered the composition of CIGS cells and their structure, the electrical characteristics of the CIGS modules, the effect of temperature, irradiance, shading and dusting on the performance of the CIGS solar module.

2.2 Composition of copper indium gallium diselenide Cells

Copper indium gallium diselenide (CIGS) is a group I-III-VI compound semiconductor material composed of copper, indium, gallium, and selenium. The material is a solid solution composed of copper indium selenide (CIS) and copper gallium selenide (CGS), with a chemical formula of $\text{CuIn}_x\text{Ga}_{(1-x)}\text{Se}_2$, where the value of x can vary from 1 (pure copper indium selenide) to 0 (pure copper gallium selenide). It is a tetrahedrally bonded semiconductor, with a chalcopyrite crystal structure. The band gap varies continuously with x from about 1.0eV (for copper indium selenide) to about 1.7eV (for copper gallium selenide). It is used as light absorber material for thin film solar cells.

Copper indium gallium diselenide is a well known polycrystalline thin film photovoltaic absorber material that is being intensively pursued for commercialization. The best efficiency of CIGS cells achieved as of December 2005 was 19.5% as reported by Contreras et al. (2005). According to NREL (2008) and Repins et al. (2008) a team at the National Renewable Energy Laboratory achieved 19.9% new world record efficiency by modifying the CIGS surface and making it look like CIS. The 19.9% efficiency was higher compared to those achieved by other thin film technologies such as Cadmium Telluride or amorphous silicon. Cadmium Telluride has a maximum efficiency of 16.5% while amorphous silicon has reached an efficiency of 13.1% according to Green et al. (2003). Another advantage of CIGS compared to CdTe is that smaller amount of toxic material cadmium are present in CIGS cells. A CIGS solar cell with an efficiency of 20.1% with 0.5cm^2 total area was fabricated by the Zentrum für Sonnenenergie und Wasserstoff Forschung (ZSW) centre for solar Energy and Hydrogen Research Germany (2010), which is the highest efficiency in the record to date for any thin film solar cell. Higher efficiencies (of around 30%) can be obtained by using optical system reflectors to

concentrate the incident light. With record CIGS efficiency wandering at just about 20% for several years according to Carlson (2010), new trend of CIGS research has shifted to investigation on low cost deposition methods that could be alternatives to expensive vacuum processes. Non-vacuum solution processes progressed quickly and efficiencies of 10%-15% have been achieved by many groups, such as International Solar Electric Technology (ISET) and International Business Machines Corporation (IBM).

2.3 Structure of copper indium gallium diselenide Cells

The structure of the Cu(In,Ga)Se_2 cell device consists of five thin layers of semiconductor materials which have successively been deposited on a glass substrate. The Cu(In,Ga)Se_2 layer is moderately doped to form the p-type semiconductor. The cadmium sulfide (CdS) and the zinc oxide (ZnO) layers are doped to form the n-type semiconductor. The two hence form the p-n junction. The Cu(In,Ga)Se_2 and CdS films are doped by intrinsic defects in the material while the top ZnO layer is doped with incorporation of aluminium (Al). Between the CdS and doped ZnO layers is an undoped layer of ZnO. The separated carriers from the electron-hole pairs are collected at the electric contacts in each end of the cell; ZnO:Al in the front and molybdenum (Mo) in the back. The structure is as illustrated in Figure 2.1. The light incident onto the cell strikes the ZnO layer, passes through the CdS buffer layer and then enters the Cu(In,Ga)Se_2 absorber layer.

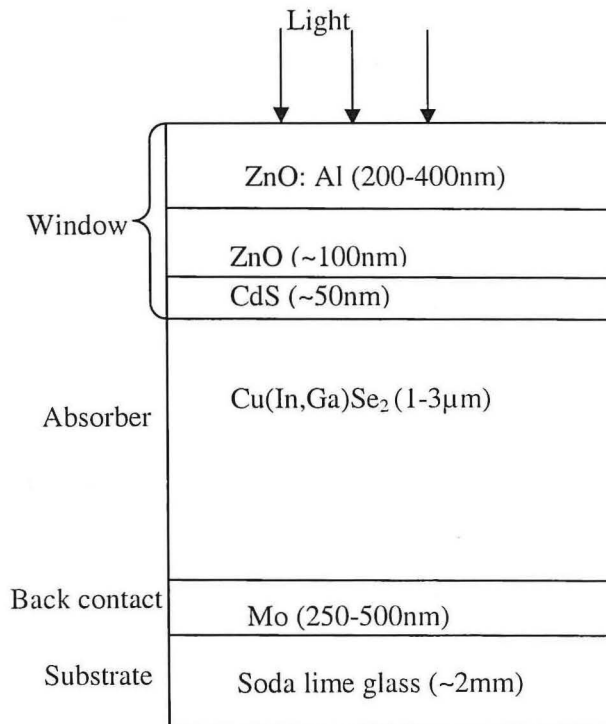


Figure 2.1: Structure of a CIGS Thin Film Solar Cell

The zinc oxide layer or transparent conductive oxide (TCO) layer forms the “window layer”. For most of the photons incident on the cell to be absorbed, it is very important for the TCO to have a large band gap of about 3.3eV according to Hedström et al. (1993). This makes the CIGS to be transparent for most of the solar spectrum. Usually an anti reflective coating is deposited on the top of the cell to minimize reflection losses.

The cadmium sulfide deposit forms the buffer layer. This layer provides good junction formation, lowers interface recombination, and decreases leakage current thus improving on the efficiency of the CIGS solar cell. Cells containing CdS have been found to be the most efficient cells for a long time, although the CdS layer introduces current loss at wave lengths below 520nm corresponding to photon energies above that of the CdS band gap. There have been many attempts to substitute CdS with alternative buffer layers such as (CdZn)S, Zn(OS), Zn(OH,S), ZnO, ZnS, ZnSe, In₂S₃, In(OH)₃, In(OH,S)₃, SnO₂ etc. as cited by Kessler et al.(1993) and Lincot et al. (1998). However until recently all the devices with alternative buffer layers performed inferior to the ones with CdS therefore the best performance is achieved using CdS buffer material, although ZnS(O,OH) gave close results to CdS when deposited on the same substrate. Recently, a cell with CdZnS buffer was produced having the same efficiency as the record CdS/CIGS cell and with a potential to surpass it.

The absorber layer is the most important layer in the PV solar cell. Copper indium diselenide (CuInSe₂) (CIS) is a direct band gap semi conductor material and has a large absorption coefficient ($\alpha \sim 10^5 \text{cm}^{-1}$) (Uda et al., 1982) that allows 99% of the incident sun light to be absorbed in the first micron of the material close to the p-n junction. This makes it an optimal, effective photovoltaic material. Therefore, the cells based on CIS can be made thin and at a low cost. To produce efficient devices, it is important to match the band gap of the absorber layer to the solar spectrum. The optical band gap for a single-junction solar cell with respect to the solar spectrum is around 1.4eV as cited by Uda et al. (1982). Pure CuInSe₂ has a band gap of 1.04eV according to Siemer et al. (2001) and because of that, the best CIS cells have achieved efficiencies of 15% (Moler, 1993). The band gap can be increased by partial substitution of indium with gallium thus obtaining CuInGaSe₂, which improves on the open-circuit voltage and the efficiency of the photovoltaic cell according to Carlson (2010). Gallium is also added to replace as much indium as possible because gallium is relatively more available compared to

indium. According to Hanna et al. (2001), an indium to gallium ratio of 20%-40% will result in a band gap of between 1.1-1.2eV which has been shown to give the best results. A device that was produced with a 30% indium substitution with gallium had a band gap of 1.15eV and an efficiency of 19.5% as reported by Contreras et al. (2005). The band gap of pure CuGaSe₂ (CGS) is 1.68eV (Hedström and Ohlsén, 1993). The band gap can also be increased by partial substitution of Se₂ for S₂, Cu(In,Ga)(S_e,S)₂ as cited by Shafarman et al. (1996). The direct band gap and high absorption coefficient of CIGS reduces on the requirement on minority carrier life time and facilitates use of thinner absorber layers since the photo-excited carriers are generated close to the depletion regions according to McCandless and Hegedus (1991). This makes CIGS become a suitable compound for thin film solar cells.

The back contact material of a solar cell collects the carriers from the absorber and delivers them to the external load. In standard thickness cells, the requirements for back contact material are to have low resistivity, not to impede the flow of majority carriers, holes, and in CIGS cells, to allow diffusion of sodium (Na) from the substrate to the semiconductor according to Engelmann et al. (2001). So far, the best cells have been produced with molybdenum as a back contact. The back contact material becomes more important and more interesting as the cells become thinner, because the carrier generation profile shifts closer to it.

The soda-lime glass is coated on one side with molybdenum (Mo) that serves as metal back contact. Soda-lime glass of 1–3 mm thickness is the most common substrate that is used because it is available, cheap and has a good thermal expansion coefficient which matches well with CIGS hence improving on the device's performance. In addition sodium from such a substrate diffuses through Mo film into CIGS which improves the crystalline quality of the layer (Granath, 1999). It replaces substitution defect where a copper (Cu) atom is replaced with In (In,Cu) that acts as compensating donors. It also catalyzes the dissociation of molecular oxygen. Oxygen atoms passivate selenium vacancies V_{Se} on the grain boundaries, which would otherwise act as recombination centers. CIGS devices have also successfully been deposited on flexible substrates such as plastic or metal foils. Although devices with these substrates do not obtain the same efficiencies as the glass substrate ones, they extend the application possibilities.

Several studies indicate that CIGS-based modules are stable over many years in field operation and they are not easily affected by light induced degradation. They tend to exhibit a slight increase in open circuit voltage and efficiency during the first hours of operation. Copper indium gallium diselenide have shown promising results in outdoor long-term performance tests according to Ullal et al. (1991), but they are also more sensitive than crystalline silicon solar cells to hot and humid environments (Karg et al., 1998). By concentrating the light falling onto a solar cell, the device will deliver a higher power output per illuminated absorber area, which can lower the electricity production costs. For CIGS-based solar cells, low-concentrated illumination could be an economically viable approach. The yearly performance of a photovoltaic system with CIGS modules can be significantly improved at a moderate cost by using parabolic aluminium mirrors as concentrating elements according to Wennerberg (2002).

2.4 Electrical Characteristics of CIGS

Characterization of solar cell devices is necessary to determine the sources of losses and suggest ways to minimize them. The current-voltage (I-V) characteristic is the most common way to describe the electrical performance of a solar cell. In the absence of light which generates current, PV cells behave like a diode. The current-voltage curve of an ideal solar cell in the dark follows the characteristics of the p-n exponential diode law.

$$I_D = I_0 \left(e^{\frac{qV}{nkT}} - 1 \right) \dots\dots\dots (2.1)$$

Where I_D is the diode or dark current, I_0 is the dark saturation current, n is diode identity factor, T is temperature, q is electric charge and k is Boltzmann constant. The diode identity factor depends on the characteristics of the material used like doping and its value is usually between 1 and 2 according to Sze (1981). Figure 2.2 describes the diode law given by equation (2.1).

When the PV cell is illuminated with light, current is generated by the cell and the diode or dark curve is shifted upward by an amount of current known as the light-generated current I_L where power can be extracted from the diode.

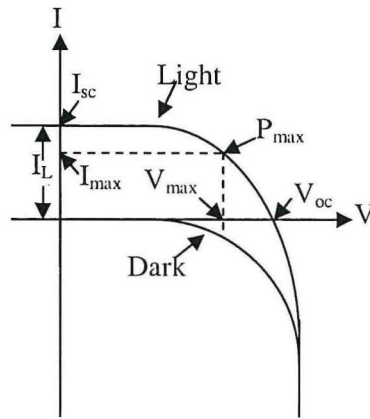


Figure 2.2: I-V Characteristic Curve in the Dark and under Light conditions

In an ideal photovoltaic cell, the total forward current I is equal to the current I_L generated by the photoelectric effect minus the diode current I_D , according to the equation (2.2):

$$I = I_L - I_D = I_L - I_0 \left(e^{\frac{qV}{nkT}} - 1 \right) \dots\dots\dots (2.2)$$

For a real solar cell, the total current in an external circuit is influenced by other factors, including series resistance R_S and shunt resistance R_{SH} . Expanding equation (2.2) the total current I is given by equation (2.3). Figure 2.3 shows an equivalent circuit of a PV cell described by equation (2.3).

$$I = I_L - I_0 \left(e^{\frac{q(V + IR_S)}{nkT}} - 1 \right) - \frac{V + IR_S}{R_{SH}} \dots\dots\dots (2.3)$$

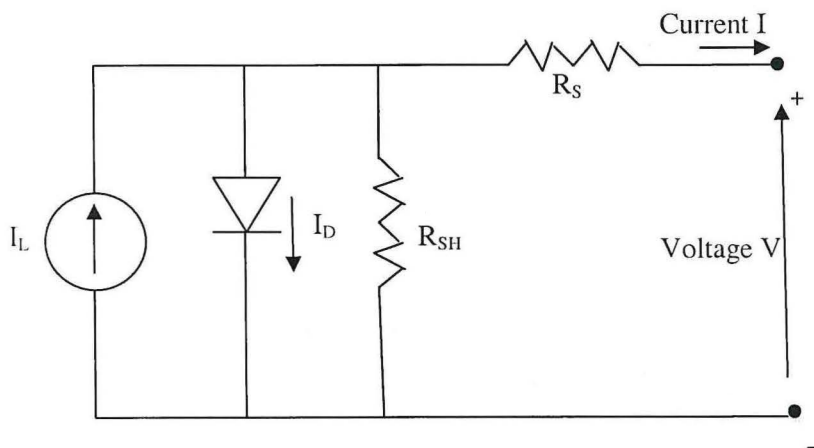


Figure 2.3: Equivalent Circuit of a PV Cell

There are several important parameters which are used to characterize the performance of solar modules. These include short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum power, fill factor (FF) and efficiency (η) parameters. All these are determined from the I-V characterization curve under illumination as discussed below.

2.4.1 Short Circuit Current

The short circuit current I_{sc} corresponds to the condition when the impedance tends to zero and is calculated when the potential difference across the circuit is zero. Short circuit current occurs at the beginning of the forward bias sweep and is the maximum current value in the power quadrant which may be drawn from the solar cell. It is due to the generation and collection of light generated charge carriers. For an ideal cell, this maximum current value is the total current produced in the solar cell by photon excitation. $I_{sc} = I_{max} = I_L$ for forward bias power quadrant.

2.4.2 Open Circuit Voltage

The open circuit voltage, V_{oc} , is the maximum voltage which occurs when there is no current passing through the cell, i.e. V (at $I=0$) = V_{oc} . This 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. $V_{oc} = V_{max}$ for forward bias power quadrant. An equation for V_{oc} is found by setting the net current equal to zero in the solar cell equation to give:

$$V_{oc} = \frac{nkT}{q} \ln \left(\frac{I_L}{I_0} + 1 \right) \dots\dots\dots (2.4)$$

Open circuit voltage depends on the saturation current of the solar cell and the light generated current. While short circuit current 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.

2.2.3 Maximum Power

The power produced by the cell can be easily calculated along the I-V sweep by the product of current and voltage ($P=IV$). At the I_{sc} and V_{oc} points, the power will be zero

and the maximum value for power will occur between the two points. The voltage and current at this maximum power point are denoted as V_{max} and I_{max} respectively.

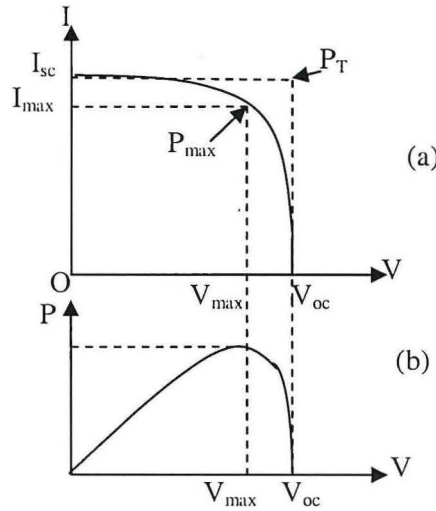


Figure 2.4: Maximum Power for an I-V Sweep

2.4.4 Fill Factor (FF)

The fill factor (FF) is essentially a measure of quality of the solar cell. It is calculated by comparing the maximum power to the theoretical power (P_T) that would be output at both the open circuit voltage and short circuit current together. Fill factor can also be interpreted graphically as the ratio of the areas of rectangle $OV_{max}P_{max}I_{max}$ to rectangle $OV_{oc}P_TI_{sc}$ depicted in Figure 2.4 (a) according to Messenger and Ventre (2000) and is given by equation (2.5).

$$FF = \frac{P_{max}}{P_T} = \frac{V_{max} I_{max}}{V_{oc} I_{sc}} \dots\dots\dots (2.5)$$

A higher voltage will have a higher possible FF. However, large variations in open circuit voltage within a given material system are relatively uncommon. A larger fill factor is desirable, and corresponds to an I-V sweep that is more square-like. Typical fill factors range from 0.5 to 0.82. Fill factor is often expressed as a percentage.

2.4.5 Efficiency (η)

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 use them to compare the performance of one device to another. The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity.

Efficiency is the ratio of the maximum electrical power output, P_{out} , to the solar power input, P_{in} into the PV cell.

$$\eta = \frac{P_{out}}{P_{in}} \Rightarrow \eta_{max} = \frac{P_{max}}{P_{in}} = \frac{V_{oc} I_{sc} FF}{P_{in}} \dots\dots\dots (2.6)$$

Where P_{in} is the total radiation incident on the solar cell.

P_{in} is taken as the product of the irradiance of the incident light, measured in W/m^2 with the surface area of the solar cell in m^2 . Efficiency of a solar cell depends on the maximum output power of the solar cell. Photovoltaic modules are rated by their P_{max} measured under standard test conditions (STC), which means an illumination of $1000W/m^2$, $25^\circ C$ cell temperature at the test, and a spectrum equivalent to Air mass 1.5.

2.4.6 Resistances of the Solar Cell

During operation, the efficiency of solar cells is reduced by the dissipation of power across internal resistances. These parasitic resistances can be modeled as a parallel shunt resistance (R_{SH}) and series resistance (R_S), as shown in Figure 2.3. For an ideal cell, R_{SH} would be infinite and would not provide an alternative path for current to flow, while R_S would be zero, resulting in no further voltage drop before the load. Decreasing R_{SH} and increasing R_S will decrease the fill factor (FF) and P_{max} as cited by Wenham et al. (1995). Shunt resistance affects the I-V curve at higher current levels, and series resistance affects the I-V curve at higher voltage levels. If R_{SH} is decreased too much, V_{oc} will drop, while increasing R_S excessively can cause I_{sc} to drop instead.

According to Schroder (1998), it is possible to approximate the series and shunt resistances, R_S and R_{SH} , as the slopes of the I-V curve at V_{oc} and I_{sc} , respectively.

$$R_s = -\frac{dV}{dI} \text{ at } I = 0 \dots\dots\dots (2.7)$$

and

$$R_{SH} = -\frac{dV}{dI} \text{ at } V = 0 \dots\dots\dots (2.8)$$

The resistance at V_{oc} , however, is at best proportional to the series resistance but it is larger than the series resistance. Shunt resistance is represented by the slope at I_{sc} . Typically, the resistances at I_{sc} and at V_{oc} will be measured and noted.

