DETERMINATION OF YEARLY PERFORMANCEAND DEGRADATION RATE OF ELECTRICAL PARAMETERS OF A MONOCRYSTALLINE PV MODULE IN MINNA, CENTRAL NIGERIA

BY

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MTech/SPS/2017/6922

DEPARTMENT OF PHYSICS

FEDERAL UNIVERSITY OF TECHNOLOGY

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ABSTRACT

There is a need for accurate knowledge of the performance, degradation rate, and lifespan of the photovoltaic (PV) module in every location for an effective solar PV power system. Outdoor degradation analysis was carried out on a mono-crystalline PV module rated 10 W using the CR1000 software-based Data Acquisition System (DAS). The PV module under test and meteorological Sensors were installed on a metal support structure on the same test plane. The data obtained was monitored from 09:00 to 18:00 hours each day continuously for a period of four years, from December 2014 to November 2018.The experiment was carried out near the Physics Department, Federal University of Technology, Minna (latitude 09^{o}37'N, longitude 06^{o}32'E, and 249 meters above sea level). The sensors were connected directly to the CR1000 Campbell Scientific data logger, while the module is connected to the logger via electronic loads. The logger was programmed to scan the load current from 0 to 1 A at intervals of 50mA every 5 minutes, and average values of short-circuit current, (I_{sc},) open-circuit voltage, (V_{oc}), current at maximum power, ($I_{max)}$, the voltage at maximum power,($V_{max)}$, power and maximum power obtained from the modules together with the ambient parameters are recorded and logged. Data download at the data acquisition site was performed every 7 days to ensure effective and close monitoring of the data acquisition system (DAS). At the end of each month and where necessary, hourly, daily and monthly averages of each of the parameters-solar irradiance, solar insolation, wind speed, ambient and module temperatures, and the output response variables (open-circuit voltage, V_{oc}, short-circuit current, I_{sc}, the voltage at maximum power, V_{max}, current at maximum power, I_{max}, efficiency, Eff, and fill factor, FF) of the photovoltaic modules were obtained.Yearly averages of the performance variables were obtained to ascertain the performance, degradation rate, and lifespan of the module. The module performance for the four years of study was compared with Standard Test Condition (STC) specifications. The maximum power achieved at 1000W/m^2 for the four years of study are 0.711W, 1.82W, 0.50W, and 0.22W representing 7.11%, 18.39%, 5.0% and 2.25% of the manufacturer's 10W specification. Module efficiency at 1000W/m^2 for the four years of study is 3.30%, 10.12%, 3.98%, and 2.82% respectively as against the manufacturer's STC specification of 46%. Accordingly, Module Performance Ratios for the PV module investigated were 0.072, 0.22, 0.087, and 0.061respectively. For the Rate of Degradation (RoD), it was observed that Open-Circuit voltage (V_{oc}), Short-Circuit Current (I_{sc}), Power-Output (P), and Maximum Power (P_{max}), has an average yearly degradation rate of 1.06V, 0.002A, 0.082W and 0.142W representing 4.9%,0.30%,0.56%, and 1.4%respectively for the four years of study. The lifespan of the module was also determined through an empirically generated statistical model given as YEAR =4.60 -0.603Voc (v)-6.83Isc(A) +1.75 Power (W) was fitted to the observed data to predict the lifetime and yearly performance status of the module at any given year.

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LIST OF ABBREVIATIONS

A	Area of the module
ANOVA	Analysis of variance
a-Si	Amorphous silicon
Coef	Coefficients of variables
Ee	irradiance
Eff	Efficiency
FF	Fill Factor
Hg	Solar irradiance
I_{max}	Current at the maximum PowerPoint
I_{mp}	Current at P_{max}
I_{sc}	Short circuit current
MPR	Module Performance Ratio
P	Power output
P_{in}	Solar power input
P_{max}	Maximum power
PV	Photovoltaic
RoD	Rate of Degradation
RH	Relative Humidity
STC	Standard Test Conditions
SWE	Stablear-Wronski effect
SE	Standard Error

StDev	Standard deviation
T_a	Ambient temperature
T_{mod}	Module Temperature
V_{mp}	Voltage at P_{max}
V_m	Voltage at the maximum PowerPoint
WS	Wind Speed
Eff	Efficiency
V_{oc}	Open circuit voltage

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CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the study

Photovoltaic is a system of renewable energy based on the availability of sunlight all year round and has come to stay as part of the electrical energy mix in Europe, the United States, Japan, China, Australia, Nigeria, and many more countries. A solar cell is a device that converts energy from sunlight to electricity using the photovoltaic (PV) effect, this technology is one of the promising ways to achieve the rapidly increasing global electricity demanding with apollution-free environment. The reliability and durability of PV modules are of extreme importance for the reliability of the entire PV system, the solar-powered grid, promote the credibility of PV, and increase the investment in the PV industry. Besides, improving PV reliability contributes to reducing the leveled cost of electricity (LCOE) for PV-generated electricity.

The science regarding the reliability of PV modules is still immature(Pramod*et al*.,2016). There is not yet a complete understanding of what qualification test or test sequence is required to guarantee that a particular PV module would survive 25 years in a particular climate. It is well understood that the degradation rate or the lifetime of PV modules and systems are greatly influenced by the climatic conditions (Ezenwora, 2016), but the exact understanding of the influence of temperature, thermal cycling, UV exposure, relative humidity, or a combination of these is far from being completed. It is, therefore, necessary to build a database of real-world performance and reliability for estimating the leveled cost of electricity in different climatic conditions. Most degradation studies have so far been based on temperate and hot-dry climates due to the abundance of data in this type of climate.