Two I-V characteristics of a solar cell measured at two different irradiance levels and constant temperature can be used to determine R_s . According to van Dyk et al. (2004), the slope of a line drawn through points corresponding to a fixed current below the respective I_{sc} on each curve gives:

$$R_s = \frac{\Delta V}{\Delta I} \dots\dots\dots (2.9)$$

A high series resistance increases voltage drop and hence the fill factor of a solar cell is reduced. Solar cells having a low shunt resistance cause a reduction in module efficiency according to Meyer (1999). At lower irradiance levels (Schroder, 1998)

$$I_{sc} \approx \frac{V_{oc}}{R_{SH}} \dots\dots\dots (2.10)$$

$\frac{1}{R_{SH}}$ is the slope of I_{sc} versus V_{oc} yielding R_{SH} .

If incident light is prevented from exciting the solar cell, a dark I-V curve is obtained. It follows that R_{SH} can be derived from the I-V plot obtained with or without providing light excitation, even when power is sourced to the cell. It is important to note, however, that for real cells, these resistances are often a function of the light level, and can differ in value between the light and dark tests.

2.5 Effect of Temperature on Solar Cells

An increase in temperature reduces the band gap of a semiconductor, which affects 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. In a solar cell, the parameter most affected by an increase in temperature is the open circuit voltage. The open-circuit voltage decreases with increase in temperature because of the temperature dependence of the saturation current, I_0 .

Many of the electrical parameters have some temperature dependence, with higher voltage solar cells being less affected by temperature. The short circuit current parameters have some temperature dependence, but the most significant effect is due to the intrinsic carrier concentration, n_i . The intrinsic carrier concentration depends on the band gap energy (with lower band gaps giving a higher intrinsic carrier concentration), and on the energy which the carriers have (with higher temperatures giving higher intrinsic carrier concentrations). The temperature sensitivity of a solar cell depends on the open circuit voltage of the solar cell. Short circuit current, I_{sc} , increases slightly with temperature, since the band gap energy, E_G , decreases and more photons have enough energy to create electron-hole (e-h) pairs. However, this is a small effect.

2.5.1 Temperature Measurement Considerations

The crystals used to make PV cells, like all semiconductors, are sensitive to temperature. Figure 2.5 depicts the effect of temperature T on an I-V curve. When a PV cell is exposed to higher temperatures, I_{sc} increases slightly, while V_{oc} decreases more significantly.

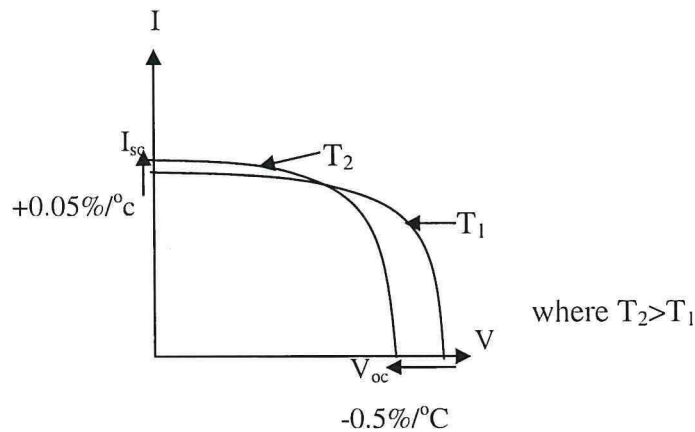


Figure 2.5: Effect of Temperature on I-V Curve

Therefore to get the maximum current output, modules should be mounted so that air can circulate around them freely to keep the cell cool. For a specified set of ambient conditions, higher temperatures result in a decrease in the maximum power output P_{max} . Since the I-V curve will vary according to temperature, it is beneficial to record the conditions under which the I-V sweep was conducted. Temperature can be measured using sensors such as Resistance Temperature Detectors (RTDs), thermistors or thermocouples. I-V curves are usually shown for cell at the temperature of 25°C.

2.6 Effect of Irradiance on Solar Cells

Spectral irradiance F is the most common way of characterizing a light source. It is the rate at which energy at a given wave length reaches a unit area at the earth's surface. The summation of solar irradiance over a given time (such as day, week, month or year) is called solar radiation or irradiance. Irradiance is the amount of sunshine reaching the solar cells at any moment. The irradiance reaching the ground varies throughout the day with the movement of the sun and the clouds. Irradiance is measured in watts per square meter (W/m^2). In a very clear weather at midday (12.p.m), the irradiance reaching a surface that faces the sun is about $1000W/m^2$ which is at 90° to the direction of the sun's rays. This irradiance is called full sun, one sun or AM1 intensity. The spectral irradiance and the photon flux are relevant when analyzing solar cells. The photon flux determines the number of electrons which are generated, and hence the current produced from a solar cell.

The current produced by the module whose position is fixed varies through the day; even when the weather is clear with no clouds. The current-voltage (I-V) curve at irradiance $1000W/m^2$ is for a module that faces the sun directly (at 90° to the direction of the sun's rays). When the sun is exactly over head in tropical countries and low in the sky at an angle of 30° above the horizon, the module should be tilted towards the sun at an angle of 60° from horizontal for maximum current. However modules are usually fixed in one position. Thus they face the sun directly only for a few times in a day. So, when the sun is low in the sky at 30° above the horizon and if the module is fixed horizontally, the irradiance is about half the value of $1000W/m^2$. When the sun is covered by thick clouds, the irradiance could be reduced to $100W/m^2$ or less and the current will be very low.

When the irradiance level increases, the number of generated electron-hole pairs separating and inducing the photogenerated current, increases. Figure 2.6 shows two I-V curves obtained at different irradiance levels, 614W/m^2 and 1000W/m^2 . It can be seen that, I_{sc} is higher at higher irradiance levels since the photogenerated current, I_L depends on the irradiance level. Voltage also depends on the irradiance level, and the relationship between I_{sc} and irradiance, and V_{oc} and irradiance is given by Lorenzo (1994):

$$I_{sc} = xI_{sc,1-sun} \dots\dots\dots (2.11)$$

and

$$V_{oc} = V_{oc,1-sun} + \delta \ln x \dots\dots\dots (2.12)$$

Where I_{-sun} represents an irradiance of 1000 W/m^2 of irradiance, x is the level of irradiance, and δ is a dimensionless coefficient that is solar cell technology specific.

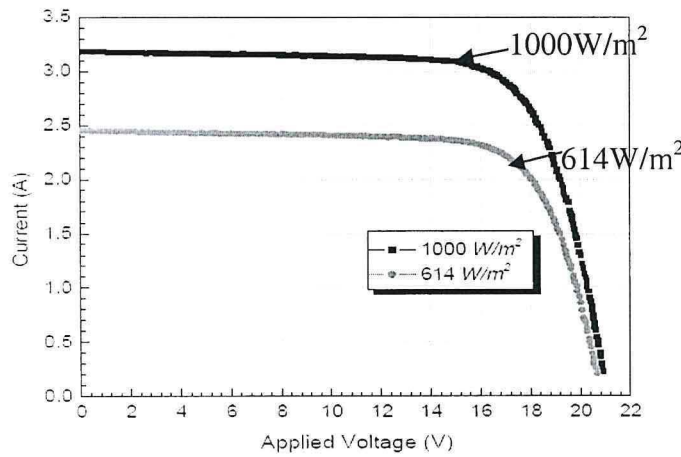


Figure 2.6: I-V Curves obtained at Irradiance levels, 614W/m^2 and 1000W/m^2

2.7 Effect of Shading on Solar Cells

When deciding to install a solar photovoltaic system, the positioning of the solar panels is vital. The solar modules should be orientated such that they face the sun at the time of day when the sun is highest in the sky, but it is also very important to put into consideration the effect of shading on the module. If even a small section of a photovoltaic module is shaded for example by the branch of a tree there will be a very significant drop in power output from the module. This is because a PV module is made

up of a string of individual solar cells connected in series with one another. The current output from the whole module is limited to that passing through the weakest link cell. If one cell (out of for example 36 in the module) is completely shaded, the power output from the module will fall to zero. If one cell is 50% shaded, then the power output from the whole module will fall by 50% which is a very significant drop for such a small area of shading. The shaded cells can also over heat and burn out.

Performance of a series connected string of solar cells is affected if all its cells are not equally illuminated (partially shaded). In a solar array spread over wide area, it is likely that shadow may fall over some of its cells due to tree leaves falling over it, birds or bird litters on the array, shade of a neighbouring construction etc. In a series connected string of cells, all the cells carry the same current. Even though a few cells under shade produce less photon current but these cells are also forced to carry the same current as the other fully illuminated cells. The shaded cells may get reverse biased, acting as loads, draining power from fully illuminated cells. If the system is not appropriately protected, hot-spot problem according to Quaschnig and Hanitsch (1996) can arise and in several cases, the system can be irreversibly damaged. In recent years, the impact of partial shading on the PV array performance has been widely discussed by Herrmann et al. (1997); Kaushika and Gautam (2003); Klenk et al. (2002); Woyte et al. (2003)

2.8 Effect of Dusting on Solar Cells

Accumulation of dust from the outdoor environment on the panels of solar photovoltaic (PV) system is natural. Several studies which were performed showed that the accumulation of dust on the solar panels can reduce on their performance in terms of efficiency as cited by Moon (2009) and Karz (2008). It was found from the study that the accumulated dust on the surface of photovoltaic solar panel can reduce the system's efficiency by up to 50%. Theoretically, dirt accumulates on top of the flat panels, whereas rain washes away most dirt on the tilted ones and leaves some accumulation in the corners.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Introduction

In this chapter, I-V characteristic measurements used to determine electrical performance parameters of the CIGS modules were discussed.

3.2 Research Design

The study was experimentally carried out. A variable load resistor was connected to the CIGS module and was varied in progressive steps from minimum (0Ω) to maximum (100Ω). The corresponding current and voltage were measured. The current-voltage (I-V) curves were then plotted and were used to obtain the main electrical parameters. The electrical parameters were short circuit current I_{sc} , open circuit voltage V_{oc} , maximum power P_{max} , fill factor FF and efficiency of the module. The value of I_{sc} and V_{oc} were obtained by extrapolating the I-V curve. The influence of temperature, irradiance, shading and dusting on the performance of the CIGS solar module were also determined. The design was limited to only one CIGS module. The module had a power rating of 15W

3.3 Experimental Measurements

For easy measurement of variables, a Data Acquisition system (DAQ) card was used in the system. The DAQ was connected to the computer in which a Labview programme was installed to record the I-V data, electrical performance parameters and irradiance. Other parameters which were measured and fed into the computer included module temperature, ambient temperature, module length and area. The time at which the measurements were performed and the module type were also fed into the computer. All these measurements were recorded using the Labview programme which was installed in the computer as shown in Appendix A.

3.3.1 Current-Voltage Measurements

A variable resistor was used as load to characterize the CIGS solar module. The circuit is as shown in Figure 3.1.

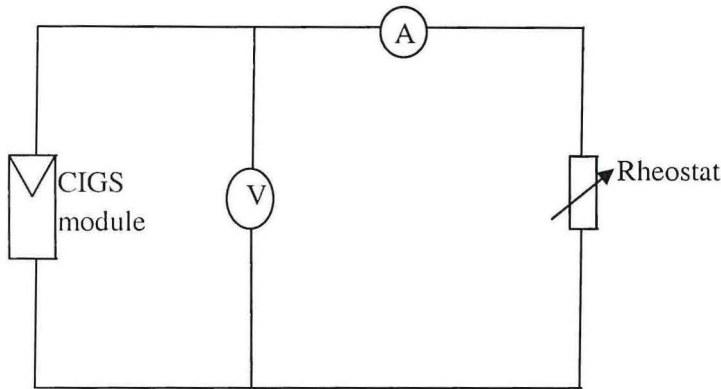


Figure 3.1: Circuit diagram for I-V Curve Measurements of CIGS Module

A Labview programme was used to trace the I-V characteristics of the CIGS solar module. A variable load resistor (rheostat) was used to determine the I-V data of the CIGS solar module. The rheostat was connected to the CIGS module output when exposed to solar irradiance (when placed outdoors) while the module was placed at a zenith angle of 0° . The I-V tracing programme was run and immediately the rheostat was varied uniformly from minimum (0Ω) to maximum (100Ω) by sliding its contact slowly. When the programme was stopped the data for the I-V and the electrical parameters were saved in the computer. When the sliding contact of the rheostat is at minimum position, the resistance value is approximately zero and the current value is maximum and equals the short circuit current I_{sc} and the voltage is zero. When the sliding contact reaches the maximum position, the resistance value is maximum. Here the current value drops to zero while the voltage value becomes maximum and is equal to the open circuit voltage V_{oc} . The current-voltage measurements were performed from morning to evening on clear sky days for an interval of about 15 minutes for good temporal resolution and throughout the day in order to investigate the effects of temperature and irradiance on the performance on the module. A plot of current against voltage gives the I-V characteristics of the CIGS solar module.

The saved I-V data was then fitted using the I-V fitting Labview programme as shown in Appendix B. I-V fitting was done in order to get a clear I-V graph (extrapolate the short circuit current and open circuit voltage).

The CIGS module was first used when clean and the corresponding measurements were made. Measurements were taken from 9:00am to 6:00pm for four days. Several measurements of I-V data were obtained on each day.

3.3.2 Temperature Measurements

Temperature was measured by using of a thermocouple (K-type). This was used to measure both the CIGS module back temperature and the ambient temperature (temperature of the surrounding). A thermocouple was attached at the back of the CIGS module using cellotape and the module was plugged into a multimeter from which the module temperature was read and recorded in the computer. The ambient temperature was also read from a multimeter and recorded in the computer in the Labview programme.

3.3.3 Irradiance Measurements

Irradiance was measured using an Apogee Logan UT Pyranometer. The pyranometer was connected to the DAQ system which was connected to the computer. The irradiance was recorded and displayed together with other electrical parameters using the Labview programme.

3.3.4 Performance Measurements on Shaded CIGS Solar Module

A ply wood of thickness 1mm was placed at a distance of 1m above the CIGS module covering a small area of 20% of the surface area of the module. This was put at different points on the upper surface of the CIGS module; first at the corners and then in the center. This was done in order to provide a partial shade to the module. The corresponding measurements were made at each point. This was done for two days from 9:00am to 5:00pm.

The ply wood was then placed at a distance of 1m above the module covering the whole module in order to provide a complete shade on the module. The corresponding measurements were made. This was done from 9:00am to 5:00pm for one day.

3.3.5 Performance Measurements on Dusted CIGS Solar Module

A thin layer of fine soil was uniformly spread all over the upper surface of the CIGS solar module to a thickness of about 1mm. The thickness was estimated by use of a dip wire and a vernier caliper. The corresponding I-V measurements were made. This was done from 9:00am to 5:00pm for one day.

A thicker layer of fine soil of thickness of about 2mm was also uniformly spread all over the upper surface of the CIGS solar module and the corresponding measurements were made. This was done from 9:00am to 5:00pm for one day.

3.4 Data Analysis

After varying the variable resistor, the Labview programme captured and recorded the I-V data and irradiance. The module and ambient temperatures, length and width of the module were fed into the programme and were also recorded in the Labview programme.

The I-V data input was used by the Labview program to work out the electrical parameters of short circuit current, open circuit voltage, maximum current and voltage, maximum power, and fill factor. The area of the module was also worked out and recorded.

The data obtained was the measured data. This was done when the CIGS module was clean, shaded and dusted. The measured data was copied from the Labview program and pasted in Ms-Excel programme and tabulated. The efficiency of each set of data was calculated and recorded using equation (3.1):

$$\eta = \frac{P_{\max}}{A \times I} \times 100 \dots\dots\dots (3.1)$$

where A is the area of the module and I is the irradiance.

Averages of each day for the data were calculated and the overall average for the days were also calculated when the module was clean, shaded and dusted.

The measured current-voltage data was then analysed using I-V fit programme in the Labview programme in Appendix B. The corresponding electrical parameters were obtained for each I-V data using I-V fit Labview programme. The data was then tabulated using Ms-Excel programme. The efficiency of each set of data was calculated and

recorded. Averages of each day for the data recorded were calculated and the overall average for the days were also calculated when the module was clean, shaded and dusted. The current-voltage curves for the I-V data from I-V fit measurements were plotted using Ms-Excel.

To obtain the electrical parameters at standard condition (STC), the fitted I-V values were normalized.

Normalization of module current to the standard condition was performed according to Equation (3.2) (Chamberlin, et al., 1995):

$$I_{std} = \frac{G_{std}}{G} I_{measured} \dots\dots\dots (3.2)$$

where; I_{std} is the current of the module at the standard condition (normalized current), G_{std} is the standard irradiance (irradiance at STC is 1000W/m²), G is the solar irradiance on the plane of the module and $I_{measured}$ is the measured current of the module.

Normalization of module voltage was performed according to Equation (3.3) (Chamberlin, et al., 1995):

$$V_{std} = V_{measured} (1 + \beta(T_{std} - T_{cel})) \dots\dots\dots (3.3)$$

where V_{std} is the voltage of the module in the standard condition (normalized voltage), $V_{measured}$ is the measured voltage of the module, β is the temperature coefficient of the voltage of a PV cell, T_{std} is the standard cell temperature (temperature at STC is 25°C) and T_{cel} is the temperature of the module.

The temperature coefficient of the voltage, β is the fraction of the voltage lost per degree temperature rise for the module. The temperature coefficient was obtained by exposing the module to solar irradiance. A thermocouple was attached at the back of the CIGS module using a cellotape and then connected to a multimeter to measure the module temperature. The output of the module was connected to a multimeter to measure V_{oc} . The module temperature and V_{oc} measurements were taken simultaneously at different temperatures. The temperature coefficient was calculated using equation (3.4) (Kullmann, 2009)

$$\beta = \left(\frac{V_{oc_i} - V_{oc_f}}{T_i - T_f} \right) / V_{oc_{av}} \dots\dots\dots (3.4)$$

$\left(\frac{V_{oc_i} - V_{oc_f}}{T_i - T_f} \right)$ is the slope S of the graph of V_{oc} against temperature of the module.

where; V_{oc_i} is initial open circuit voltage, V_{oc_f} is final circuit voltage, $V_{oc_{av}}$ is average open circuit voltage, T_i is initial temperature and T_f is final temperature.

$S = -0.0727V/^{\circ}C$, $V_{oc_{av}} = 15.5381V$, therefore $\beta = -0.0047/^{\circ}C$

The normalized current and voltage data were then plotted using Ms-Excel from which the performance parameters were obtained. The efficiency was calculated and then compared with the rated value of the CIGS module.

Graphs showing the variation of electrical parameters (I_{sc} , V_{oc} , P_{max} , FF and η) on temperature and irradiance were also plotted.

CHAPTER FOUR: RESULTS OF THE STUDY

4.1 Introduction

The results of this study basically focused on the performance parameters of the CIGS solar module. The performance parameters were also determined under the effect of temperature, irradiance, shading and dusting on the CIGS solar module.

4.2 Electrical Performance Parameters of the CIGS Solar Module

The results of the performance of the CIGS module were based on a CIGS module of area 62cmx30cm whose cells were manufactured in United States of America and assembled in India. The current-voltage characteristic measurements were captured using the Data Acquisition system and the Labview programme was used to process and display the electrical parameters.

4.2.1 Performance Parameters for Measured Data

The performance parameters for the measured data for a clean CIGS module from each set of I-V characteristic measurements captured were obtained from the Labview programme. The averages for each set of data obtained and the overall average for the four days were as shown in table 4.1 below.

Table 4.1: Performance Parameters of clean CIGS Module using Measured Data

Date	Electrical Parameters				
	$I_{sc}(A)$	$V_{oc}(V)$	$P_{max}(W)$	FF	η (%)
09 th -Dec-2012	0.584	15.559	8.178	0.90	8.2
10 th -Dec-2012	0.459	14.166	5.787	0.89	7.3
11 th -Dec-2012	0.310	14.837	4.328	0.941	7.1
12 th -Dec-2012	0.828	15.889	12.656	0.962	8.5
Overall average	0.545	15.113	7.737	0.939	7.8

The electrical parameters kept on varying on the different days. This was because the temperature and irradiance kept on varying on each day.