It is important to know that the sun is the nearest star to the earth and therefore the source of all renewable energy on earth which provides sustenance for both plants, animals and also serves as the source for the solar system. Indeed, solar energy is used for industry, communities as well as individual needs. Over the past decade, the photovoltaic (PV) market has experienced unprecedented growth and besides these, the photovoltaic market has reached a cumulative installed capacity of roughly 40 GW worldwide, with an annual added capacity of 16.6 GW (EPIA, 2011). However, there is little information on PV module degradation in terms of frequency, speed of evolution, and degree of impact on module lifetime and reliability. Research on photovoltaic modules is rather focused on the race to develop new technologies to provide sufficient experience feedback on already operational technologies (Larondee*t al*., 2012; Tiwari*et al.*, 2010 and Dubey*et al., 2010*). For economic development in a society, the rate at which the demands for electricity will keep increasing as the population keeps increasing. Let us consider the present situation whereby primary energy account for 40% of the global energy used for power generation, and solar or renewable energy only account for 3.6% (Nasiror, 2018). It implies that the renewable energy demands that work needed to be done on it to be able to withstand higher population. The investigation of the performance evaluation and degradation rate of the monocrystalline photovoltaic module in the local environment will establish a degradation rate comparison between the locally available modules and the laboratory projection and a database will be generated where necessary.The result of these investigations will assist the designers, scientists, and Energy Research centers to get first-hand information on the performance of the module in the local environment before they proceed on design and installation for power supply.

1.2 Solar Energy availability

Solar energy has been harnessed by humans for thousands of years for heating purposes, and more recently for electricity generation. Solar power is an extremely vast resource, a good and accurate knowledge of the availability of solar radiation data in a location is primarily important for designing a system using solar energy by engineers and scientistsbut it has some limitations on availability that can affect its deployment around the world.(https://sciencing.com/availability-solar-energy-5518265.html).The sun imparts a huge amount of sunlight on the Earth every day, and although about half of it is reflected by the atmosphere. The Earth absorbs about 3,850,000 joules of solar energy every year. More so, solar energy is absorbed by the Earth in one hour than the entire human population uses in one year.

Locations close to the north and south poles experience extended hours of sunlight, but it is only for a portion of the year, and they experience reduced hours of sunlight at opposite times of the year. Some solar power facilities employ energy storage systems to store excess power during off-peak periods and to deliver power during peak periods or overnight. Solar radiation is electromagnetic radiation and occurs over a wide range of wavelengths. The main range of solar radiation includes Ultraviolet (UV), 0.001- 0.4µm, Visible Spectrum (Light), 0.4 – 0.7µm, and Infrared radiation (IR), 0.7-100µm (www.eesc.columbia.edu/course/ees/climate/lectures/radiation/,2013). Solar radiation is fundamental to life on Earth, providing the ceaseless supply of energy that fuels nearly every ecosystem on the planet. Beyond making our very existence possible, energy from the sun has for decades attracted attention as a clean, renewable alternative to fossil fuels. Though at present it supplies only a fraction of global energy, the solar industry is a rapidly expanding component of the renewable energy sector. While debate certainly continues over the cost, practicability, and performance of industrial-scale solar installations, the technology offers much promise as a sustainable source of energy. (https://sciencing.com/availability-solar-energy-5518265.html). Each second, the sun turns a tiny fraction – half a trillionth – of this energy falls on Earth after a journey of about 150 million kilometers, which takes a little more than eight minutes. The solar irradiance, *i.e. the* amount of power that the Sun deposits per unit areaare 1368 watts per square meter (W/m^2) at that distance. This measure is called the solar constant. However, sunlight on the surface of our planet is attenuated by the earth's atmosphere, so less power arrives at the surface with about 1000 W/m^2 in clear conditions when the sun is near the zenith. Our planet is not a disk, however, but a kind of rotating ball. The surface area of a globe is four times the surface area of a same-diameter disk. As a consequence, the incoming energy received from the sun averaged over the year and the surface area of the globe is one-fourth of 1 368 W/m^2*i.e.* 342 W/m^2. Of these 342 W/m^2 roughly 77 W/$m^2$are reflected in space by clouds, aerosols, and the atmosphere, and 67 W/m^2 are absorbed by the atmosphere (IPCC, 2001). The remaining 198 W/m^2, *i.e.* about 57% of the total hits the earth's surface (on average). The solar radiation reaching the earth's surface has two components: direct radiation, which comes directly from the sun's disk; and diffuse radiation, which comes experienced as "sunshine", a combination of bright light and radiant heat. Diffuse irradiance is experienced as "daylight". On any solar device, one may also account for a third component – the diffuse radiation reflected by ground surfaces. The term global solar radiation refers to the sum of the direct and diffuse components.