4.2.2 Performance Parameters for Fitted Data

The Performance parameters for the fitted I-V data for a clean CIGS module were obtained after fitting the measured data using I-V fitting Labview programme shown in Appendix B. The averages for each set of fitted data obtained and the overall average for the four days were as shown in tables 4.2 below.

Table 4.2: Performance Parameters of clean CIGS Module using Fitted Data

Date	Electrical Parameters				
	$I_{sc}(A)$	$V_{oc}(V)$	$P_{max}(W)$	FF	η (%)
09 th -Dec-2012	0.577	16.766	5.398	0.528	6.3
10 th -Dec-2012	0.509	15.823	5.301	0.658	6.2
11 th -Dec-2012	0.383	19.027	4.609	0.613	5.2
12 th -Dec-2012	0.867	19.603	7.404	0.446	7.5
Overall average	0.584	17.805	5.678	0.561	6.3

After fitting the I-V data, the electrical parameters still kept on varying on the different days but slightly different from the measured data. This was because the fitted I-V data gave the exact short circuit current and open circuit voltage after extrapolating the I-V data.

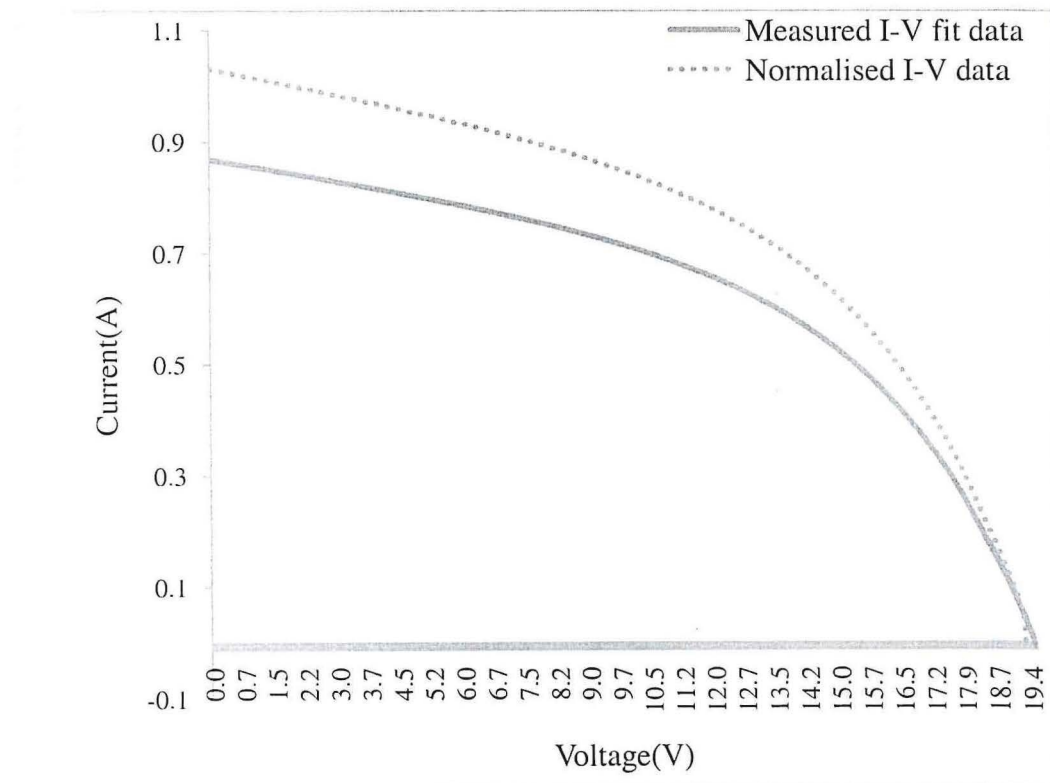
4.2.3 Normalisation of I-V data at Standard Condition (STC)

The I-V data were normalized using equation (3.2) and (3.3). The normalized data were then plotted to generate I-V characteristics curve from which electrical parameters were obtained. These parameters were compared to the rated parameters.

Table 4.3: Rated and Measured Values of Performance Parameters of CIGS Module

	$I_{sc}(A)$	$V_{oc}(V)$	$I_{max}(A)$	$V_{max}(V)$	$P_{max}(W)$	FF	η (%)
Rated Value	1.05	30.00	0.81	18.5	15.0	0.48	8.1
Measured Normalised value	1.03	19.25	0.71	13.4	9.5	0.48	6.1

The short circuit current reduced by 1.9% from the rated value. The open circuit voltage reduced by 35.8% from the rated value. The maximum current reduced by 12.3% from the rated value. The maximum voltage reduced by 37.9% from the rated value. The maximum power reduced by 36.7%. There was no change in the fill factor. The efficiency reduced by 24.7% from the rated value. Figure 4.1 shows an I-V characteristic curve of a CIGS solar module before being normalized and after being normalized.

**Figure 4.1:** I-V Characteristic for a clean CIGS Module using I-V fit Data

There was an increase in short circuit current in the normalized data by 0.12% and a reduction in the open circuit voltage in the normalized data by 0.01%.

4.3 Effect of Temperature on the Performance Parameters of CIGS Solar Module

Each of the five performance parameters were investigated with reference to temperature and graphs showing variation of each parameter with temperature were plotted.

The first parameter investigated was short circuit current. A graph showing variation of short circuit current with module temperature was plotted as shown in figure 4.2.

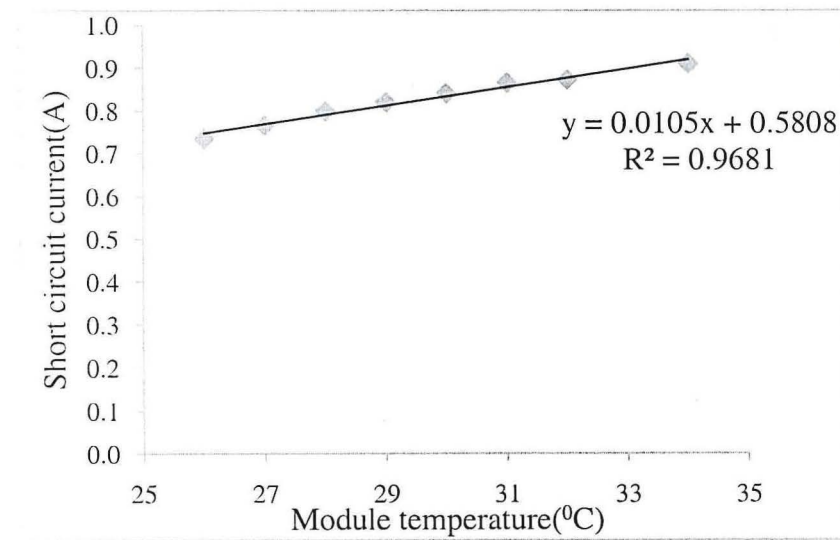


Figure 4.2: Graph of Short Circuit Current against Module temperature

The figure shows that short circuit current increases linearly with module temperature. It increases at a rate of 0.04% with module temperature.

The second parameter investigated was open circuit voltage. A graph showing variation of open circuit voltage with module temperature was plotted as shown in figure 4.3.

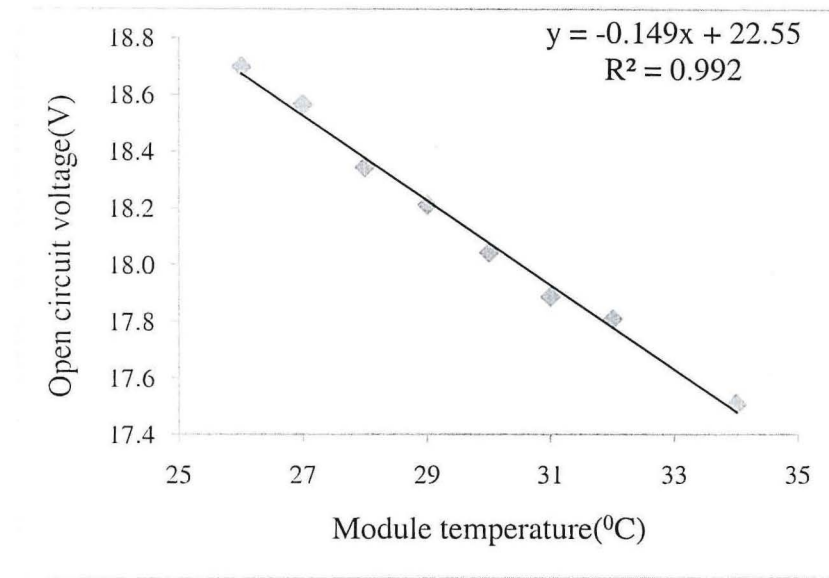


Figure 4.3: Graph of Open Circuit Voltage against Module temperature

The figure shows that open circuit voltage decreases linearly with module temperature. It decreases at a rate of 0.4% with module temperature.

The third parameter investigated was maximum power. A graph showing variation of maximum power with module temperature was plotted as shown in figure 4.4.

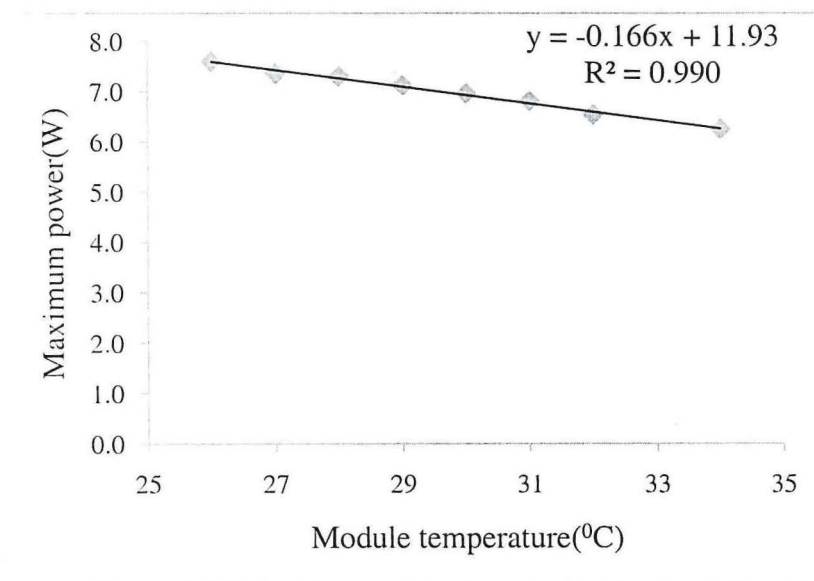


Figure 4.4: Graph of Maximum Power against Module temperature

The figure shows that maximum power decreases linearly with module temperature. The power produced by PV cells is the product of current and voltage. Because the drop in voltage is greater than the increase in current, the net effect of an increase in module temperature is a drop in power production. Maximum power decreases at a rate of 0.2% with module temperature. Solar cells work best at low temperatures.

The fourth parameter investigated was fill factor. A graph showing variation of fill factor with module temperature was plotted as shown in figure 4.5.

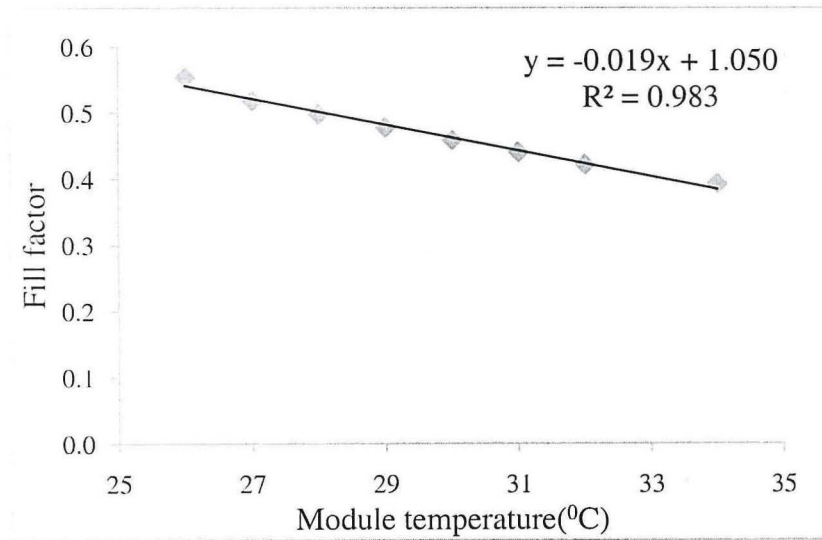


Figure 4.5: Graph of Fill factor against Module temperature

The figure shows that fill factor decreases linearly with module temperature. It decreases at a rate of 0.2% with module temperature.

The fifth parameter investigated was efficiency. A graph showing variation of efficiency with module temperature was plotted as shown in figure 4.6.

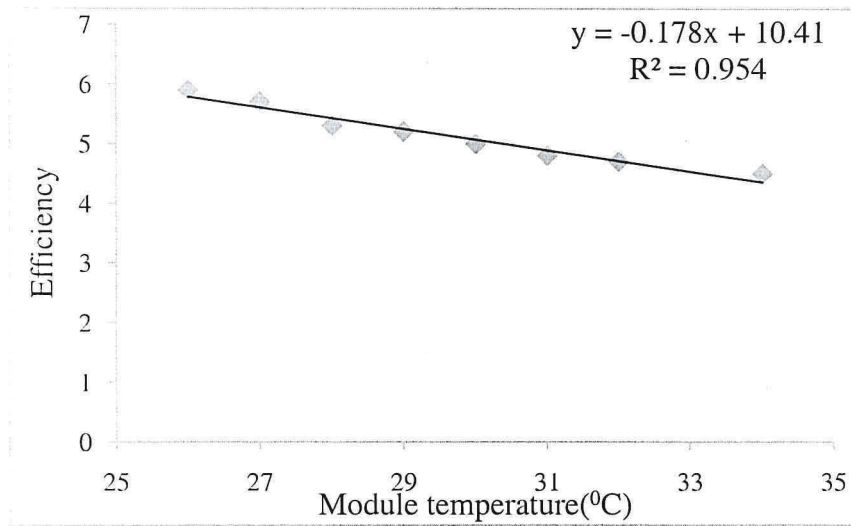


Figure 4.6: Graph of Efficiency against Module temperature

The figure shows that efficiency decreases linearly with module temperature. It decreases at a rate of 0.2% with module temperature.

4.4 Effect of Irradiance on the Performance Parameters of CIGS Solar Module

When PV modules are deployed outdoors, their I-V characteristics change due to the continual changing of irradiance levels. The irradiance levels affect the electrical performance parameters of the modules. A typical clear sky solar noon value of irradiance falling on the surface of the earth at sea level is 1000W/m^2 . At higher elevations less air is between the surface and the sun and the range of irradiance values is higher than at sea level. In this study irradiance values were less than 1000W/m^2 because the study was carried out at a lower elevation. Each of the five performance parameters were investigated with reference to irradiance and graphs showing variation of each parameter with irradiance were plotted.

The first parameter investigated was short circuit current. A graph showing variation of short circuit current with irradiance was plotted as shown in figure 4.7.

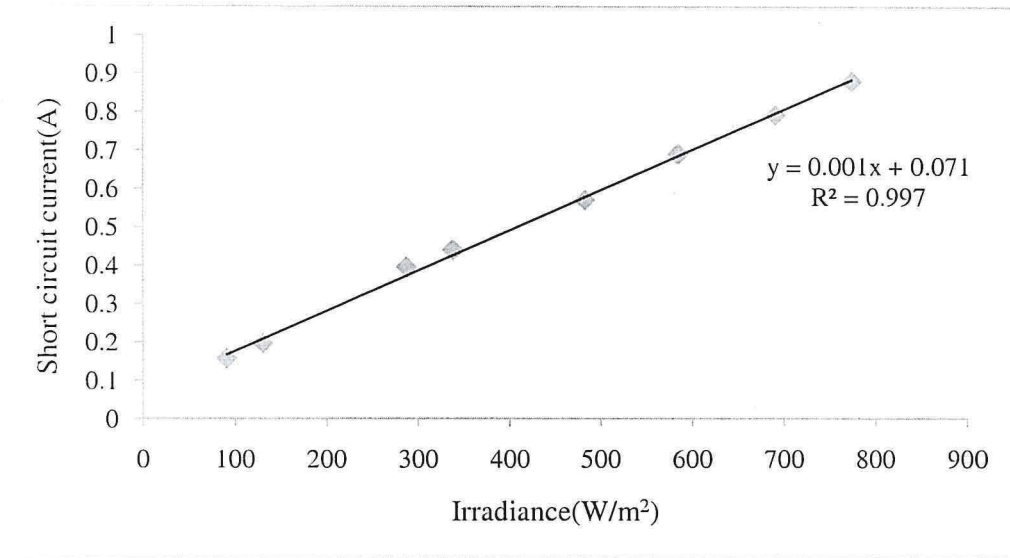


Figure 4.7: Graph of Short Circuit Current against Irradiance

The figure shows that short circuit current increases linearly with irradiance. It increases at a rate of 0.4% with irradiance.

The second parameter investigated was open circuit voltage. A graph showing variation of open circuit voltage with irradiance was plotted as shown in figure 4.8.

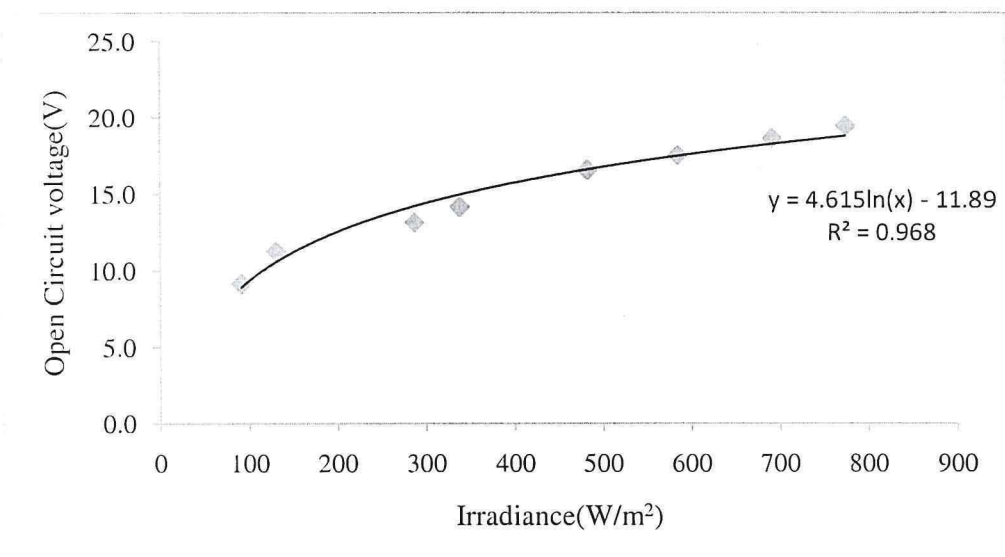


Figure 4.8: Graph of Open Circuit Voltage against Irradiance

The figure shows that open circuit voltage increases logarithmically with irradiance. It increases at a rate of 0.04% with irradiance.

The third parameter investigated was maximum power. A graph showing variation of maximum power with irradiance was plotted as shown in figure 4.9.

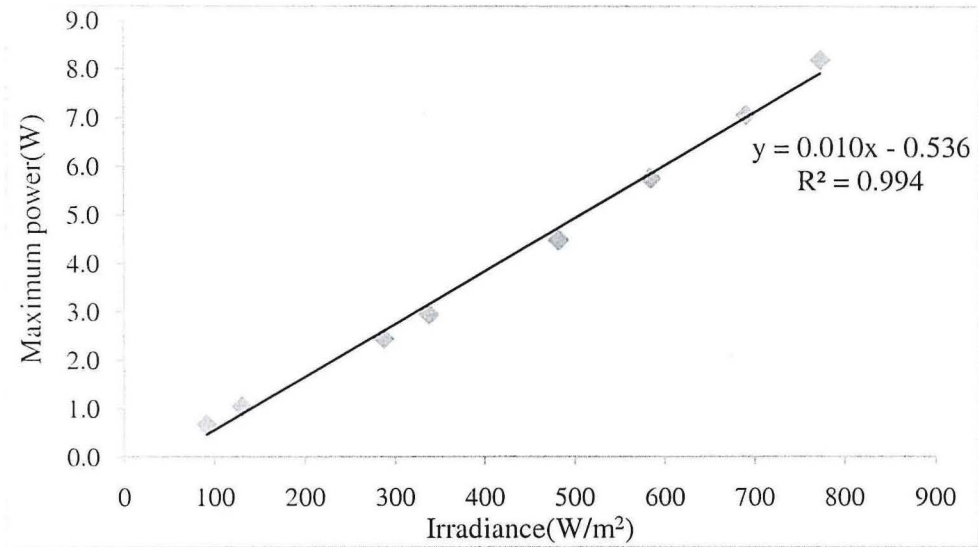


Figure 4.9: Graph of Maximum Power against Irradiance

The figure shows that maximum power increases linearly with irradiance. The power produced by PV cells is the product of current and voltage. Because of this relationship, the net effect of an increase in irradiance is an increase in power production. Maximum power increases at a rate of 0.6% with irradiance. Solar cells work best with high levels of irradiance.

The fourth parameter investigated was fill factor. A graph showing variation of fill factor with irradiance was plotted as shown in figure 4.10.

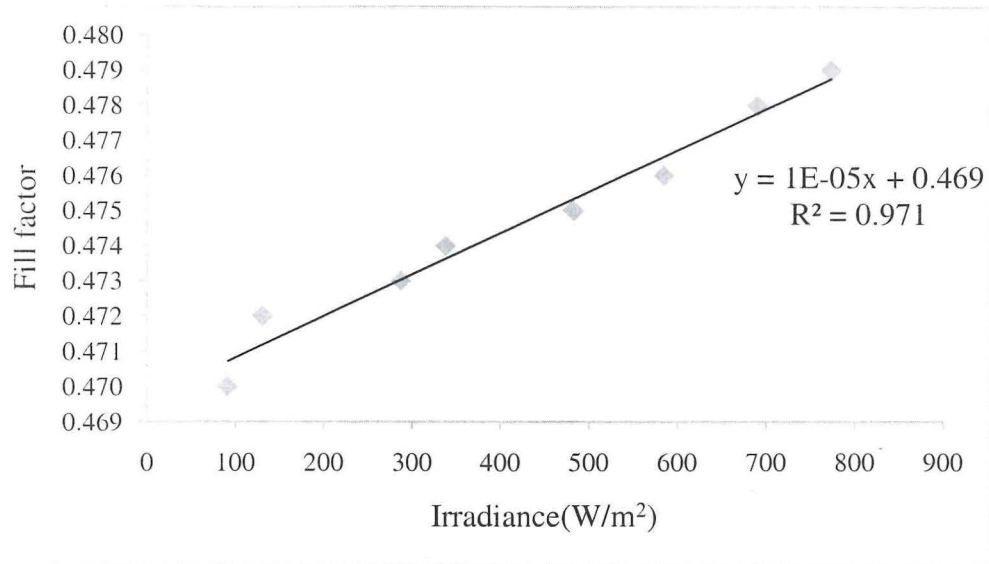


Figure 4.10: Graph of Fill factor against Irradiance

The figure shows that fill factor increases linearly with irradiance. It increases at rate of 0.5% with irradiance.

The fifth parameter investigated was efficiency. A graph showing variation of efficiency with irradiance was plotted as shown in figure 4.11.

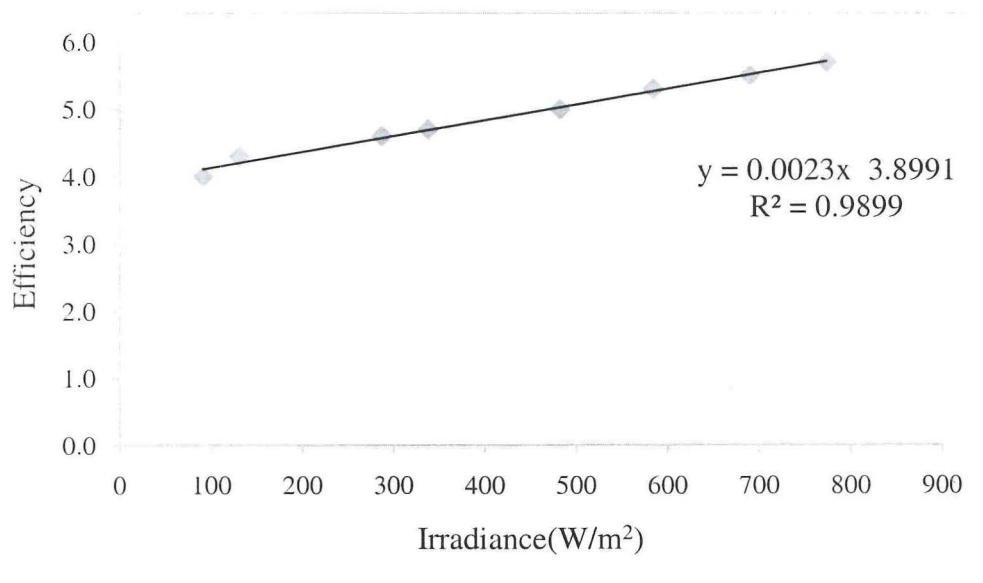


Figure 4.11: Graph of Efficiency against Irradiance

The figure shows that efficiency increases linearly with irradiance. It increases at rate of 0.5% with irradiance.

4.5 Effect of Shading on the Performance Parameters of CIGS Solar Module

The performance parameters for measured data for a partially and completely shaded CIGS module from each set of I-V characteristic measurements captured were obtained from the Labview programme. The averages for each set of data obtained are as shown in table 4.4 below.

Table 4.4: Performance Parameters of Shaded CIGS Module

	$I_{sc}(A)$	$V_{oc}(V)$	$P_{max}(W)$	FF	η (%)
Clear CIGS module	0.882	15.773	13.905	0.999	8.9
Partial shading	0.117	4.591	0.537	0.998	0.0
Complete shading	0.026	0.075	0.003	0.997	0.0

Table 4.4 shows that short circuit current reduced by 86.7% with partial shading and by 97.1% with complete shading. Open circuit voltage reduced by 70.9% with partial shading and by 99.5% with complete shading. Maximum power reduced by 96.1% with partial shading and by 100% with complete shading. Fill factor reduced by 0.1% with partial shading and by 0.2% with complete shading. Efficiency reduced by 100% with both partial and complete shading.

The Performance parameters for the fitted I-V data for a partially and completely shaded CIGS module were obtained after fitting the measured data using I-V fitting Labview programme in Appendix B. The averages for each set of fitted data obtained are as shown in table 4.5 below. The I-V graph showing the effect of shading on the CIGS module was plotted as shown in figure 4.12.

Table 4.5: Performance Parameters of Shaded CIGS Module using I-V fit data

	$I_{sc}(A)$	$V_{oc}(V)$	$P_{max}(W)$	FF	η (%)
Clear module	0.867	19.437	8.095	0.480	5.2
Partial shading	0.131	7.962	0.700	0.467	0.1
Complete shading	0.026	3.206	0.037	0.444	0.0

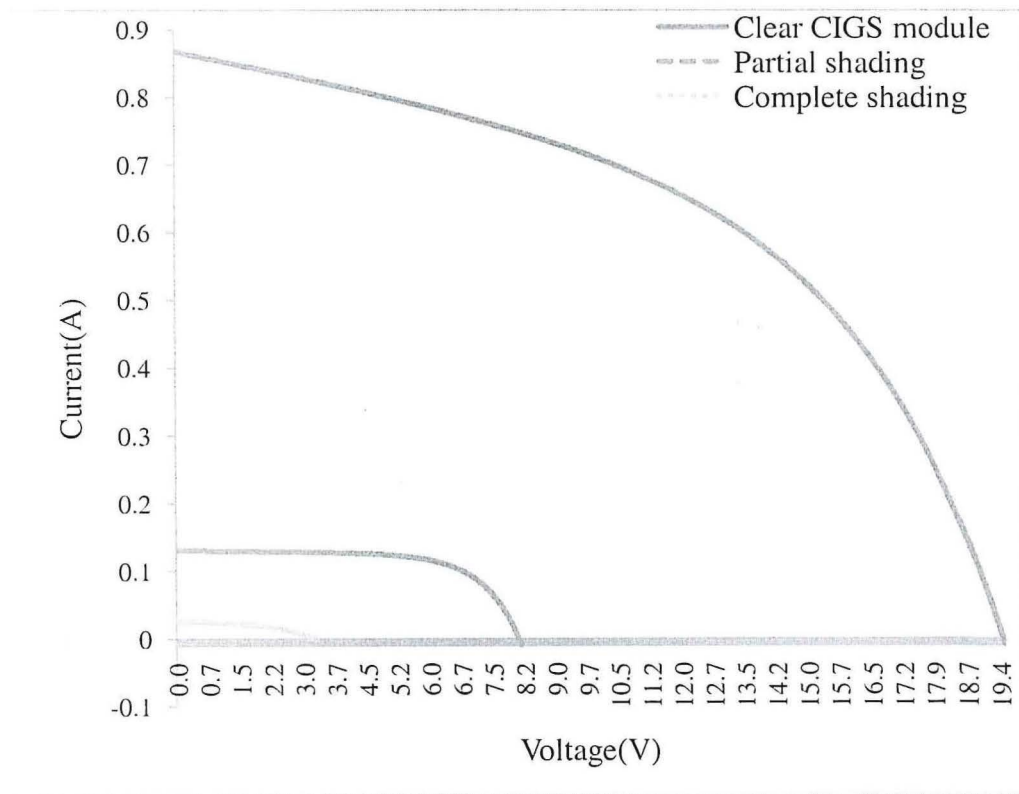
**Figure 4.12:** I-V Characteristic Curve of Shaded CIGS Solar Module

Figure 4.12 shows that current and voltage decreased with shading. The short circuit current dropped from 0.867A to 0.131A with partial shading and to 0.026A with complete shading. The open circuit voltage dropped from 19.437V to 7.962V with partial shading and to 3.206V with complete shading.

4.6 Effect of Dusting on the Performance Parameters of CIGS Solar Module

The performance parameters for measured data for a 1mm layer dusted and a 2mm layer dusted CIGS module from each set of I-V characteristic measurements captured were

obtained from the Labview programme. The averages for each set of data obtained are as shown in table 4.6 below.

Table 4.6: Performance Parameters of Dusted CIGS Module

	$I_{sc}(A)$	$V_{oc}(V)$	$P_{max}(W)$	FF	η (%)
Clear CIGS module	0.882	15.773	13.905	0.999	8.9
1mm layer of dust	0.674	14.350	9.648	0.998	6.0
2mm layer Of dust	0.054	0.004	0.000	0.997	0.0

Table 4.6 shows that short circuit current reduced by 23.6% with 1mm dusting and by 93.9% with 2mm dusting. Open circuit voltage reduced by 9% with 1mm dusting and by 100% with 2mm dusting. Maximum power reduced by 30.6% with 1mm dusting and by 100% with 2mm dusting. Fill factor reduced by 0.1% with 1mm dusting and by 0.2% with 2mm dusting. Efficiency reduced by 32.6% with 1mm dusting and by 100% with 2mm dusting.

The Performance parameters for the fitted I-V data for a 1mm layer dusted and a 2mm layer dusted CIGS module were obtained after fitting the measured data using I-V fitting Labview programme. The averages for each set of fitted data obtained are as shown in tables 4.7 below. The I-V graph showing the effect of dusting on the CIGS module was plotted as shown in figure 4.13.

Table 4.7: Performance Parameters of Dusted CIGS Module from I-V fit I-V Data

	$I_{sc}(A)$	$V_{oc}(V)$	$P_{max}(W)$	FF	η (%)
Clear module	0.867	19.437	8.095	0.480	5.2
1mm layer of dust	0.664	16.327	6.061	0.469	3.0
2mm layer Of dust	0.026	0.822	0.007	0.454	0.0

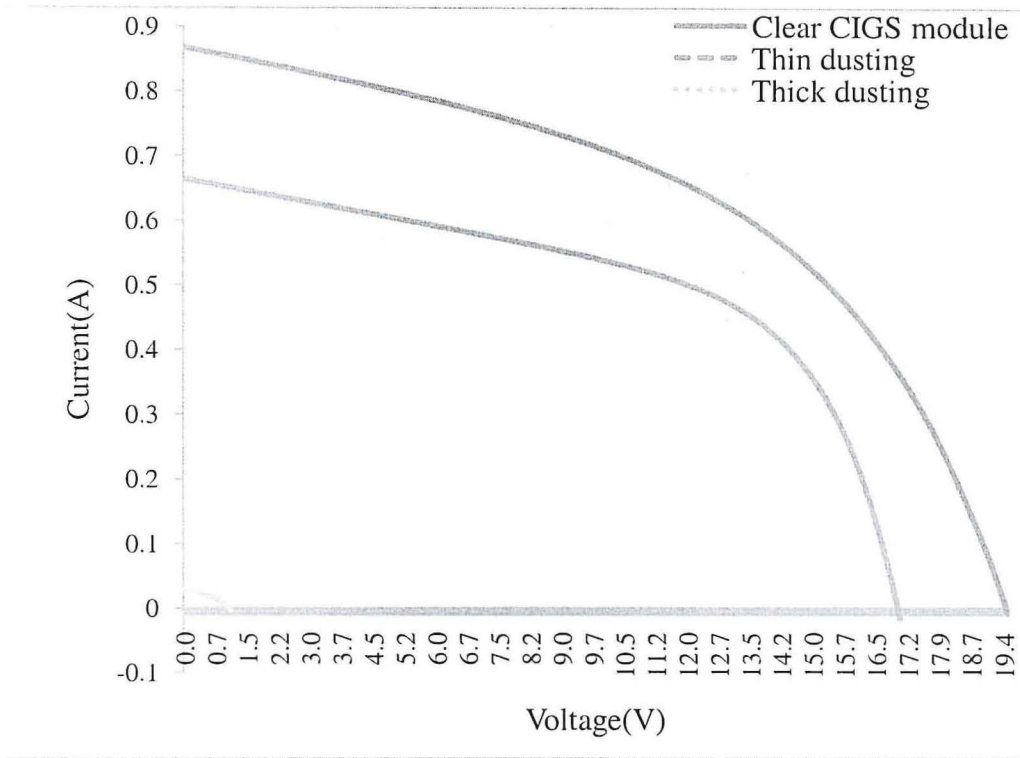


Figure 4.13: I-V Characteristic Curve of Dusted CIGS Solar Module

Figure 4.13 shows that current and voltage decrease with dusting. There is a small decrease in current and voltage with a 1mm layer of dust but a very big decrease in current and voltage with a 2mm layer of dust. The short circuit current dropped from 0.867A to 0.664A with a 1mm layer of dust and to 0.026A with a 2mm layer of dust. The open circuit voltage dropped from 19.437V to 16.327V with a 1mm layer of dust and to 0.822V with a 2mm layer of dust.

CHAPTER FIVE: DISCUSSION OF RESULTS, CONCLUSIONS AND RECOMMENDATIONS

5.1 Discussion of Results

5.1.1 Electrical Performance Parameters of the CIGS Solar Module

The electrical parameters were obtained. The short circuit current was found to be 1.03A and was less by 0.02A from the rated value of 1.05A, a reduction of 1.9%. The open circuit voltage was found to be 19.25V and was less by 10.75V from the rated value of 30V, a reduction of 35.8%. The maximum current was found to be 0.71A and was less by 0.101A from the rated value of 0.81A, a reduction of 12.3%. The maximum voltage was found to be 13.4V and was less by 5.1V from the rated value of 18.5V, a reduction of 37.9%. The maximum power was found to be 9.5W and was less by 5.5W from the rated value of 15W, a reduction of 36.7%. There was no change in the fill factor. The efficiency was found to be 6.1% and was less by 2 from the rated value of 8.1% a reduction of 24.7%.

The results obtained in this study show that out of the seven parameters it was only the fill factor which had the same value with the rated value. The short circuit current was close to the rated value while other parameters were significantly lower than the rated value varying between 12.3% and 37.9%.

5.1.2 Effect of Temperature on the Performance Parameters of CIGS Solar Module

Short circuit current increases slightly and linearly with module temperature. Open circuit voltage decreases greatly and linearly with module temperature. Maximum power decreases linearly with module temperature. The power produced by PV cells is the product of current and voltage. Because the drop in voltage is greater than the increase in current, the net effect of an increase in module temperature is a drop in power production. Fill factor and efficiency also decrease linearly with increase in module temperature.

5.1.3 Effect of Irradiance on the Performance Parameters of CIGS Solar Module

Short circuit current increases greatly and linearly with irradiance. Open circuit voltage increases slightly and logarithmically with irradiance. Maximum power increases linearly with irradiance. The power produced by PV cells is the product of current and voltage.

Because of this relationship, the net effect of an increase in irradiance is an increase in power production. Fill factor and efficiency also increase linearly with irradiance.

5.1.4 Effect of Shading on the Performance Parameters of CIGS Solar Module

Short circuit current reduced by 85% with partial shading and by 97% with complete shading. Open circuit voltage reduced by 59% with partial shading and by 84% with complete shading. Maximum power reduced by 91% with partial shading and by 99.5% with complete shading. Fill factor reduced by 2.7% with partial shading and by 7.5% with complete shading. Efficiency reduced by 98% with partial shading and by 100% with complete shading.

The results in this study show that out of the five performance parameters, efficiency reduced more by shading followed by maximum power followed by short circuit current and then open circuit voltage. There was less reduction in fill factor.

5.1.5 Effect of Dusting on the Performance Parameters of CIGS Solar Module

Short circuit current reduced by 23% with 1mm dusting and by 97% with 2mm dusting. Open circuit voltage reduced by 16% with 1mm dusting and by 96% with 2mm dusting. Maximum power reduced by 25% with 1mm dusting and by 99.9% with 2mm dusting. Fill factor reduced by 2% with 1mm dusting and by 5% with 2mm dusting. Efficiency reduced by 42% with 1mm dusting and by 100% with 2mm dusting.

The results in this study show there is less reduction in the performance parameters of the CIGS module with 1mm dusting and a greater reduction in the performance parameters of the module with 2mm dusting. Out of the five performance parameters, efficiency reduced more by dusting followed by maximum power followed by short circuit current and then open circuit voltage. There was less reduction in fill factor.

5.2 Conclusions

The results obtained in this study proved that I-V characteristics of a CIGS module can predict the device performance when put outdoors. The study also shows that I-V characteristics of a CIGS solar module can be regarded as a useful tool for better understanding of the device parameters. It also revealed that the CIGS solar module can

perform well in the Ugandan climate since there was little diversion of the measured values from the rated values.

The study revealed that short circuit current increases linearly with module temperature. Since it increases slightly with module temperature, the variation can be considered negligible in PV designs. Open circuit voltage decreases linearly with module temperature. It decreases greatly with module temperature. Maximum power decreases linearly with module temperature. The power produced by PV cells is the product of current and voltage. Because the drop in voltage is greater than the increase in current, the net effect of an increase in module temperature is a drop in power production. Solar cells work best at low temperatures. Fill factor and efficiency also decrease linearly with module temperature.