In total, the sun offers a considerable amount of power: about 885 million terawatt-hours (TWh) reach the earth's surface in a year, that is 6 200 times the commercial primary

energy consumed by humankind in 2008 and 4200 times the energy that mankind would consume in 2035 following the IEA's Current Policies Scenario. (https://sciencing.com/renewable-vs-nonrenewable-energy-resources 12071170.html).The unavailability of irradiation data for many places led to the development of various methods of estimating these parameters theoretically. (Sayigh,1977;Ugwuoke *et al*.,2005a) and The International Energy Agency (IEA) gave examples of the various relations that use meteorological data to estimate solar radiation.The most convenient and most widely used relationship is given by (Luhanga and Andringa, 1990; Ugwuoke,2005b; Ezanwora,2016).

$$H = H_O(a + b \times \frac{S}{S_O}) \qquad (1.1)$$

where: $H_O$are the extraterrestrial radiations

$S_O$is the daylights and is given as S_O= (2/15)cos^{-1}(-tanθtan δ) (1.2)

whereθ and $\delta$are latitude and declination angle respectively,

The spectral distribution of light emitted by the sun extends from a wavelength of less than 0.3µm to 4.0µm (Leckner, 1978; Ezenwora, 2016).This is attenuated by at least 30% during its passage through the earth's atmosphere. The causes of the attenuation include:

(i)The Rayleigh scattering or scattering by molecules in the atmosphere

(ii)Scattering by Aerosols and dust particles.

(iii)Absorption by the atmosphere and its constituents gases like oxygen, ozone, water vapor and carbon dioxide in particular.

1.3 Statement of the Research problem

It should be noted that consumers are becoming more and more interested in the reliability and lifetime of their PV system, though we have the lifetime of solar modules in works of literature but in most cases, it is a projection from the laboratory condition since the manufacturer's specifications on solar panels are obtained under controlled laboratory condition known as standard test condition (solar irradiance of 1000 W/m^2, Air Mass (AM) of 1.5 and operating temperature of 25^o(C) (Kifilideen *et al*., 2018) or sometimes it is usually from a foreign climate zone other than ours which is not the true representation of the real conditions in which the PV devices have to operate. Research has shown that the output of PV modules differs significantly once exposed to outdoor conditions (Ryan *et al*., 2012: Ezenwora, 2016).Consequently, laboratory conditions are suspect and contestable, and actual outdoor evaluation as regards degradation rateand lifetime has not been done inMinna's local environment since the atmospheric parameters that are responsible for the degradation changes with location.

Therefore, the need to study the rate at which atmospheric parameters affects the electrical parameters of monocrystalline PV modules in Minna local environment is important

1.4 Aim and Objectives of the study

The research is aimed at determining the yearly averagerate of degradation of electrical parameters of a monocrystalline photovoltaic Module in Minna, North Central Nigeria.

The Objectives of the research are to:

(i) characteriseand evaluate the performance of the monocrystallinemodules using four years of data obtained.

(ii) compare yearly performance variables of the module and deduce the rate of degradation using the four years of data obtained.

(iii) deduce empirically determined model for prediction of yearly performance and life span of the module in our environment.

1.5 Justification of the Research

Knowledge of the degradation rate and lifetime ofmonocrystalline silicon PV module will assist researchers, policymakers, PV energy designers, and installers in designing an effective PV power system best suitable for Minna local environment. It will equally give consumers firsthand information on what to expect from their PV power system before installation, comparative cost advantage and also energy payback.

1.6 Study Area

Photovoltaic effect availabilities on the earth's surface are site dependents and vary throughout the year. It is only worthwhile installing solar radiation-based energy equipping an area where one can be reasonably assured of an adequate supply of such radiation. Minna is located in the latitude $09^{o}36'50$" North and longitude of $06^{o}33'\,25$"East at altitude 249 meters above sea level. The climate of the northern zone in Nigeria is characterised by two seasons which include, the wet (or rainy) and the dry seasons (Harmattan).The annual onset and cessation of the dry and wet seasons follow the quasi-periodic North-South to andfro movement of the inter-tropic convergence zone(ITCZ). The ITCZ demarcates the dry dust-laden North-East trade wind from the moisture-laden south-west trade. The dry season in the Sahel zone of Nigeria set in about October every year and persists till about May of the next year. This is the period when the ITCZ is displaced to the prevailing North-East trade wind. It transports large quantities of dust smoke from biomass burning into the atmosphere over the entire region (Anuforom*et al*.,2007).

Dust and smoke aerosols affect the climate system at local, regional and global scales in severalways. Due to its direct radiation impact, dust, aerosol effects, atmospheric temperature, thereby tampering with the vertical temperature distribution in the troposphere as a result of the changes in heating and cooling rates at different altitudes (Carlson and Benjamin,1980;Quijano,2000).The stability of the atmosphere is therefore affected bythesun (Ezenwora,2016;*Bala et al.*,2000).Based on the above facts, Minna canusesolar cells as an alternative to electricity generation. Figure 1.1 shows the map of the study area.