The study also revealed that short circuit current increases linearly with irradiance. Short circuit current is directly proportional to irradiance. Open circuit voltage increases logarithmically with irradiance. The effect of irradiance on voltage is so small that it is negligible. Maximum power increases linearly with irradiance. The power produced by PV cells is the product of current and voltage. Because of this relationship, the net effect of an increase in irradiance is an increase in power production. Solar cells work best with high levels of irradiance. Fill factor and efficiency also increase linearly with irradiance.

The study also revealed that the electrical performance parameters of the CIGS solar module are greatly affected by both partial and complete shading hence affecting on the performance of the CIGS module. The maximum power of the CIGS module reduced by 91% with partial shading and by 99.5% with complete shading. The efficiency reduced by 98% with partial shading and by 100% with complete shading.

Finally the study revealed that when a thin layer of dust goes on the CIGS module very small current and voltage passes through the module. There is reduction in the power output and efficiency of the solar module and therefore a reduction in its performance. When a 1mm layer of dust was put on the CIGS module, the maximum power reduced by 25% and the efficiency by 42%. When a thick layer of dust goes on the CIGS module very little or no current and voltage goes through the module. This reduces the power output and efficiency of the module and therefore a great reduction in its performance.

When a 2mm layer of dust was put on the CIGS module, the maximum power reduced by 99.9% and the efficiency by 100%.

5.3 Recommendations

Basing on the findings of this study, it is recommended that a further study should be done over a longer period of time for example a year in both dry and wet seasons to cross check the reliability of the findings of this study.

The results of this study will be useful to compare the performance of this type of module with others in the market to find out if they would give similar values.

Current-voltage (I-V) characteristics measurements under the dark should also be considered to determine the performance of the CIGS solar modules. This would determine other electrical parameters such as series resistance, shunt resistance and diode parameters (ideality factor and reverse saturation current).

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APPENDICES

APPENDIX A

SCREEN VIEW IN LABVIEW PROGRAMME FOR I-V TRACING

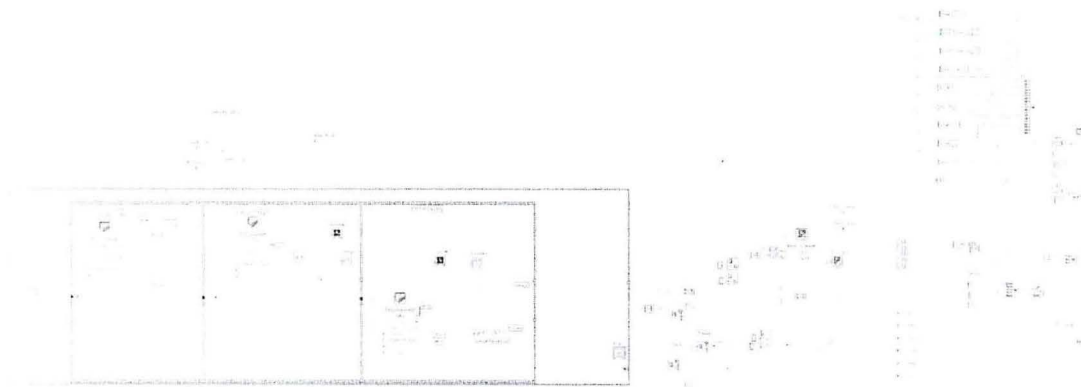


Figure A1: Circuit diagram in Labview Programme for I-V Tracing

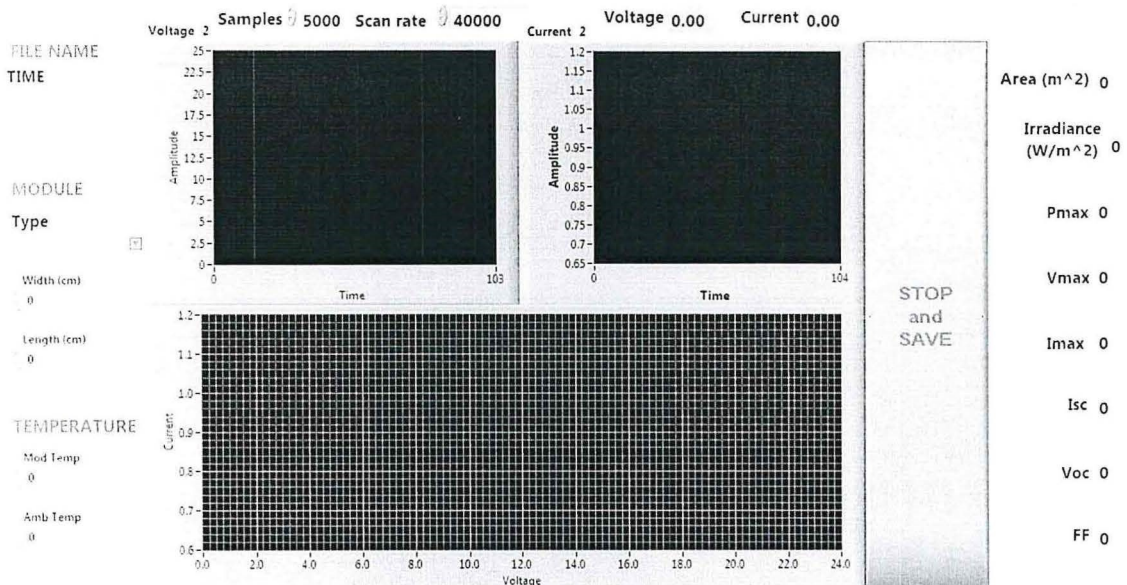


Figure A2: I-V Tracing Circuit in Labview Programme for the CIGS Module

APPENDIX B

SCREEN VIEW IN LABVIEW PROGRAMME FOR I-V CURVE TRACING

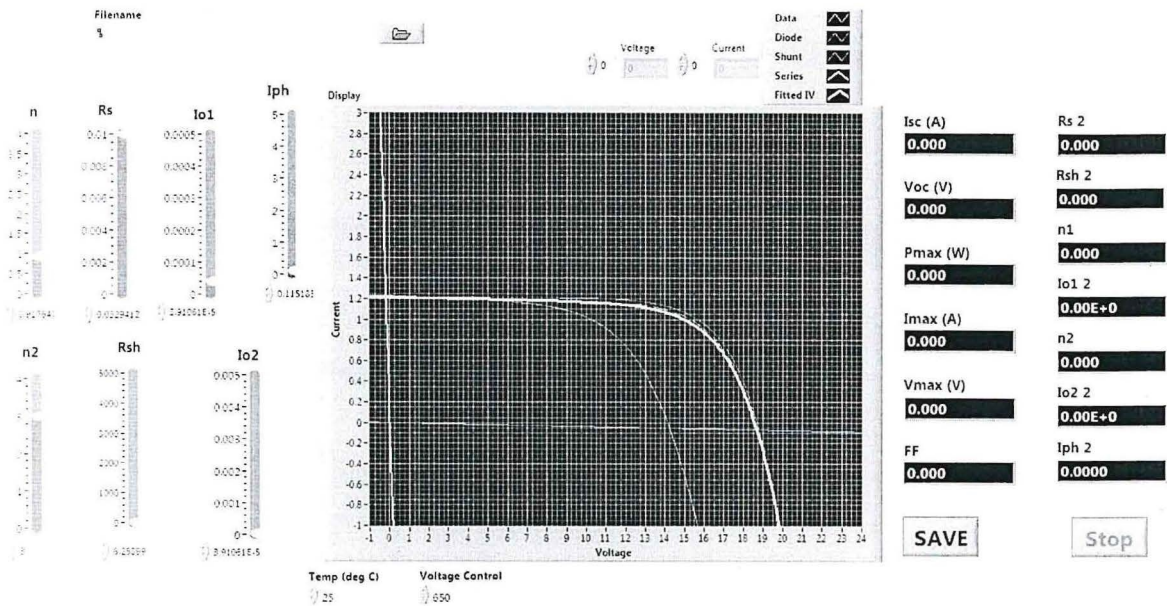


Figure B1: I-V Curve fitting Programme in Labview Programme

APPENDIX C

ANALYSED DATA FOR MEASURED AND FITTED I-V PARAMETERS

Measured data for a clean module compiled taken on 09th-Dec-2012.

Time	Isc	Voc	Imax	Vmax	Pmax	FF	ModT	AmbT	Ird	Area	A*I	EFF
931	0.542	14.011	0.535	14.01	7.499	1.012	21	25	206.411	0.186	38.392	19.5
947	0.54	14.072	0.54	14.072	7.599	1	21	25	333.049	0.186	61.947	12.3
950	0.564	14.086	0.564	13.919	7.855	1.012	20	25	337.357	0.186	62.748	12.5
1027	0.656	14.921	0.656	14.877	9.76	1.003	21	28	350.619	0.186	65.215	15.0
1042	0.757	15.711	0.757	15.701	11.878	1.001	16	27	690.052	0.186	128.350	9.3
1048	0.658	14.598	0.651	14.461	9.415	1.02	17	27	778.984	0.186	144.891	6.5
1054	0.517	12.763	0.517	12.693	6.561	1.005	20	27	586.838	0.186	109.152	6.0
1100	0.364	11.058	0.364	11.019	4.006	1.004	21	28	286.868	0.186	53.357	7.5
1115	0.821	15.762	0.821	15.752	12.927	1.001	20	28	790.133	0.186	146.965	8.8
1120	0.822	15.477	0.822	15.47	12.709	1	17	29	807.422	0.186	150.180	8.5
1123	0.807	15.51	0.807	15.505	12.516	1	16	29	758.991	0.186	141.172	8.9
1130	0.845	15.539	0.845	15.539	13.128	1	18	29	773.304	0.186	143.835	9.1
1140	0.745	15.866	0.745	15.798	11.771	1.004	19	29	829.857	0.186	154.353	7.6
1159	0.397	12.017	0.393	12.011	4.719	1.012	26	29	299.393	0.186	55.687	8.5
1228	0.477	13.279	0.477	13.27	6.324	1.001	19	24	337.61	0.186	62.795	10.1
1233	0.887	16.151	0.887	16.136	14.307	1.001	24	32	834.508	0.186	155.218	9.2
1234	0.491	13.675	0.491	13.673	6.715	1	17	25	298.079	0.186	55.443	12.1
1239	0.882	15.773	0.882	15.761	13.905	1.001	23	32	841.591	0.186	156.536	8.9
1244	0.871	15.599	0.87	15.599	13.57	1.001	21	31	838.989	0.186	156.052	8.7
1307	0.806	15.061	0.806	15.061	12.133	1	18	30	340.516	0.186	63.336	19.2
1317	0.65	15.101	0.649	15.073	9.785	1.003	18	30	721.554	0.186	134.209	7.3
1325	0.877	15.667	0.877	15.664	13.734	1.001	21	30	837.909	0.186	155.851	8.8
1338	0.837	15.298	0.837	15.293	12.807	1	27	31	840.288	0.186	156.294	8.2
1342	0.834	15.193	0.834	15.193	12.674	1	28	32	822.498	0.186	152.985	8.3
1351	0.86	15.098	0.86	15.09	12.973	1.001	31	34	810.883	0.186	150.824	8.6

1416	0.309	7.451	0.283	7.323	2.072	1.112	26	32	130.202	0.186	24.218	8.6
1421	0.847	15.993	0.845	15.984	13.511	1.003	26	31	808.483	0.186	150.378	9.0
1435	0.42	9.633	0.42	9.633	4.042	1	26	30	211.322	0.186	39.306	10.3
1438	0.792	15.778	0.792	15.775	12.499	1	26	30	763.993	0.186	142.103	8.8
1450	0.775	15.109	0.775	15.094	11.695	1.001	26	30	772.213	0.186	143.632	8.1
1532	0.411	6.48	0.411	6.441	2.648	1.006	28	28	482.105	0.186	89.672	3.0
1538	0.572	14.164	0.572	14.134	8.091	1.002	28	28	584.204	0.186	108.662	7.4
1542	0.253	6.608	0.253	6.589	1.665	1.003	28	28	523.855	0.186	97.437	1.7
1554	0.224	6.315	0.21	6.308	1.327	1.067	24	28	135.795	0.186	25.258	5.3
1611	0.189	5.512	0.178	5.483	0.974	1.067	25	27	118.254	0.186	21.995	4.4
1628	0.328	9.965	0.324	9.896	3.204	1.021	25	26	269.505	0.186	50.128	6.4
1646	0.286	9.045	0.26	9.024	2.343	1.103	25	26	227.57	0.186	42.328	5.5
1704	0.157	4.107	0.147	4.09	0.6	1.076	25	26	90.996	0.186	16.925	3.5
1706	0.152	4.317	0.151	4.078	0.618	1.065	25	26	89.373	0.186	16.623	3.7
1800	0.147	4.124	0.141	4.104	0.578	1.051	25	26	86.732	0.186	16.132	3.6
AVERAGE	0.584	12.57	0.581	12.515	8.178	1.0165	23	28	516.208	0.186	96.015	8.5

I-V fit data for a clean module compiled taken on 09th-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
931	0.524	17.606	0.419	13.111	5.499	0.597	22	23	394.874	0.186	73.447	7.5
947	0.524	17.312	0.431	12.96	5.582	0.616	22	23	412.636	0.186	76.75	7.3
1027	0.656	18.002	0.469	13.077	6.135	0.52	21	25	206.411	0.186	38.392	16.0
1042	0.761	18.766	0.528	13.487	7.12	0.498	21	25	333.049	0.186	61.947	11.5
1048	0.656	17.633	0.489	12.956	6.336	0.548	20	25	337.357	0.186	62.748	10.1
1054	0.498	16.768	0.391	11.877	4.645	0.557	20	27	586.838	0.186	109.15	4.3
1100	0.367	15.565	0.309	11.703	3.617	0.634	21	28	286.868	0.186	53.357	6.8
1115	0.812	18.431	0.578	13.519	7.814	0.522	20	28	790.133	0.186	146.96	5.3
1120	0.814	18.525	0.564	13.185	7.44	0.493	17	29	807.422	0.186	150.18	5.0
1123	0.788	18.759	0.545	13.432	7.315	0.495	16	29	758.991	0.186	141.17	5.2

1130	0.843	19.225	0.54	13.515	7.303	0.45	18	29	773.304	0.186	143.83	5.1
1140	0.734	17.947	0.612	13.72	8.391	0.637	19	29	829.857	0.186	154.35	5.4
1159	0.393	20.382	0.312	14.534	4.541	0.567	26	29	299.393	0.186	55.687	8.2
1228	0.471	18.518	0.368	12.998	4.784	0.548	19	24	337.61	0.186	62.795	7.6
1233	0.896	20.467	0.573	14.426	8.27	0.451	24	32	834.508	0.186	155.22	5.3
1234	0.498	20.645	0.345	14.773	5.092	0.496	17	25	298.079	0.186	55.443	9.2
1239	0.867	19.437	0.597	13.561	8.095	0.48	23	32	841.591	0.186	156.54	5.2
1244	0.867	19.169	0.596	13.345	7.956	0.479	21	31	838.989	0.186	156.05	5.1
1307	0.814	18.893	0.555	13.081	7.257	0.472	18	30	340.516	0.186	63.336	11.5
1317	0.655	19.778	0.5	14.145	7.069	0.545	18	30	721.554	0.186	134.21	5.3
1325	0.867	19.264	0.597	13.417	8.005	0.479	21	30	837.909	0.186	155.85	5.1
1338	0.814	18.989	0.555	13.153	7.302	0.472	27	31	840.288	0.186	156.29	4.7
1342	0.841	18.85	0.576	13.051	7.515	0.474	28	32	822.498	0.186	152.98	4.9
1351	0.841	19.252	0.577	13.375	7.712	0.477	31	34	810.883	0.186	150.82	5.1
1416	0.288	13.826	0.251	10.739	2.696	0.677	26	32	130.202	0.186	24.218	11.1
1421	0.841	18.829	0.602	14.329	8.622	0.544	26	31	808.483	0.186	150.38	5.7
1435	0.393	16.102	0.303	12.037	3.643	0.575	26	30	211.322	0.186	39.306	9.3
1438	0.789	17.987	0.575	14.103	8.106	0.571	26	30	763.993	0.186	142.1	5.7
1450	0.785	17.536	0.565	13.356	7.542	0.548	26	30	772.213	0.186	143.63	5.3
1532	0.342	8.494	0.172	4.703	0.809	0.278	28	28	482.105	0.186	89.672	0.9
1538	0.577	19.302	0.423	13.487	5.701	0.512	28	28	584.204	0.186	108.66	5.2
1542	0.262	12.932	0.173	8.982	1.553	0.458	28	28	523.855	0.186	97.437	1.6
1554	0.209	9.954	0.176	7.571	1.333	0.64	24	28	135.795	0.186	25.258	5.3
1611	0.183	9.786	0.153	7.421	1.136	0.634	25	27	118.254	0.186	21.995	5.2
1628	0.314	17.746	0.261	13.102	3.42	0.613	25	26	269.505	0.186	50.128	6.8
1646	0.262	21.596	0.213	16.781	3.577	0.633	25	26	227.57	0.186	42.328	8.5
1704	0.157	7.2	0.112	4.756	0.532	0.47	25	26	90.996	0.186	16.925	3.1
1706	0.157	7.2	0.112	4.756	0.532	0.47	25	26	89.373	0.186	16.623	3.2
1800	0.157	7.2	0.112	4.756	0.532	0.47	25	26	86.732	0.186	16.132	3.3
AVERAGE	0.577	16.766	0.416	12.084	5.398	0.528	23	28	503.491	0.186	93.649	6.3

Measured data for a clean module compiled taken on 10th-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
1034	0.342	10.865	0.342	10.848	3.707	1.002	26	19	290.97	0.186	54.120	6
1050	0.339	10.677	0.339	10.669	3.615	1.001	25	19	302.062	0.186	56.184	6
1105	0.382	11.535	0.382	11.475	4.38	1.005	29	20	294.048	0.186	54.693	8
1125	0.443	12.439	0.443	12.425	5.504	1.001	31	20	386.7	0.186	71.926	7
1140	0.45	12.555	0.45	12.555	5.651	1	32	18	391.725	0.186	72.861	7
1155	0.565	13.665	0.565	13.544	7.647	1.01	31	16	562.687	0.186	104.660	7
1210	0.695	14.597	0.695	14.404	10.016	1.013	30	30	500.42	0.186	93.078	10
AVERAGE	0.459	12.333	0.459	12.274	5.789	1.005	29	20	389.802	0.186	72.503	7.3

I-V fit data for a clean module compiled taken on 10th-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
1034	0.34	15.054	0.298	11.688	3.483	0.68	26	19	290.97	0.186	54.120	6
1050	0.34	15.054	0.298	11.688	3.483	0.68	25	19	302.062	0.186	56.184	6
1105	0.366	15.173	0.321	11.797	3.791	0.682	29	20	294.048	0.186	54.693	6
1125	0.419	15.387	0.369	11.981	4.415	0.685	31	20	386.7	0.186	71.926	6
1140	0.419	15.387	0.369	11.981	4.415	0.685	32	18	391.725	0.186	72.861	6
1155	0.55	15.562	0.475	11.918	5.665	0.662	31	16	562.687	0.186	104.660	5
1210	0.682	16.818	0.549	12.792	7.029	0.613	30	30	500.42	0.186	93.078	7
1225	0.734	16.986	0.595	12.952	7.712	0.619	30	30	617.341	0.186	114.825	6
1235	0.734	16.986	0.595	12.952	7.712	0.619	31	19	494.194	0.186	91.920	8
AVERAGE	0.509	15.823	0.430	12.194	5.301	0.658	29	21	426.683	0.186	79.363	6.2