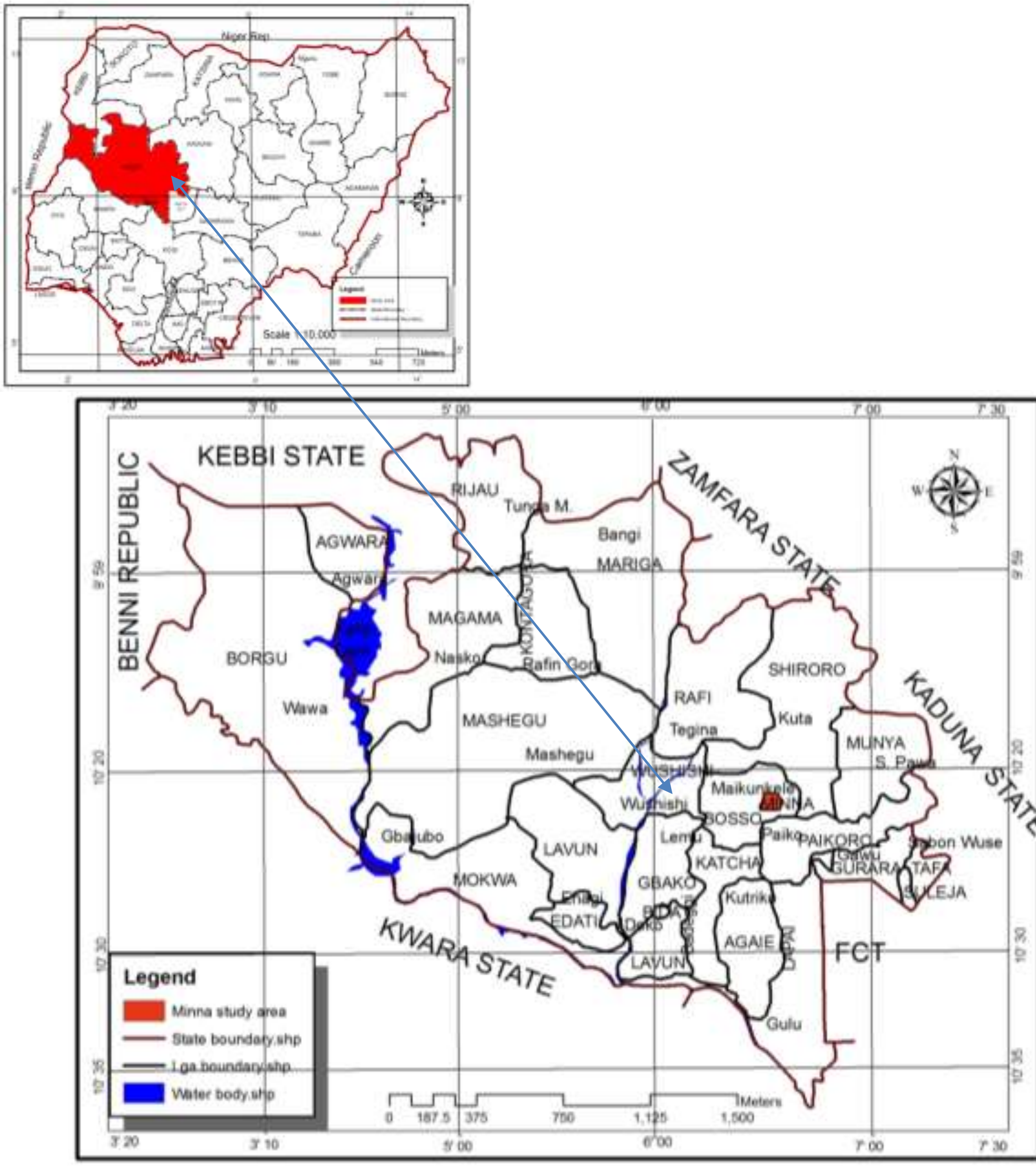


Figure 1.1 Map of study Area, Minna. (Ezenwora,2016)

1.7 Scope and limitations

Since the performance and degradations rate of photovoltaic module greatly depends on location, this studyis carried out in Minna, North-Central Nigeria. The rate at which atmospheric parameters will affect its performance in Minna will differ from other locations. Those atmospheric parameters are solar irradiance, ambient, temperature, wind, and relative humidity which may influence the performance variables of open-circuit voltage, short circuit current, the voltage at maximum power, current at maximum, power output, and maximum power. There are different types of photovoltaic modules which include; Moncrystalline silicon, Polycrystalline silicon, and Amorphous silicon whichmay degrade differently to different atmospheric parametersbutthis research is only limitedtoMonocrystalline silicon.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Photovoltaic Energy

A solar cell is an electronic device that consists of a potential energy barrier within semiconductor materials and is capable of converting a fraction of the energy contained in sunlight directly to electrical energy by separating the electrons and holes that are generated by the absorption of the light within the semiconductor. The general performance of solar photovoltaic cells in any location is a function of both the intensity and the spectral distribution of sunlight in such a location. The sun is the source of an electromagnetic wave through visible and invisible (light with different wavelengths) radiation. The first practical photovoltaic solar cell was developed in1954 at bell laboratories by Daryl Chapin, Calvin Souther Fuller and Gerard Pearson.The researchers used a diffused silicon p-n junction that reached about 6% efficiency, compared to the selenium cells that found it difficult to reach 1%. There are different type of silicon solar cell which includes: crystalline silicon solar cell (monocrystalline and polycrystalline) and the amorphous silicon solar cells. Most photovoltaic modules available in the market today are silicon-based and are assembled with 35 (or multiples) of solar cells connected in series or parallel to achieve the desired voltage and current respectively (Kuku,2000; Ezenwora*et al.*,2010).

The crystalline silicon solar cell had the major share of the world market in 1998 because it is holding a structure of a semiconductor device that is characterised by an orderly array of its component atoms. At low temperature, the electron in the crystal occupies the lowest possible energy level and might, therefore, be expected that the equilibrium state of a crystal would be one in which the electrons are all in the allowed energy level. This is not certain becausethe Pauli

Exclusion principle,which is the fundamentals physical theory showing that each allowed energy level can be occupied by at most,two electrons each of opposite spin. As the temperature increase, some electrons gain energy abovetheFermi level.The probability of occupation of an allowed state by an electron of any given energy E can be represented and as well calculated using equation 2.1 taking into account the constraints imposed by the Pauli Exclusion principle (Hovel,1975 and Ezenwora,2010).

$$F(E)= \frac{1}{1+e^{(E-E_f)/KT}} \qquad (2.1)$$

where K is the Boltzmann’s constant and T is the absolute temperature.

For the monocrystalline silicon module, theoretical studies have shown that cells made from monocrystalline silicon could reach efficiencies of more than 30% under standard test conditions (Bucher*et al*.,1985;Ugwuoke,2005a).These cells are made from pure monocrystalline silicon. In these cells, the silicon has a single continuous crystal lattice structure with almost no defects or impurities. The main advantage of mono-crystalline cells is their high efficiency, which is typically around 15%. The disadvantage of these cells is that a complicated manufacturing process is required to produce monocrystalline silicon, which results in slightly higher costs than those of other technologies. (Soteris,2009).Monocrystalline silicon is the pioneer of solar cell technology (Ezenwora, 2016.).And was first used for photovoltaic in 1954. When investigated,Bell telephone laboratories produced a PV device that converted 6% of sunlight striking it into electrical energy. An ideal monocrystalline silicon solar cell or module is characterised by an orderly and periodic arrangement of the atoms of the silicon material.

The polycrystalline silicon solar cell has a lower-cost alternative to mono-crystalline silicon because the device made of polycrystalline are generally less efficient than those of monocrystalline silicon, the polycrystalline materials have certain advantages but it requires less purity of materials and can be adapted to automated mass-production techniques because of the way the starting materials were prepared. These cells make use of abundant silicon materials and have relatively high frequencies.The cell efficiency of the mono-crystalline and polycrystalline silicon is between 18% and 22%   while the module efficiencies remained between 13 % and 15%. They demonstrate good stability and share the broad technology base associated with monocrystalline silicon (Milstein,1983).Also, the amorphous silicon PV materials hold one of the most promising options for low-cost solar modules and are by far the most mature and commercially viable technology among the thin-film photovoltaic technologies. Amorphous silicon displays no atomic order or regularity on any macroscopic scale unlike crystalline silicon with its uniform lattice crystal structures.This disorder in amorphous silicon greatly limits the current flows even more than the grain boundaries do in polycrystalline materials. One of the advantages of amorphous silicon includes the ability to absorb solar radiation 40 times more efficiently than monocrystalline and polycrystalline silicon. Stable efficiency of 13% for amorphous silicon (a-sc) was achieved (Yang, 1997)

2.2 Temperature Variation and Performance of PV Modules Response

The temperature has a significant effect on the PV module characteristics. The photocurrent will increase slightly with increases in temperature, T. The slight increase in photocurrent arises from a decrease in the band-gap energy,E_g of the material as the temperature, T increases according to equation 2.2 (Emery, 1996; Ugwuoke, 2005b; Ezenwora, 2016)

$$E_g(\mathrm{T}) = E_g(0) - \frac{\alpha T^2}{T+b} \qquad (2.2)$$

where a and b are constants.

The open-circuit voltage would decrease linearly with cell temperature, owing to the exponential increase in reverse current. The reverse saturation current is a current of minority carries created by thermal excitation. Its variation with temperature can be expressed by equation 2.3 (Duffie and Bechman,1991;Nordmamn,2003)

$$I_0 = AT^3 \exp\left(-\frac{E_g}{KT}\right) \qquad (2.3)$$

A combination of slight increase in current (photocurrent) and a linear decrease in open-circuit voltage (Voc) with temperature causes the maximum power to decreases by about 0.35% $/o_C$ approximately, and therefore there is a proportional decrease in maximum efficiency according to equation 2.5 (Emery,1996;Ezenwora,2016)

$$Eff(XE_{e,}T) = EffE_{e,}T_o)[(E_1 - \beta_O(T - T_O)(1 + \frac{KT}{q})\frac{Inx}{V_{ov}(E_{O,}T_0)}) \qquad (2.4)$$

where To = initial absolute temperature and βo = temperature coefficient

2.3 Theoretical and Experimental Applications

The theory of metals, insulators, and semiconductors is that metals have electronic structures as its Fermi level (E_f) lies within an allowed band while insulators have one of it band occupied by electron but with a large empty gap between the next highest band,whichis deprived of electrons at low temperature. Hence, an insulator does not conduct electricity, whereas a metal do conduct electricity.A semiconductor is an insulator with a narrow forbidden gap and for which the allowed energy band of the highest energy for electrons is almost totally occupied. There are intrinsic semiconductors in which the motion of free electrons in the conduction band and the free holes in the valence band originate solely from thermal excitations across the band-gap.