Measured data for a clean module compiled taken on 11th-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
1116	0.365	17.763	0.365	17.741	6.471	1.001	26	26	338	0.186	62.868	10
1131	0.361	17.123	0.359	17.122	6.146	1.005	28	26	318	0.186	59.148	10

1146	0.275	12.311	0.266	12.311	3.276	1.032	27	27	122	0.186	22.692	14
1201	0.274	11.859	0.266	11.859	3.153	1.031	27	27	145	0.186	26.97	11
1216	0.24	10.066	0.237	9.808	2.324	1.04	28	29	171	0.186	31.806	7
1252	0.337	15.879	0.283	15.19	4.301	1.245	28	23	443	0.186	82.398	5
1307	0.253	10.909	0.253	10.801	2.731	1.01	29	15	508	0.186	94.488	2
1322	0.254	10.726	0.249	10.698	2.662	1.024	28	27	104	0.186	19.344	13
1352	0.373	17.672	0.373	17.653	6.589	1.001	28	27	298	0.186	55.428	11
1407	0.323	14.626	0.293	14.626	4.286	1.102	29	29	218	0.186	40.548	10
1422	0.356	16.213	0.356	15.934	5.67	1.017	29	28	413	0.186	76.818	7
AVERAGE	0.310	14.104	0.3	13.977	4.328	1.046	28	26	279.818	0.186	52.046	9.1

I-V fit data for a clean module compiled taken on 11th-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
1116	0.367	21.915	0.306	21.279	6.51	0.81	26	26	338	0.186	62.868	10
1131	0.472	21.385	0.363	16.221	5.891	0.584	28	26	318	0.186	59.148	9
1146	0.42	16.569	0.299	11.375	3.403	0.49	27	27	122	0.186	22.692	14
1201	0.42	16.569	0.299	11.375	3.403	0.49	27	27	145	0.186	26.97	12
1216	0.315	15.431	0.217	10.373	2.252	0.464	28	29	171	0.186	31.806	7
1252	0.366	21.564	0.3	21.564	6.479	0.82	28	23	443	0.186	82.398	7
1307	0.366	15.567	0.263	10.476	2.756	0.483	29	15	508	0.186	94.488	2
1322	0.366	15.567	0.263	10.476	2.756	0.483	28	27	104	0.186	19.344	14
1352	0.419	21.597	0.323	20.734	6.703	0.741	28	27	298	0.186	55.428	12
1407	0.34	21.566	0.279	16.71	4.656	0.634	29	29	218	0.186	40.548	11
1422	0.366	21.569	0.307	19.194	5.888	0.745	29	28	413	0.186	76.818	7
AVERAGE	0.383	19.027	0.293	15.434	4.609	0.613	28	26	279.818	0.186	52.046	9.5

Measured data for a clean module compiled taken on 12th-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
1120	0.268	9.143	0.267	9.123	2.435	1.006	25	25	461.41	0.186	85.822	2

1135	0.787	15.355	0.787	15.33	12.059	1.002	27	27	529.983	0.186	98.577	12
1150	0.866	15.562	0.866	14.969	12.958	1.04	26	27	882.005	0.186	164.053	7
1205	0.939	15.235	0.939	15.218	14.292	1.001	27	27	941.759	0.186	175.167	8
1220	0.921	14.967	0.921	14.946	13.768	1.001	28	28	873.724	0.186	162.513	8
1235	0.974	15.202	0.974	15.176	14.781	1.002	27	28	874.579	0.186	162.672	9
1305	0.989	15.186	0.989	15.177	15.014	1.001	29	29	960.778	0.186	178.705	8
1320	0.934	14.697	0.934	14.697	13.73	1	29	29	881.785	0.186	164.01201	8
1335	0.908	16.848	0.908	16.847	15.289	1	29	29	781.488	0.186	145.357	10
1350	0.998	16.076	0.998	16.061	16.024	1.001	29	29	886.619	0.186	164.911	9
1405	1.053	17.02	1.053	17.005	17.901	1.001	29	29	886.97	0.186	164.976	10
1420	0.468	15.843	0.468	15.843	7.421	1	29	28	836.021	0.186	155.500	4
1435	0.947	15.972	0.947	15.968	15.127	1	28	29	824.863	0.186	153.425	9
1450	0.883	15.326	0.883	15.305	13.514	1.001	28	29	753.562	0.186	140.163	9
1505	0.875	15.282	0.875	15.256	13.352	1.002	29	29	717.387	0.186	133.43398	10
1520	0.83	15.331	0.83	15.311	12.71	1.001	29	29	713.123	0.186	132.641	9
1535	0.808	15.183	0.808	15.16	12.249	1.002	29	29	762.949	0.186	141.909	8
1550	0.737	14.805	0.737	14.799	10.903	1	19	29	717.648	0.186	133.483	8
1605	0.7	14.505	0.7	14.488	10.146	1.001	18	29	613.079	0.186	114.033	8
1620	0.669	14.253	0.669	14.117	9.449	1.01	21	29	612.31	0.186	113.890	8
AVERAGE	0.828	15.090	0.828	15.040	12.656	1.004	27	28	775.602	0.186	144.26199	8.2

I-V fit data for a clean module compiled taken on 12th-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
1120	0.262	15.458	0.211	11.128	2.344	0.579	25	25	461.41	0.186	85.822	2
1135	0.789	18.366	0.552	13.267	7.328	0.506	27	27	229.983	0.186	42.777	17
1150	0.864	17.341	0.637	12.384	7.895	0.527	26	27	882.005	0.186	164.053	4
1205	0.916	17.65	0.61	12.384	7.555	0.467	27	27	941.759	0.186	175.167	4
1220	0.981	21.597	0.503	12.961	6.52	0.308	28	28	873.724	0.186	162.513	4
1235	1.034	21.615	0.532	13.583	7.225	0.323	27	28	874.579	0.186	162.672	4

1305	1.034	21.615	0.532	13.583	7.225	0.323	29	29	960.778	0.186	178.705	4
1320	0.981	21.597	0.503	12.961	6.52	0.308	29	29	881.785	0.186	164.012	3
1335	0.942	19.495	0.718	13.651	9.799	0.533	29	29	781.488	0.186	145.357	6
1350	1.021	19.215	0.669	12.93	8.653	0.441	4	29	886.619	0.186	164.911	5
1405	1.073	20.195	0.707	13.723	9.7	0.447	29	29	886.97	0.186	164.976	5
1420	0.969	19.666	0.627	13.218	8.287	0.435	29	28	836.021	0.186	155.500	5
1435	0.943	19.916	0.605	13.398	8.1	0.431	28	29	824.863	0.186	153.425	5
1450	0.89	19.609	0.565	13.109	7.406	0.424	28	29	753.562	0.186	140.163	5
1505	0.89	19.609	0.565	13.109	7.406	0.424	29	29	717.387	0.186	133.434	5
1520	0.813	19.533	0.555	13.761	7.637	0.481	29	29	713.123	0.186	132.641	5
1535	0.813	19.533	0.555	13.761	7.637	0.481	29	29	762.949	0.186	141.909	5
1550	0.761	21.148	0.46	15.223	6.997	0.435	19	29	717.648	0.186	133.483	5
1605	0.708	19.314	0.496	13.644	6.768	0.495	18	29	613.079	0.186	114.033	5
1620	0.655	19.592	0.5	14.149	7.075	0.551	21	29	612.31	0.186	113.890	6
AVERAGE	0.867	19.603	0.555	13.296	7.404	0.446	26	28	760.602	0.186	141.472	5.2

Measured data for a shaded module compiled taken on 13th-Dec-2012.

Time	Isc(A)	Voc(V)	I _{max} (A)	V _{max} (V)	P _{max} (W)	FF	ModT	AmbT	I _{rd}	Area	A*I	EFF
1009	0.106	3.978	0.106	3.977	0.422	1	27	26	354	0.186	65.844	0
1039	0.121	5.311	0.104	5.31	0.554	1.162	26	26	352	0.186	65.472	0
1054	0.13	5.452	0.109	5.393	0.588	1.206	27	26	260	0.186	48.36	1
1109	0.117	4.591	0.117	4.588	0.537	1.001	27	26	336	0.186	62.496	0
1124	0.097	3.24	0.097	3.231	0.314	1.003	27	28	382	0.186	71.052	0
1139	0.073	2.476	0.073	2.476	0.181	1	27	26	368	0.186	68.448	0
1154	0.088	3.149	0.087	3.098	0.269	1.035	26	26	253	0.186	47.058	0
AVERAGE	0.105	4.028	0.099	4.010	0.409	1.058	27	26	329.286	0.186	61.247	0.1

I-V fit data for a shaded module compiled taken on 13th-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
1009	0.158	4.726	0.121	3.384	0.41	0.55	27	26	354	0.186	65.844	0
1039	0.131	6.156	0.109	4.665	0.507	0.629	26	26	352	0.186	65.472	0
1054	0.131	7.962	0.112	6.253	0.7	0.671	27	26	260	0.186	48.36	1
1109	0.131	7.962	0.112	6.253	0.7	0.671	27	26	336	0.186	62.496	1
1124	0.105	7.763	0.089	6.045	0.536	0.658	27	28	382	0.186	71.052	0
1139	0.105	7.763	0.089	6.045	0.536	0.658	27	26	368	0.186	68.448	0
1154	0.079	7.504	0.065	5.801	0.378	0.641	26	26	253	0.186	47.058	0
AVERAGE	0.12	7.119	0.100	5.492	0.538	0.640	27	26	329.286	0.186	61.247	0.3

Measured data for a shaded module compiled taken on 17th-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
954	0.018	0.045	0.043	0.09	0.004	0.209	23	24	167.803	0.186	31.211	0
1009	0.026	0.03	0.006	0.046	0	0.998	23	26	104.458	0.186	19.429	0
1024	0.026	0.054	0.009	0.068	0.001	0.38	25	26	109.814	0.186	20.425	0
1039	0.029	0.049	0.013	0.065	0.001	0.581	26	26	172.957	0.186	32.170	0
1054	0.033	0.012	0.025	0.012	0	1.272	25	26	178.639	0.186	33.227	0
1109	0.05	0.038	0	0.099	0	0.947	30	28	69.28	0.186	12.886	0
1124	0.026	0.075	0.002	1.826	0.003	0.563	34	34	99.548	0.186	18.516	0
1139	0.007	0.058	0.002	2.585	0.005	-0.079	32	33	85.958	0.186	15.988	0
1154	0.054	0.013	0.009	0.087	0.001	0.905	31	29	124.935	0.186	23.238	0
1254	0.003	0.106	0.012	3.074	0.036	0.008	30	30	82.616	0.186	15.367	0
1309	0.024	0.029	0.009	0.029	0	0.775	29	29	73.409	0.186	13.654	0
1324	0.002	0.061	0.013	2.503	0.033	0.003	30	29	40.509	0.186	7.535	0
1339	0.014	0.051	0.026	3.085	0.079	0.009	28	28	65.483	0.186	12.180	0
1354	0.01	0.039	0.019	3.527	0.065	0.006	28	28	72.766	0.186	13.534	0
1409	0.021	0.028	0.012	0.029	0	1.723	28	28	50.051	0.186	9.3095	0
AVERAGE	0.019	0.046	0.007	1.142	0.015	8.535	28	28	99.882	0.186	18.578	0

I-V fit data for a shaded module compiled taken on 17th-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
954	0	0	0	0	0	NaN	23	24	167.803	0.186	31.211	0
1009	0	0	0	0	0	NaN	23	26	104.458	0.186	19.429	0
1024	0	0	0	0	0	NaN	25	26	109.814	0.186	20.425	0
1039	0	0	0	0	0	NaN	26	26	172.957	0.186	32.170	0
1054	0	0	0	0	0	NaN	25	26	178.639	0.186	33.227	0
1109	0	0	0	0	0	NaN	30	28	69.280	0.186	12.886	0
1124	0.026	3.206	0.018	2.109	0.037	0.444	34	34	99.548	0.186	18.516	0
1139	0	0	0	0	0	NaN	32	33	85.958	0.186	15.988	0
1154	0.052	3.856	0.038	2.638	0.101	0.5	31	29	124.935	0.186	23.238	0
1254	0	0	0	0	0	NaN	30	30	82.616	0.186	15.367	0
1309	0	0	0	0	0	NaN	29	29	73.409	0.186	13.654	0
1324	0	0	0	0	0	NaN	30	29	40.509	0.186	7.535	0
1339	0	0	0	0	0	NaN	28	28	65.483	0.186	12.180	0
1354	0	0	0	0	0	NaN	28	28	72.766	0.186	13.534	0
1409	0	0	0	0	0	NaN	28	28	50.051	0.186	9.309	0
AVERAGE	0.005	0.471	0.004	0.316	0.009	0.472	28	28	99.882	0.186	18.578	0

Measured data for a shaded module compiled taken on 19th-Dec-2013.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
1056	0.098	2.571	2.549	2.549	0.244	1.032	25	25	59.86	0.186	11.134	2
1111	0.092	2.116	2.109	2.109	0.184	1.061	28	26	57.806	0.186	10.752	1
1126	0.113	2.774	2.758	2.758	0.306	1.021	25	26	46.128	0.186	8.580	3
1211	0.134	3.284	3.218	3.218	0.425	1.034	27	26	159.214	0.186	29.614	1
1226	0.155	3.648	3.609	3.609	0.547	1.035	26	26	165.964	0.186	30.869	1
1241	0.174	4.204	4.173	4.173	0.679	1.077	28	27	132.455	0.186	24.637	2
1256	0.142	2.907	2.897	2.897	0.397	1.036	28	27	153.98	0.186	28.640	1
1311	0.118	2.261	2.246	2.246	0.257	1.038	26	27	78.452	0.186	14.592	1

AVERAGE	0.12825	2.970625	2.944875	2.944875	0.379875	1.04175	27	26	106.73238	0.186	19.852	1.5
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I-V fit data for a shaded module compiled taken on 19th-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
1056	0.105	4.27	0.075	2.933	0.221	0.491	25	25	59.86	0.186	11.134	1
1111	0.079	3.967	0.055	2.657	0.145	0.462	28	26	57.806	0.186	10.752	1
1126	0.105	4.554	0.079	3.262	0.258	0.54	25	26	46.128	0.186	8.580	3
1211	0.131	4.758	0.102	3.432	0.349	0.558	27	26	159.214	0.186	29.614	1
1226	0.158	4.923	0.123	3.602	0.445	0.573	26	26	165.964	0.186	30.869	1
1241	0.157	7.561	0.137	5.923	0.813	0.685	28	27	132.455	0.186	24.637	3
1256	0.131	7.405	0.113	5.786	0.656	0.677	28	27	153.98	0.186	28.640	2
1311	0.131	4.68	0.103	3.398	0.349	0.568	26	27	78.452	0.186	14.592	2
AVERAGE	0.125	5.265	0.098	3.874	0.405	0.569	27	26	106.732	0.186	19.852	2

Measured data for a dusted module compiled taken on 20th-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
1021	0.634	14.102	0.634	14.032	8.902	1.005	9	24	810.966	0.186	150.840	5
1036	0.674	14.35	0.674	14.311	9.648	1.003	23	24	816.9	0.186	151.943	6
1051	0.694	14.212	0.694	14.206	9.858	1	25	24	858.405	0.186	159.663	6
1106	0.704	14.173	0.704	14.072	9.901	1.007	24	25	854.193	0.186	158.880	6
1121	0.75	14.457	0.75	14.424	10.818	1.002	25	25	872.062	0.186	162.204	6
1136	0.782	14.571	0.782	14.506	11.348	1.005	25	25	912.582	0.186	169.740	6
1151	0.787	14.405	0.787	14.326	11.277	1.006	26	26	913.087	0.186	169.834	6
1206	0.806	14.635	0.806	14.635	11.797	1	26	26	932.631	0.186	173.469	6
1221	0.811	14.615	0.811	14.547	11.794	1.005	3	26	945.068	0.186	175.783	6
1236	0.844	15.248	0.844	15.158	12.795	1.006	8	26	937.806	0.186	174.432	7
1251	0.853	14.977	0.853	14.89	12.699	1.006	9	27	940.509	0.186	174.935	7
1306	0.833	14.75	0.833	14.686	12.234	1.004	8	27	942.268	0.186	175.262	6
1321	0.853	14.513	0.849	14.511	12.314	1.005	8	27	925.442	0.186	172.132	7

1336	0.842	14.415	0.842	14.374	12.098	1.003	6	27	899.327	0.186	167.275	7
1351	0.846	14.54	0.846	14.536	12.299	1	13	28	900.595	0.186	167.511	7
1406	0.836	14.768	0.836	14.76	12.344	1.001	10	29	877.843	0.186	163.279	7
1421	0.795	14.517	0.795	14.515	11.546	1	20	29	887.499	0.186	165.0748	6
1436	0.809	14.63	0.809	14.523	11.744	1.007	29	29	883.407	0.186	164.314	7
1451	0.803	14.626	0.803	14.568	11.703	1.004	27	29	757.643	0.186	140.922	8
1506	0.745	14.456	0.745	14.381	10.719	1.005	16	28	728.926	0.186	135.580	7
1521	0.732	14.118	0.732	14.084	10.305	1.002	20	29	656.675	0.186	122.141	8
1536	0.785	14.244	0.785	14.162	11.113	1.006	12	29	627.352	0.186	116.688	9
1551	0.79	14.104	0.79	14.008	11.072	1.007	22	30	584.639	0.186	108.743	10
1606	0.78	13.84	0.78	13.723	10.704	1.009	31	31	497.963	0.186	92.621	11
AVERAGE	0.783	14.469	0.783	14.414	11.293	1.004	18	27	831.825	0.186	154.719	7

I-V fit data for a dusted module compiled taken on 20th-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
1021	0.642	18.085	0.375	13.189	4.952	0.426	9	24	810.966	0.186	150.840	3
1036	0.664	16.327	0.471	12.87	6.061	0.559	23	24	816.9	0.186	151.943	3
1051	0.695	16.077	0.444	12.298	5.458	0.488	25	24	858.405	0.186	159.663	3
1106	0.685	16.148	0.437	12.469	5.451	0.493	24	25	854.193	0.186	158.880	3
1121	0.738	16.121	0.477	12.268	5.85	0.492	25	25	872.062	0.186	162.204	3
1136	0.764	16.201	0.499	12.384	6.178	0.499	25	25	912.582	0.186	169.740	3
1151	0.791	16.053	0.514	12.065	6.202	0.489	26	26	913.087	0.186	169.834	3
1206	0.791	16.053	0.514	12.065	6.202	0.489	26	26	932.631	0.186	173.469	3
1221	0.791	16.053	0.514	12.065	6.202	0.489	3	26	945.068	0.186	175.783	3
1236	0.817	17.557	0.538	13.154	7.072	0.493	8	26	937.806	0.186	174.432	4
1251	0.84	17.396	0.558	12.715	7.09	0.485	9	27	940.509	0.186	174.935	4
1306	0.817	17.281	0.534	12.324	6.58	0.466	8	27	942.268	0.186	175.262	3
1321	0.817	17.37	0.533	12.324	6.572	0.463	8	27	925.442	0.186	172.132	3
1336	0.817	17.37	0.533	12.324	6.572	0.463	6	27	899.327	0.186	167.275	3

1351	0.817	17.37	0.533	12.324	6.572	0.463	13	28	900.595	0.186	167.511	3
1406	0.817	17.37	0.533	12.324	6.572	0.463	10	29	877.843	0.186	163.279	4
1421	0.79	17.248	0.512	12.208	6.246	0.458	20	29	887.499	0.186	165.075	3
1436	0.843	17.525	0.554	12.511	6.929	0.469	29	29	883.407	0.186	164.314	4
1451	0.817	17.409	0.534	12.36	6.598	0.464	27	29	757.643	0.186	140.922	4
1506	0.736	17.525	0.514	12.713	6.536	0.507	16	28	728.926	0.186	135.580	4
1521	0.736	17.525	0.514	12.713	6.536	0.507	20	29	656.675	0.186	122.142	5
1536	0.815	17.854	0.581	13.025	7.563	0.52	12	29	627.352	0.186	116.687	6
1551	0.815	17.854	0.581	13.025	7.563	0.52	22	30	584.639	0.186	108.743	6
1606	0.815	18.903	0.577	13.888	8.018	0.52	31	31	497.963	0.186	92.621	8
AVERAGE	0.78	17.111	0.516	12.567	6.482	0.487	18	27	831.825	0.186	154.719	3.8

Measured data for a dusted module compiled taken on 21st-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
1030	0.06	0.076	0.091	4.069	0.369	0.012	24	25	739.36	0.186	137.52096	0
1045	0.063	0.104	0.092	4.302	0.398	0.016	25	25	817.768	0.186	152.105	0
1100	0.06	0.198	0.09	4.471	0.404	0.029	19	26	820.035	0.186	152.527	0
1115	0.063	0.125	0.096	4.665	0.446	0.018	26	25	542.129	0.186	100.83599	0
1130	0.065	0.231	0.1	4.932	0.496	0.03	26	26	824.927	0.186	153.436	0
1145	0.064	0.245	0.099	4.944	0.49	0.032	26	26	874.945	0.186	162.740	0
1200	0.058	0.129	0.093	5.064	0.473	0.016	26	26	619	0.186	115.134	0
1215	0.022	0.194	0.052	4.348	0.225	0.019	13	27	334	0.186	62.124	0
1230	0.035	0.324	0.065	4.419	0.289	0.039	26	27	874.25	0.186	162.611	0
1245	0.042	0.224	0.076	4.485	0.342	0.027	27	27	884.741	0.186	164.562	0
1315	0.04	0.289	0.075	4.54	0.342	0.034	28	28	905.872	0.186	168.492	0
1330	0.035	0.256	0.067	4.513	0.301	0.03	28	28	902.37	0.186	167.841	0
1345	0.022	0.286	0.056	4.462	0.251	0.025	28	29	863.407	0.186	160.594	0
1400	0.013	0.249	0.043	4.385	0.191	0.017	29	29	864.163	0.186	160.734	0
1415	0.023	0.228	0.054	4.386	0.238	0.022	29	29	848.551	0.186	157.830	0

1430	0.018	0.184	0.051	4.135	0.209	0.016	29	29	826.625	0.186	153.752	0
1445	0.054	0.004	0.044	0.004	0	1.215	24	29	802.494	0.186	149.264	0
1500	0.012	0.183	0.051	3.61	0.185	0.012	28	29	121.411	0.186	22.582	0
AVERAGE	0.036	0.196	0.067	4.207	0.314	0.089	26	27	748.114	0.186	139.149	0

I-V fit data for a dusted module compiled taken on 21st-Dec-2012.

Time	Isc(A)	Voc(V)	Imax(A)	Vmax(V)	Pmax(W)	FF	ModT	AmbT	Ird	Area	A*I	EFF
1030	0	0	0	0	0	NaN	24	25	739.36	0.186	137.52096	0
1045	0	0	0	0	0	NaN	25	25	817.768	0.186	152.105	0
1100	0	0	0	0	0	NaN	19	26	820.035	0.186	152.527	0
1115	0	0	0	0	0	NaN	26	25	542.129	0.186	100.836	0
1130	0	0	0	0	0	NaN	26	26	824.927	0.186	153.436	0
1145	0	0	0	0	0	NaN	26	26	874.945	0.186	162.740	0
1200	0	0	0	0	0	NaN	26	26	0.619	0.186	0.115	0
1215	0	0	0	0	0	NaN	13	27	0.334	0.186	0.062	0
1230	0	0	0	0	0	NaN	26	27	874.25	0.186	162.611	0
1245	0	0	0	0	0	NaN	27	27	884.741	0.186	164.562	0
1315	0	0	0	0	0	NaN	28	28	905.872	0.186	168.492	0
1330	0	0	0	0	0	NaN	28	28	902.37	0.186	167.841	0
1345	0	0	0	0	0	NaN	28	29	863.407	0.186	160.594	0
1400	0	0	0	0	0	NaN	29	29	864.163	0.186	160.734	0
1415	0	0	0	0	0	NaN	29	29	848.551	0.186	157.830	0
1430	0	0	0	0	0	NaN	29	29	826.625	0.186	153.752	0
1445	0.026	0.822	0.016	0.474	0.007	0.34	24	29	802.494	0.186	149.264	0
1500	0	0	0	0	0	NaN	28	29	121.411	0.186	22.582	0
AVERAGE	0.001	0.046	0.001	0.026	0.000	0.34	26	27	695.222	0.186	129.311	0

APPENDIX D

I-V DATA

I-V data for a clear CIGS solar module

V	I	V	I	V	I	V	I	V	I	V	I	V	I
-0.043	0.868	1.464	0.848	3.006	0.828	4.548	0.807	6.09	0.784	7.63	0.758	9.17	0.729
-0.007	0.867	1.5	0.848	3.042	0.827	4.584	0.806	6.125	0.783	7.666	0.757	9.206	0.728
0.029	0.867	1.536	0.847	3.078	0.827	4.62	0.805	6.161	0.782	7.702	0.757	9.242	0.727
0.065	0.866	1.571	0.847	3.114	0.826	4.656	0.805	6.197	0.782	7.738	0.756	9.277	0.726
0.101	0.866	1.607	0.846	3.15	0.826	4.691	0.804	6.233	0.781	7.774	0.755	9.313	0.726
0.137	0.865	1.643	0.846	3.185	0.825	4.727	0.804	6.269	0.781	7.809	0.755	9.349	0.725
0.172	0.865	1.679	0.845	3.221	0.825	4.763	0.803	6.305	0.78	7.845	0.754	9.385	0.724
0.208	0.864	1.715	0.845	3.257	0.825	4.799	0.803	6.34	0.78	7.881	0.754	9.42	0.723
0.244	0.864	1.751	0.845	3.293	0.824	4.835	0.802	6.376	0.779	7.917	0.753	9.456	0.722
0.28	0.863	1.787	0.844	3.329	0.824	4.871	0.802	6.412	0.778	7.953	0.752	9.492	0.722
0.316	0.863	1.823	0.844	3.365	0.823	4.907	0.801	6.448	0.778	7.988	0.752	9.528	0.721
0.352	0.863	1.858	0.843	3.401	0.823	4.942	0.801	6.484	0.777	8.024	0.751	9.564	0.72
0.388	0.862	1.894	0.843	3.436	0.822	4.978	0.8	6.52	0.777	8.06	0.75	9.599	0.719
0.424	0.862	1.93	0.842	3.472	0.822	5.014	0.8	6.555	0.776	8.096	0.75	9.635	0.719
0.459	0.861	1.966	0.842	3.508	0.821	5.05	0.799	6.591	0.776	8.132	0.749	9.671	0.718
0.495	0.861	2.002	0.841	3.544	0.821	5.086	0.799	6.627	0.775	8.168	0.748	9.707	0.717
0.531	0.86	2.038	0.841	3.58	0.82	5.122	0.798	6.663	0.774	8.203	0.748	9.742	0.716
0.567	0.86	2.074	0.84	3.616	0.82	5.158	0.798	6.699	0.774	8.239	0.747	9.778	0.715
0.603	0.859	2.109	0.84	3.652	0.819	5.193	0.797	6.735	0.773	8.275	0.746	9.814	0.715
0.639	0.859	2.145	0.839	3.687	0.819	5.229	0.797	6.77	0.773	8.311	0.746	9.85	0.714
0.675	0.858	2.181	0.839	3.723	0.818	5.265	0.796	6.806	0.772	8.347	0.745	9.886	0.713
0.711	0.858	2.217	0.838	3.759	0.818	5.301	0.796	6.842	0.771	8.382	0.744	9.921	0.712
0.746	0.857	2.253	0.838	3.795	0.817	5.337	0.795	6.878	0.771	8.418	0.744	9.957	0.711
0.782	0.857	2.289	0.837	3.831	0.817	5.373	0.794	6.914	0.77	8.454	0.743	9.993	0.71
0.818	0.857	2.325	0.837	3.867	0.816	5.408	0.794	6.95	0.77	8.49	0.742	10.029	0.71

0.854	0.856	2.361	0.837	3.903	0.816	5.444	0.793	6.985	0.769	8.526	0.741	10.064	0.709
0.89	0.856	2.396	0.836	3.938	0.815	5.48	0.793	7.021	0.768	8.561	0.741	10.1	0.708
0.926	0.855	2.432	0.836	3.974	0.815	5.516	0.792	7.057	0.768	8.597	0.74	10.136	0.707
0.962	0.855	2.468	0.835	4.01	0.814	5.552	0.792	7.093	0.767	8.633	0.739	10.172	0.706
0.998	0.854	2.504	0.835	4.046	0.814	5.588	0.791	7.129	0.767	8.669	0.739	10.207	0.705
1.033	0.854	2.54	0.834	4.082	0.813	5.624	0.791	7.165	0.766	8.705	0.738	10.243	0.705
1.069	0.853	2.576	0.834	4.118	0.813	5.659	0.79	7.2	0.765	8.74	0.737	10.279	0.704
1.105	0.853	2.612	0.833	4.154	0.812	5.695	0.79	7.236	0.765	8.776	0.737	10.315	0.703
1.141	0.852	2.647	0.833	4.189	0.812	5.731	0.789	7.272	0.764	8.812	0.736	10.35	0.702
1.177	0.852	2.683	0.832	4.225	0.811	5.767	0.789	7.308	0.764	8.848	0.735	10.386	0.701
1.213	0.852	2.719	0.832	4.261	0.811	5.803	0.788	7.344	0.763	8.884	0.734	10.422	0.7
1.249	0.851	2.755	0.831	4.297	0.81	5.839	0.787	7.38	0.762	8.919	0.734	10.458	0.699
1.284	0.851	2.791	0.831	4.333	0.81	5.874	0.787	7.415	0.762	8.955	0.733	10.493	0.698
1.32	0.85	2.827	0.83	4.369	0.809	5.91	0.786	7.451	0.761	8.991	0.732	10.529	0.698
10.744	0.692	12.279	0.646	13.81	0.586	15.369	0.498	16.917	0.371	18.447	0.179		
10.779	0.691	12.314	0.645	13.845	0.584	15.404	0.496	16.952	0.367	18.481	0.174		
10.815	0.69	12.35	0.644	13.881	0.582	15.44	0.494	16.987	0.364	18.516	0.168		
10.851	0.689	12.386	0.643	13.916	0.581	15.475	0.491	17.022	0.36	18.55	0.163		
10.887	0.688	12.421	0.642	13.952	0.579	15.51	0.489	17.057	0.356	18.584	0.157		
10.922	0.687	12.457	0.64	13.987	0.577	15.545	0.486	17.092	0.353	18.619	0.151		
10.958	0.686	12.493	0.639	14.023	0.575	15.581	0.484	17.127	0.349	18.653	0.146		
10.994	0.685	12.528	0.638	14.058	0.574	15.616	0.481	17.162	0.345	18.688	0.14		
11.03	0.684	12.564	0.637	14.094	0.572	15.651	0.479	17.197	0.342	18.722	0.134		
11.065	0.683	12.6	0.635	14.129	0.57	15.687	0.476	17.231	0.338	18.756	0.129		
11.101	0.682	12.635	0.634	14.165	0.568	15.722	0.474	17.266	0.334	18.791	0.123		
11.137	0.681	12.671	0.633	14.2	0.567	15.757	0.471	17.301	0.33	18.825	0.117		
11.172	0.68	12.706	0.631	14.236	0.565	15.792	0.468	17.336	0.326	18.859	0.111		
11.208	0.679	12.742	0.63	14.271	0.563	15.828	0.466	17.371	0.322	18.894	0.105		
11.244	0.678	12.778	0.629	14.307	0.561	15.863	0.463	17.406	0.318	18.928	0.099		
11.28	0.677	12.813	0.627	14.342	0.559	15.898	0.46	17.441	0.314	18.962	0.092		

11.315	0.676	12.849	0.626	14.378	0.557	15.933	0.458	17.476	0.31	18.996	0.086
11.351	0.675	12.885	0.625	14.413	0.556	15.969	0.455	17.511	0.306	19.031	0.08
11.387	0.674	12.92	0.623	14.449	0.554	16.004	0.452	17.545	0.302	19.065	0.074
11.422	0.673	12.956	0.622	14.484	0.552	16.039	0.449	17.58	0.298	19.099	0.067
11.458	0.672	12.991	0.621	14.519	0.55	16.074	0.447	17.615	0.293	19.133	0.061
11.494	0.671	13.027	0.619	14.555	0.548	16.109	0.444	17.65	0.289	19.167	0.054
11.529	0.67	13.063	0.618	14.59	0.546	16.145	0.441	17.685	0.285	19.201	0.048
11.565	0.669	13.098	0.616	14.626	0.544	16.18	0.438	17.719	0.281	19.236	0.041
11.601	0.668	13.134	0.615	14.661	0.542	16.215	0.435	17.754	0.276	19.27	0.034
11.637	0.667	13.169	0.613	14.697	0.54	16.25	0.432	17.789	0.272	19.304	0.027
11.672	0.666	13.205	0.612	14.732	0.538	16.285	0.429	17.824	0.267	19.338	0.02
11.708	0.665	13.241	0.611	14.768	0.536	16.32	0.426	17.858	0.263	19.372	0.013
11.744	0.664	13.276	0.609	14.803	0.534	16.356	0.423	17.893	0.258	19.406	0.006
11.779	0.663	13.312	0.608	14.838	0.532	16.391	0.42	17.928	0.254	19.44	-0.001
11.815	0.662	13.347	0.606	14.874	0.53	16.426	0.417	17.962	0.249	19.474	-0.008
11.851	0.66	13.383	0.605	14.909	0.528	16.461	0.414	17.997	0.244		
11.886	0.659	13.419	0.603	14.945	0.525	16.496	0.411	18.032	0.239		
11.922	0.658	13.454	0.602	14.98	0.523	16.531	0.408	18.066	0.235		
11.958	0.657	13.49	0.6	15.015	0.521	16.566	0.404	18.101	0.23		
11.993	0.656	13.525	0.598	15.051	0.519	16.601	0.401	18.136	0.225		
12.029	0.655	13.561	0.597	15.086	0.517	16.636	0.398	18.17	0.22		
12.065	0.654	13.596	0.595	15.121	0.514	16.672	0.395	18.205	0.215		
12.1	0.652	13.632	0.594	15.157	0.512	16.707	0.391	18.239	0.21		
12.136	0.651	13.667	0.592	15.192	0.51	16.742	0.388	18.274	0.205		
12.172	0.65	13.703	0.591	15.228	0.508	16.777	0.385	18.309	0.2		
12.207	0.649	13.739	0.589	15.263	0.505	16.812	0.381	18.343	0.195		
12.243	0.648	13.774	0.587	15.298	0.503	16.882	0.374	18.378	0.189		

I-v data for a partially shaded CIGS solar module

V	I	V	I	V	I	V	I	V	I	V	I	V	I
-0.061	0.131	1.162	0.13	2.457	0.129	3.679	0.127	4.899	0.124	6.111	0.114	7.288	0.074
-0.025	0.131	1.198	0.13	2.493	0.129	3.715	0.127	4.935	0.124	6.147	0.114	7.322	0.072
0.011	0.131	1.234	0.13	2.529	0.129	3.751	0.127	4.971	0.124	6.182	0.113	7.355	0.07
0.047	0.131	1.27	0.13	2.565	0.129	3.787	0.127	5.007	0.124	6.217	0.113	7.388	0.068
0.083	0.131	1.306	0.13	2.601	0.129	3.823	0.127	5.043	0.124	6.253	0.112	7.421	0.065
0.119	0.131	1.414	0.13	2.637	0.129	3.859	0.127	5.079	0.124	6.288	0.111	7.454	0.062
0.155	0.131	1.45	0.13	2.673	0.129	3.895	0.127	5.114	0.123	6.323	0.111	7.487	0.06
0.191	0.131	1.486	0.13	2.709	0.129	3.931	0.127	5.15	0.123	6.358	0.11	7.519	0.057
0.227	0.131	1.522	0.13	2.745	0.129	3.967	0.127	5.186	0.123	6.393	0.109	7.552	0.054
0.263	0.131	1.558	0.13	2.781	0.129	4.003	0.127	5.222	0.123	6.429	0.108	7.584	0.051
0.299	0.131	1.594	0.13	2.816	0.129	4.038	0.127	5.257	0.123	6.464	0.108	7.616	0.047
0.335	0.131	1.63	0.13	2.852	0.129	4.074	0.127	5.293	0.122	6.499	0.107	7.648	0.044
0.371	0.131	1.666	0.13	2.888	0.129	4.11	0.127	5.329	0.122	6.534	0.106	7.68	0.04
0.407	0.131	1.702	0.13	2.924	0.128	4.146	0.127	5.365	0.122	6.569	0.105	7.712	0.037
0.443	0.131	1.738	0.13	2.96	0.128	4.182	0.127	5.4	0.122	6.603	0.104	7.743	0.033
0.479	0.131	1.774	0.13	2.996	0.128	4.218	0.126	5.436	0.121	6.638	0.103	7.774	0.029
0.515	0.131	1.81	0.13	3.032	0.128	4.254	0.126	5.472	0.121	6.673	0.102	7.805	0.025
0.551	0.131	1.846	0.13	3.068	0.128	4.29	0.126	5.507	0.121	6.708	0.101	7.836	0.02
0.587	0.131	1.882	0.129	3.104	0.128	4.326	0.126	5.543	0.121	6.743	0.1	7.867	0.016
0.623	0.131	1.918	0.129	3.14	0.128	4.362	0.126	5.579	0.12	6.777	0.099	7.897	0.011
0.659	0.13	1.953	0.129	3.176	0.128	4.397	0.126	5.614	0.12	6.812	0.098	7.927	0.006
0.695	0.13	1.989	0.129	3.212	0.128	4.433	0.126	5.65	0.12	6.846	0.096	7.957	0.001
0.731	0.13	2.025	0.129	3.248	0.128	4.469	0.126	5.686	0.119	6.881	0.095	7.987	-0.005
0.767	0.13	2.061	0.129	3.284	0.128	4.505	0.126	5.721	0.119	6.915	0.094	8.016	-0.01
0.803	0.13	2.097	0.129	3.32	0.128	4.541	0.126	5.757	0.119	6.95	0.092		
0.839	0.13	2.133	0.129	3.356	0.128	4.577	0.126	5.792	0.118	6.984	0.091		
0.875	0.13	2.169	0.129	3.392	0.128	4.613	0.125	5.828	0.118	7.018	0.089		
0.911	0.13	2.205	0.129	3.428	0.128	4.649	0.125	5.863	0.118	7.052	0.088		

0.946	0.13	2.241	0.129	3.464	0.128	4.684	0.125	5.899	0.117	7.086	0.086		
0.982	0.13	2.277	0.129	3.499	0.128	4.72	0.125	5.934	0.117	7.12	0.084		
1.018	0.13	2.313	0.129	3.535	0.128	4.756	0.125	5.97	0.116	7.154	0.083		
1.054	0.13	2.349	0.129	3.571	0.128	4.792	0.125	6.005	0.116	7.188	0.081		
1.09	0.13	2.385	0.129	3.607	0.128	4.828	0.125	6.041	0.115	7.221	0.079		
1.126	0.13	2.421	0.129	3.643	0.128	4.864	0.125	6.076	0.115	7.255	0.077		