There is also an extrinsic type in which additional electrons are present in the conduction band or valence band because of ionized acceptor or donor imperfection. These cause two situations (degenerate and non-degenerate).When many donor imperfections are present such that states at the bottom of the conduction band are almost totally occupied by electrons and Fermi level lies within the conduction band such a situation of the acceptor imperfection bring about degeneration status, but the state at the top of the valence band and almost totally occupied by holes and Fermi level lies within the valence is a non-degenerate situation. (Fahrenbruch and Bube,1983;Ugwuoke,2005b). In a non-degenerate case, whenimpurity known as dopants is introduced into the semiconductor, they can control relative concentrations of electrons in the conduction band of semiconductors and holes in the valence band.Careers in these bands can flow by drift and diffusion when the appropriate perturbation are present for electrons lying within the conduction band by considering the direct band-gap. Newton's law shows in equation 2.5

$$F= m_e a = \frac{dP}{dt} \qquad (2.5)$$

where F= the applied force, m_e= an effective mass of the electron which was introduced to effect the applied force of the lattice atoms and P is the crystal momentum. For a free electron, energy and momentum are related by equation 2.6.

$$E = \frac{P^2}{2m} \qquad (2.6)$$

For conduction band $E - E_c = \frac{P^2}{2m_e^*}$ (2.7)

And for the valence band, $E_v - E = \frac{P^2}{2m_h^*}$ (2.8)

Under the influence of applied field E, a randomly free moving electron would have an acceleration $\mathbf{a} = \frac{\boldsymbol{E}}{\boldsymbol{M}}$in the direction opposite to the field with its velocity increases with time.

Since a p-n junction solar cell only absorbs light photons with energy equal to or greater than its band-gap, different band-gap materials will respond differently to the same spectral distribution

(Green, 1995). The ability of a solar cell to absorb light photons with energy,hf is approximately expressed in equation 2.9 (Sze,1981, Green,1995)

$$\alpha = A(hf-E_g) \tag{2.9}$$

whereα = absorption coefficient in cm

A = 2×10^4

h = plank's constant

f = photon frequency

E_g = band-gap in E_V

Generally, a solar cell absorbs radiation from the sun when it strikes the solar module and uses the effect of photovoltaic to convert it directly to electricity.The operation of a photovoltaic (PV) cell requires three basic attributes (Kefilideen and Adewole,2018).

- The absorption of light, generating either electron-hole pairs.
- The separation of various types of charge carriers.
- The separate extraction of those carriers to an external circuit.

2.4Review of Previous Works

Some previous works on degradation and performance evaluation done by other researchers at different locations are presented in this section.

Huili*et al.*, 2018 analysed the performance degradation of a 110 kWp PV system after 18 years of operation under hot–humid climate conditions. Results show that the median power degradation of these modules is 24.38% or 1.54% per year. The median maximum power (*Pm*), open-circuit voltage (*V*oc), short-circuit current (*I*sc), and fill factor (FF) decreased by 24.38%, 2.02%, 7.37%, and 15.74%, respectively, compared with the nameplate values. It appears that the annual degradation of the power output of the modules varies between 0.94% per year and 2.51% per year, with a median value of 1.54% per year.

Ezenwora *et al*. (2018) carried out a comparative study on the different types of photovoltaic modules underoutdoor operating conditionsfor one year in Minna, Nigeria. The result reveals that the actual values of the performance variables of the modules differ greatly from the manufacturer's specifications. The magnitude of the difference between STC specification and the realistic outdoor performance, in this particular study, points to the fact that overrated modules are entering our local market.The maximum power output achieved for themono-crystalline module at an irradiance of 1000W/m^2 was 0.711 W, while module efficiency for the module type peaked at an irradiance of 375 W/m^2 with a value of 5.86%. This maximum value then decreased steadily with increased irradiance and at 1000 W/m^2, the efficiency reduced to 3.30 %, as against the manufacturer's specifications of 46 %.

Pramod*et al*. (2015) carried out the degradation of mono-crystalline modules after 22 years of outdoor exposure in the composite climate of India and the degradation rate of the P_{max} has been found with an average valueof 1.9%/year which is higher than the usually estimated 1.4%/year (Chandel*et al*., 2015).The maximum rate of power degradation was4.1%/year and the minimum is 0.3%/year. While the average rate of degradation of I_{sc} and V_{oc} was 1.8%/year and 1.4%/year respectively.

Kifilideen and Adewole(2018),**i**nvestigated the performance evaluation of monocrystalline photovoltaic panels in Funaab, Alabata, Ogun State, Nigeria weather conditions. The performance of the solar panel was evaluated from the short circuit current (Isc), open-circuit voltage (Voc), maximum current ($Imax$), maximum voltage ($Imax$), maximum output power, conversion efficiency, normalized output power efficiency and fill factor of each solar panel. The maximum output power of each panel was obtained from the I-V and P-V curves. The conversion efficiency of the six 80 W (480 W) solar panels ranged from 9.44 to 10.56% while the normalized output power efficiency ranged from 69.7 to 70.1%. The fill factors and the maximum output power of the six panels respectively are 0.57, 0.55, 0.57, 0.58, 0.60, 0.62 and 55.8, 54.1, 53.2, 59.4, 53.1, 59.4. A total of 335 W (69.8%) for the six panels was obtained. The results revealed that the actual performance of the solar panels does not correspond with the technical data provided by the manufacturer.

Dirk and Sarah (2012) worked on an analytical review of Photovoltaic degradation rates using field tests reported in the literature during the last 40 years. Nearly 2000 degradation rates, measured on individual modules or entire systems, have been assembled from the literature and show a mean degradation rate of 0·8%/year and a median value of 0·5%/year. The majority, 78% of all data, reported a degradation rate of <1%/year. Thin-film degradation rates have improved significantly during the last decade, although they are statistically closer to 1%/year than to the 0·5%/year necessary to meet the 25-year commercial warranties. The significant difference between a module and system degradation rates observed early on has narrowed, implying that substantial improvement toward the stability of the balance-of-system components has been achieved.

Ugwuokeand Okeke, (2012) worked on Characterisation and performance evaluationonthree different types of commercially available silicon PV module simultaneously; monocrystalline, polycrystalline and Amorphous with 55W,50W and 10W respectively. The experiment was carried out at the ground of Energy Research Center, University of Nigeria, Nsukka, South East of Nigeria at latitude $6^o 52N$ and longitude $7^0 24E$ between October 2004 and September, 2005.The performance of the modules was evaluated in terms of their response variables (V_{oc},V_{max}, I_{sc}, I_{max}, P_{max}, and Eff) as a function of ambient parameters. The result shows a significant decrease in efficiency, Eff, Maximum Voltage, open-circuit voltage, and Fill factor with an increase in module temperature at irradiances above 600 W/m^2 while maximum current,(I_{max},) and short-circuit current (I_{sc}) showed no noticeable effect of the module temperature rise. The results exhibit seasonal variations correlated with the average module temperature at different irradiance levels. The maximum power output obtained at an irradiance of 1000W//m^2 are 37.52W, 28.84W, and 6.94W for the mono-crystalline, polycrystalline and Amorphous silicon modules respectively. The module performance ratios (MPRs) defined as the effective efficiency of the efficiency at STC, varied from 34% to 77% depending on the module and irradiance level.

Durish*et al. (*1996). used a PC- based measuring system foroutdoor testing of solar cells and modules under real operating conditions which consists of a sun-tracked sample holder, different electronic loads (including control),digital millimeters, a PC and a laser printer. The insolation is measured and recorded with pyrometers, and a reference cell Current-voltage curves were acquired in the range of irradiance from 10 $W/m^2$to over 1000W/m^2.Two commercially available modules both consisting of monocrystalline silicon modules specified by the manufactures to produce under STC conditions, Maximum Powers of 55W and 85W,respectively were tested and evaluated.The efficiency of the two modulesis shown at constant irradiance and at varying module temperature. These data were used to determine the temperature coefficients of the efficiency of the two modules and using those coefficients and additional measurement, the corresponding efficiencies for varying irradiance were determined. The result presented exhibits maximum efficiencies of 16.05% at an irradiance of 661W/m^2 for module 1 and of 14.74% at an irradiance of 754 W/m^2. At irradiance of 1000W/m^2, the fits yielded 15.76% and 14.50% for the two modules respectively. The manufacturer's specifications of their efficiencies at STC are 16% for module 1 and 16.3% for module 2and at low intensities module 2 showed significant lower efficiencies than module 1

Ababacar*et al.*(2013). did a literature review on the degradation of silicon photovoltaic modules and he pointed out that the alleged reliability has led to the long warranty period for modules up to 25 years and that currently,failure resulting in module degradation is generally not considered because of the difficulty of measuring the power of a single module in a PV system and the lack of feedback on the various degradations modes of PV modules and he did point out that, temperature and humidity are factors of PV modules degradation in most of the identified degradation modes.Despite the identification of PV modules degradations mode,it is still difficult to study them in real conditions.

CHAPTER THREE

3.0 RESEARCH METHODOLOGY

This work involves characterisation and evaluation of the yearly performanceof the monocrystalline photovoltaic module in other to estimate the degradation rate of the various electrical parameters of themonocrystalline module type in Minna local environment using four years of data acquired. The research process involved two processes which include dataacquisition by continuous monitoring and data analysis

3.1 Data Acquisition

The degradation rate of electrical parameters of the monocrystalline PV modules to ambient weather parameters: solar irradiance, temperature, wind speed, and relative humidity, was monitored in Minna local environment, using a CR1000 software-based data logging system with a computer interface. The PV modules under test, and meteorological sensors, were installed on a support structure at the same test plane, at about three meters of height, to ensure adequate exposure to insolation and enough wind speed, since wind speed is proportional to height. The elevation equally ensures that the system is free from any shading from shrubs and also protected from damage or interference by intruders. Also, the whole experimental setup was secured in an area of about 16 square meters. The module was tilted at approximately 10^o (since Minna is on latitude 09^o37' N) to horizontal and south facing to ensure maximum insolation (Ezenwora, 2016; Scheller and Strong,1991). The data monitoring was from 9.00 am to 6.00 pm local time each day continuously for a period of four years, starting from December 2014 to November 2018. The experiment was carried out in the experimental garden at Bosso campus of the Federal University of Technology, Minna (latitude 09^o37' N, longitude 06^o32' E and 249 meters above sea level). The sensors were connected directly to the CR1000 Campbell Scientific data logger, while the module was connected to the logger via electronic load. The logger was programmed to scan the load current from 0 to 1 A at an interval of 50 mA every 5 minutes, and average values of short-circuit current,(I_{sc}), open-circuit voltage, (Voc), current at maximum power,(I_{max}), the voltage at maximum power(Vmax,) power and maximum power obtained from the modules together with the ambient parameters are recorded and logged. Data download at the data acquisition site was performed every 7 days to ensure effective and close monitoring of the data acquisition system. The global solar radiation was monitored using Li-200SA M200 Pyra-nometer, manufactured by LI-COR Inc. USA, with the calibration of 94.62 microamperes per 1000 W/m^2. The ambient temperature and relative humidity were monitored using HC2S3-L Rotronic Hy-groClip2 Temperature/Relative Humidity probe, manufactured in Switzerland. Wind speed was monitored using 03002-L RM Young Wind Sentry Set. And module temperature was monitored using a110PV-L Surface-Mount Temperature probe. All sensors were installed in the CR1000 Campbell Scientific data logger with the measurement and control module. The experimental set up is shown in plateI