I-V data for a completely shaded CIGS solar module

V	I	V	I	V	I	V	I	V	I	V	I
-0.041	0.026	0.677	0.025	1.215	0.023	1.752	0.02	2.287	0.016	2.818	0.009
-0.005	0.026	0.713	0.025	1.251	0.023	1.788	0.02	2.323	0.016	2.854	0.008
0.031	0.026	0.749	0.024	1.287	0.023	1.824	0.02	2.358	0.015	2.889	0.007
0.067	0.026	0.785	0.024	1.323	0.022	1.859	0.02	2.394	0.015	2.924	0.007
0.103	0.026	0.821	0.024	1.358	0.022	1.895	0.019	2.429	0.014	2.959	0.006
0.139	0.026	0.857	0.024	1.394	0.022	1.931	0.019	2.465	0.014	2.994	0.005
0.175	0.026	0.892	0.024	1.43	0.022	1.966	0.019	2.5	0.014	3.029	0.005
0.211	0.026	0.928	0.024	1.466	0.022	2.002	0.019	2.536	0.013	3.064	0.004
0.246	0.026	0.964	0.024	1.502	0.022	2.038	0.018	2.571	0.013	3.099	0.003
0.282	0.026	1	0.024	1.537	0.021	2.073	0.018	2.606	0.012	3.134	0.002
0.318	0.026	1.036	0.024	1.573	0.021	2.109	0.018	2.642	0.012	3.169	0.001
0.354	0.025	1.072	0.023	1.609	0.021	2.145	0.017	2.677	0.011	3.204	0
0.39	0.025	1.108	0.023	1.645	0.021	2.18	0.017	2.713	0.011	3.239	-0.001
0.426	0.025	1.143	0.023	1.681	0.021	2.216	0.017	2.748	0.01	3.274	-0.002
0.462	0.025	1.179	0.023	1.716	0.02	2.251	0.016	2.783	0.009		

I-V data for a thin dusted CIGS solar module

V	I	V	I	V	I	V	I	V	I	V	I	V	I
-0.04	0.664	1.06	0.651	2.16	0.638	3.26	0.624	4.36	0.611	5.46	0.597	6.56	0.584
-0.005	0.664	1.096	0.651	2.196	0.637	3.296	0.624	4.396	0.61	5.496	0.597	6.596	0.583

0.031	0.663	1.131	0.65	2.231	0.637	3.331	0.623	4.431	0.61	5.531	0.597	6.631	0.583
0.066	0.663	1.166	0.65	2.267	0.636	3.367	0.623	4.467	0.61	5.567	0.596	6.667	0.582
0.102	0.663	1.202	0.649	2.302	0.636	3.402	0.623	4.502	0.609	5.602	0.596	6.702	0.582
0.137	0.662	1.237	0.649	2.338	0.636	3.438	0.622	4.538	0.609	5.638	0.595	6.738	0.582
0.173	0.662	1.273	0.648	2.373	0.635	3.473	0.622	4.573	0.608	5.673	0.595	6.773	0.581
0.208	0.661	1.308	0.648	2.409	0.635	3.509	0.621	4.609	0.608	5.709	0.594	6.809	0.581
0.35	0.66	1.45	0.646	2.551	0.633	3.651	0.62	4.751	0.606	5.851	0.593	6.951	0.579
0.386	0.659	1.486	0.646	2.586	0.633	3.686	0.619	4.786	0.606	5.886	0.592	6.986	0.578
0.421	0.659	1.521	0.645	2.622	0.632	3.722	0.619	4.822	0.605	5.922	0.592	7.021	0.578
0.457	0.658	1.557	0.645	2.657	0.632	3.757	0.618	4.857	0.605	5.957	0.591	7.057	0.578
0.492	0.658	1.592	0.645	2.693	0.631	3.793	0.618	4.893	0.604	5.993	0.591	7.092	0.577
0.528	0.657	1.628	0.644	2.728	0.631	3.828	0.617	4.928	0.604	6.028	0.59	7.128	0.577
0.563	0.657	1.663	0.644	2.764	0.63	3.864	0.617	4.964	0.604	6.064	0.59	7.163	0.576
0.599	0.657	1.699	0.643	2.799	0.63	3.899	0.617	4.999	0.603	6.099	0.59	7.199	0.576
0.741	0.655	1.841	0.642	2.941	0.628	4.041	0.615	5.141	0.601	6.241	0.588	7.341	0.574
0.776	0.654	1.876	0.641	2.976	0.628	4.077	0.614	5.177	0.601	6.277	0.587	7.376	0.573
0.812	0.654	1.912	0.641	3.012	0.627	4.112	0.614	5.212	0.6	6.312	0.587	7.412	0.573
0.847	0.654	1.947	0.64	3.047	0.627	4.148	0.614	5.248	0.6	6.347	0.586	7.447	0.573
0.883	0.653	1.983	0.64	3.083	0.626	4.183	0.613	5.283	0.6	6.383	0.586	7.482	0.572
1.025	0.651	2.125	0.638	3.225	0.625	4.325	0.611	5.425	0.598	6.525	0.584	7.624	0.57
9.856	0.539	10.949	0.521	12.037	0.497	13.111	0.462	14.16	0.404	15.155	0.303	16.043	0.111
9.891	0.539	10.985	0.52	12.072	0.496	13.146	0.46	14.193	0.402	15.186	0.298	16.069	0.102
9.926	0.538	11.02	0.519	12.107	0.495	13.18	0.459	14.226	0.4	15.216	0.294	16.095	0.093
9.962	0.538	11.055	0.519	12.142	0.494	13.214	0.457	14.259	0.397	15.247	0.289	16.12	0.084
9.997	0.537	11.09	0.518	12.176	0.493	13.248	0.456	14.292	0.394	15.277	0.284	16.145	0.075
10.032	0.537	11.125	0.517	12.211	0.492	13.283	0.454	14.325	0.392	15.307	0.279	16.17	0.066
10.068	0.536	11.161	0.517	12.246	0.491	13.317	0.453	14.358	0.389	15.338	0.275	16.195	0.056
10.103	0.535	11.196	0.516	12.281	0.49	13.351	0.451	14.39	0.387	15.368	0.269	16.219	0.047
10.138	0.535	11.231	0.515	12.316	0.489	13.385	0.45	14.423	0.384	15.397	0.264	16.244	0.037
10.174	0.534	11.266	0.514	12.351	0.488	13.419	0.448	14.456	0.381	15.427	0.259	16.268	0.027

10.209	0.534	11.301	0.514	12.385	0.487	13.453	0.446	14.488	0.378	15.457	0.254	16.291	0.016
10.244	0.533	11.336	0.513	12.42	0.486	13.487	0.445	14.521	0.375	15.486	0.248	16.315	0.006
10.279	0.532	11.371	0.512	12.455	0.485	13.521	0.443	14.553	0.372	15.516	0.243	16.338	-0.005
10.315	0.532	11.407	0.511	12.49	0.484	13.555	0.441	14.586	0.369	15.545	0.237	16.361	-0.016
10.35	0.531	11.442	0.511	12.524	0.483	13.589	0.44	14.618	0.366	15.574	0.231		
10.385	0.531	11.477	0.51	12.559	0.482	13.623	0.438	14.65	0.363	15.603	0.225		
10.421	0.53	11.512	0.509	12.594	0.48	13.657	0.436	14.682	0.36	15.632	0.219		
10.456	0.53	11.547	0.508	12.628	0.479	13.691	0.434	14.715	0.356	15.661	0.213		
10.491	0.529	11.582	0.508	12.663	0.478	13.725	0.432	14.747	0.353	15.689	0.207		
10.527	0.528	11.617	0.507	12.698	0.477	13.758	0.43	14.779	0.35	15.717	0.2		
10.562	0.528	11.652	0.506	12.732	0.476	13.792	0.428	14.81	0.346	15.745	0.193		
10.597	0.527	11.687	0.505	12.767	0.475	13.826	0.426	14.842	0.343	15.773	0.187		
10.632	0.526	11.722	0.504	12.801	0.473	13.859	0.424	14.874	0.339	15.801	0.18		
10.668	0.526	11.757	0.504	12.836	0.472	13.893	0.422	14.905	0.335	15.829	0.173		
10.703	0.525	11.792	0.503	12.87	0.471	13.926	0.42	14.937	0.331	15.856	0.166		
10.738	0.525	11.827	0.502	12.905	0.47	13.96	0.418	14.968	0.328	15.884	0.158		
10.773	0.524	11.862	0.501	12.939	0.468	13.993	0.416	15	0.324	15.911	0.151		
10.809	0.523	11.897	0.5	12.974	0.467	14.027	0.414	15.031	0.32	15.938	0.143		
10.844	0.523	11.932	0.499	13.008	0.466	14.06	0.411	15.062	0.315	15.964	0.135		
10.879	0.522	11.967	0.498	13.043	0.464	14.093	0.409	15.093	0.311	15.991	0.127		
10.914	0.521	12.002	0.497	13.077	0.463	14.126	0.407	15.124	0.307	16.017	0.119		

I-V data for a thick dusted CIGS solar module

V	I	V	I	V	I	V	I	V	I	V	I
-0.241	0.03	-0.026	0.027	0.188	0.023	0.402	0.018	0.58	0.012	0.757	0.004
-0.205	0.029	0.009	0.026	0.224	0.022	0.438	0.017	0.616	0.01	0.793	0.002
0	0.029	0.045	0.026	0.26	0.021	0.474	0.016	0.651	0.009	0.828	0
-0.134	0.028	0.081	0.025	0.295	0.021	0.509	0.014	0.687	0.007	0.863	-0.003
-0.098	0.028	0.117	0.024	0.331	0.02	0.545	0.013	0.722	0.006	0.898	-0.005
-0.062	0.027	0.153	0.024	0.367	0.019						

APPENDIX E

NORMALIZED I-V DATA

V	I	V	I	V	I	V	I	V	I	V	I	V	I
0	1.030	1.308	1.010	2.622	0.990	3.937	0.968	5.251	0.946	6.565	0.921	7.878	0.893
0.029	1.030	1.343	1.010	2.658	0.988	3.972	0.967	5.287	0.944	6.600	0.920	7.913	0.893
0.064	1.029	1.379	1.009	2.693	0.988	4.008	0.967	5.322	0.943	6.636	0.920	7.949	0.892
0.100	1.029	1.415	1.009	2.729	0.987	4.044	0.966	5.357	0.943	6.672	0.918	7.984	0.891
0.136	1.028	1.450	1.007	2.765	0.987	4.079	0.966	5.393	0.942	6.706	0.918	8.020	0.891
0.170	1.028	1.486	1.007	2.800	0.986	4.115	0.965	5.428	0.942	6.742	0.917	8.056	0.890
0.206	1.026	1.522	1.006	2.836	0.986	4.150	0.965	5.464	0.941	6.778	0.916	8.091	0.889
0.242	1.026	1.556	1.006	2.871	0.985	4.185	0.963	5.500	0.941	6.813	0.916	8.126	0.889
0.277	1.025	1.592	1.005	2.906	0.985	4.221	0.963	5.535	0.940	6.849	0.915	8.162	0.887
0.313	1.025	1.628	1.005	2.942	0.984	4.257	0.962	5.571	0.940	6.885	0.915	8.197	0.886
0.349	1.025	1.663	1.004	2.978	0.984	4.292	0.962	5.606	0.939	6.919	0.914	8.233	0.886
0.384	1.024	1.699	1.004	3.013	0.982	4.328	0.961	5.641	0.939	6.955	0.912	8.269	0.885
0.420	1.024	1.735	1.004	3.049	0.982	4.364	0.961	5.677	0.937	6.991	0.912	8.303	0.884
0.455	1.023	1.770	1.003	3.085	0.981	4.398	0.960	5.713	0.937	7.026	0.911	8.339	0.884
0.490	1.023	1.806	1.003	3.120	0.981	4.434	0.960	5.748	0.936	7.062	0.911	8.375	0.883
0.526	1.022	1.841	1.001	3.155	0.980	4.470	0.959	5.784	0.935	7.098	0.910	8.410	0.881
0.562	1.022	1.876	1.001	3.191	0.980	4.505	0.959	5.819	0.935	7.132	0.909	8.446	0.880
0.597	1.020	1.912	1.000	3.226	0.980	4.541	0.958	5.854	0.934	7.168	0.909	8.481	0.880
0.633	1.020	1.948	1.000	3.262	0.979	4.577	0.956	5.890	0.934	7.204	0.908	8.516	0.879
0.669	1.019	1.983	0.999	3.298	0.979	4.612	0.956	5.926	0.933	7.239	0.908	8.552	0.878
0.704	1.019	2.019	0.999	3.333	0.978	4.647	0.955	5.961	0.933	7.275	0.906	8.588	0.878
0.739	1.018	2.055	0.998	3.369	0.978	4.683	0.955	5.997	0.931	7.311	0.905	8.623	0.877
0.775	1.018	2.089	0.998	3.404	0.977	4.718	0.954	6.033	0.931	7.345	0.905	8.658	0.876
0.810	1.018	2.125	0.997	3.439	0.977	4.754	0.954	6.067	0.930	7.381	0.904	8.694	0.876
0.846	1.017	2.160	0.997	3.475	0.975	4.790	0.953	6.103	0.929	7.417	0.904	8.729	0.874
0.882	1.017	2.196	0.996	3.511	0.975	4.825	0.953	6.139	0.929	7.452	0.903	8.765	0.873

0.917	1.016	2.232	0.996	3.546	0.974	4.861	0.952	6.174	0.928	7.488	0.902	8.800	0.872
0.953	1.016	2.267	0.994	3.582	0.974	4.896	0.952	6.210	0.928	7.523	0.902	8.835	0.872
0.989	1.015	2.303	0.994	3.618	0.973	4.931	0.950	6.246	0.927	7.558	0.901	8.871	0.871
1.023	1.015	2.339	0.994	3.652	0.973	4.967	0.950	6.280	0.927	7.594	0.899	8.906	0.870
1.059	1.013	2.373	0.993	3.688	0.972	5.003	0.949	6.316	0.925	7.630	0.899	8.942	0.870
1.095	1.013	2.409	0.993	3.724	0.972	5.038	0.949	6.352	0.924	7.665	0.898	8.978	0.868
1.130	1.012	2.445	0.992	3.759	0.971	5.074	0.948	6.387	0.924	7.701	0.897	9.012	0.867
1.166	1.012	2.480	0.992	3.795	0.971	5.110	0.948	6.423	0.923	7.736	0.897	9.048	0.866
1.202	1.012	2.516	0.991	3.831	0.969	5.144	0.947	6.459	0.923	7.771	0.896	9.084	0.866
1.237	1.011	2.552	0.991	3.866	0.969	5.180	0.947	6.493	0.922	7.807	0.896	9.119	0.865
1.272	1.011	2.587	0.990	3.901	0.968	5.216	0.946	6.529	0.922	7.843	0.895	9.155	0.864
10.501	0.827	11.810	0.782	13.117	0.726	14.418	0.651	15.714	0.550	17.001	0.410	18.274	0.213
10.536	0.826	11.846	0.781	13.151	0.723	14.453	0.649	15.749	0.546	17.035	0.406	18.307	0.207
10.572	0.824	11.880	0.779	13.187	0.722	14.489	0.646	15.783	0.544	17.069	0.402	18.342	0.200
10.607	0.823	11.916	0.778	13.222	0.720	14.523	0.644	15.819	0.541	17.104	0.397	18.376	0.194
10.643	0.822	11.952	0.777	13.257	0.719	14.559	0.642	15.854	0.537	17.138	0.392	18.409	0.187
10.678	0.821	11.986	0.775	13.293	0.716	14.594	0.639	15.888	0.533	17.173	0.387	18.444	0.179
10.713	0.820	12.022	0.773	13.328	0.715	14.629	0.637	15.923	0.531	17.208	0.383	18.478	0.173
10.749	0.819	12.058	0.772	13.363	0.713	14.664	0.634	15.958	0.527	17.242	0.378	18.512	0.166
10.785	0.817	12.092	0.771	13.398	0.710	14.699	0.632	15.993	0.524	17.277	0.373	18.546	0.159
10.819	0.816	12.128	0.770	13.434	0.709	14.734	0.630	16.028	0.520	17.312	0.368	18.580	0.153
10.855	0.815	12.164	0.767	13.468	0.707	14.769	0.627	16.063	0.517	17.346	0.364	18.614	0.146
10.891	0.814	12.198	0.766	13.504	0.706	14.805	0.624	16.097	0.513	17.380	0.359	18.648	0.139
10.926	0.813	12.234	0.765	13.539	0.703	14.839	0.621	16.132	0.510	17.415	0.354	18.682	0.132
10.961	0.811	12.270	0.764	13.574	0.702	14.874	0.619	16.167	0.506	17.449	0.348	18.716	0.125
10.997	0.810	12.304	0.763	13.610	0.700	14.910	0.617	16.202	0.503	17.484	0.343	18.750	0.118
11.032	0.809	12.340	0.760	13.645	0.697	14.944	0.614	16.237	0.499	17.519	0.339	18.784	0.109
11.067	0.808	12.376	0.759	13.680	0.696	14.979	0.611	16.272	0.495	17.552	0.334	18.817	0.102
11.103	0.807	12.410	0.758	13.715	0.694	15.015	0.608	16.306	0.492	17.587	0.328	18.852	0.095
11.138	0.805	12.446	0.757	13.751	0.691	15.049	0.606	16.341	0.488	17.622	0.323	18.886	0.088

11.174	0.804	12.482	0.754	13.785	0.690	15.085	0.604	16.376	0.485	17.656	0.317	18.919	0.080
11.209	0.803	12.516	0.753	13.821	0.688	15.120	0.600	16.410	0.480	17.690	0.312	18.953	0.072
11.244	0.802	12.552	0.752	13.856	0.685	15.154	0.598	16.445	0.476	17.725	0.307	18.987	0.064
11.280	0.801	12.587	0.750	13.891	0.683	15.190	0.595	16.480	0.473	17.759	0.302	19.021	0.057
11.315	0.800	12.622	0.748	13.926	0.682	15.225	0.592	16.515	0.469	17.793	0.296	19.055	0.049
11.350	0.798	12.658	0.747	13.962	0.680	15.259	0.589	16.550	0.465	17.828	0.290	19.25	0.000
11.386	0.797	12.693	0.745	13.996	0.677	15.295	0.587	16.585	0.461	17.862	0.284		
11.421	0.796	12.728	0.744	14.032	0.675	15.330	0.583	16.619	0.457	17.896	0.279		
11.456	0.795	12.764	0.743	14.067	0.674	15.364	0.581	16.654	0.453	17.931	0.273		
11.492	0.794	12.799	0.740	14.102	0.671	15.399	0.577	16.689	0.449	17.966	0.267		
11.528	0.792	12.834	0.739	14.137	0.669	15.435	0.575	16.723	0.444	17.999	0.261		
11.562	0.791	12.869	0.738	14.173	0.666	15.469	0.571	16.758	0.441	18.034	0.255		
11.598	0.790	12.905	0.735	14.207	0.664	15.504	0.569	16.793	0.436	18.068	0.249		
11.634	0.789	12.940	0.734	14.243	0.662	15.540	0.565	16.827	0.432	18.102	0.244		
11.668	0.788	12.975	0.732	14.278	0.661	15.574	0.563	16.862	0.428	18.137	0.238		
11.704	0.786	13.011	0.731	14.313	0.658	15.609	0.560	16.897	0.423	18.171	0.232		
11.740	0.784	13.045	0.728	14.348	0.656	15.644	0.556	16.931	0.419	18.205	0.225		
11.774	0.783	13.081	0.727	14.383	0.653	15.679	0.554	16.966	0.415	18.239	0.219		