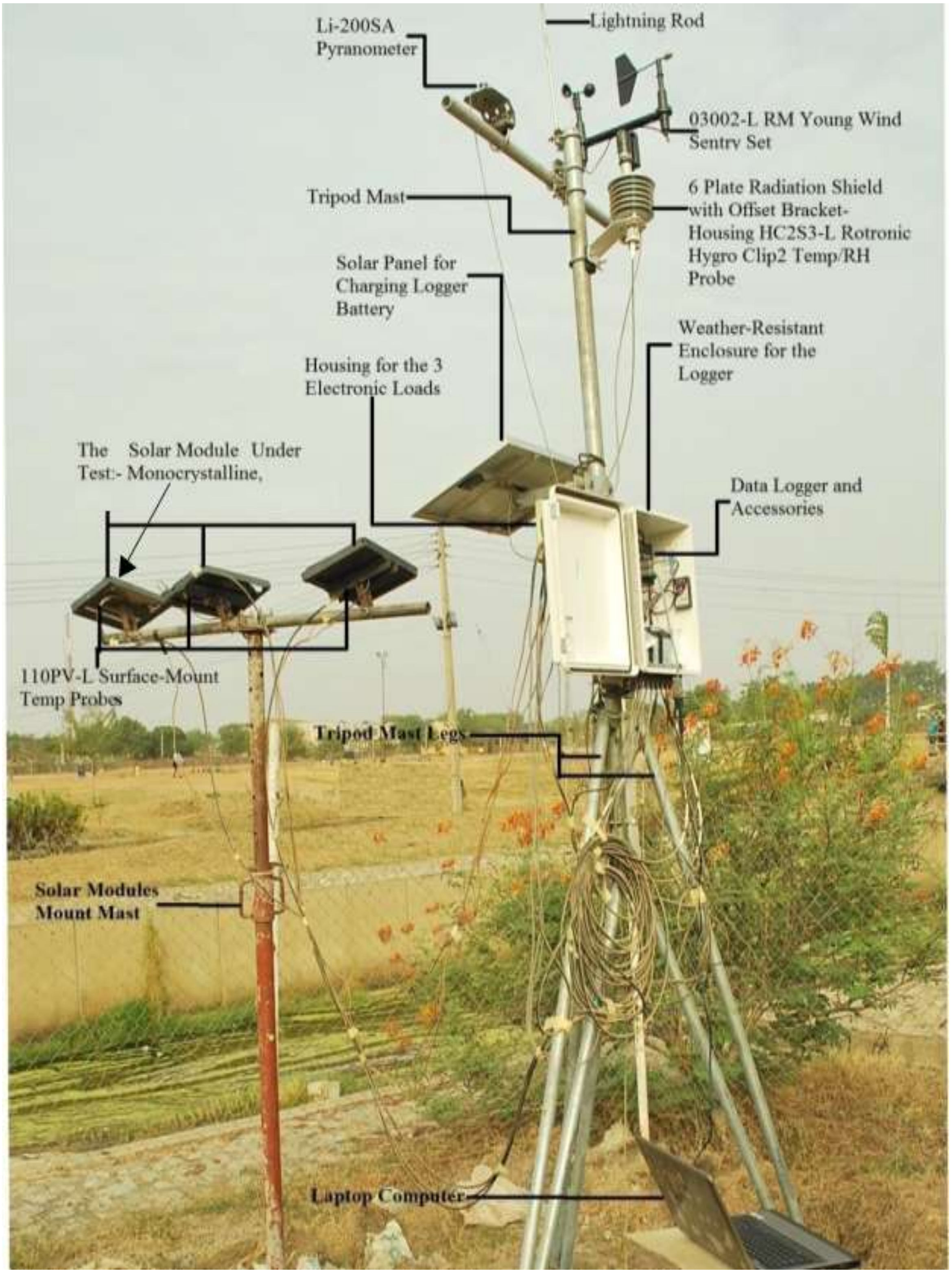


Plate I: The Experimental set up

Table:3.1: Manufacturer’s specifications of the monocrystalline module at standard test conditionand its dimensions.

Cell Technology	No of cells per Module	Max. Rated Power (W)	Max. Rated Voltage (V)	Max. Rated Current (A)	Open-Circuit Voltage (V)	Short-Circuit Current (A)	Module Dimensions (m x m)	Cell Dimensions (m x m)	Total Surface Area of Cells (m^2)	Model/Make	Eff (%)
MonocrystallineModule	72 Cells of 4 parallel and 18 series straing	10	17.4	0.57	21.6	0.67	0.29 x 0.16	0.025 x 0.012	0.0216	SLP 10.12 / China	46*

Table 3.1give the details of the manufacturer’s specification of the performance variables and dimensions of the monocrystalline photovoltaic module under investigation. The maximum rated power is 10W, the maximum rated voltage is 17.4V, and the maximum current is 0.57A, the open-circuit voltage Voc is 21.6 V, short circuit current of 0.67A.The frequency of the module was calculated to be 46 % using equation 3.2

3.2 Method of Data Analysis

Analysis of the yearly degradation rate of the monocrystallinemodule was investigated in terms of open-circuit voltage (Voc),Short-circuit current (Isc), Voltage at Maximum power (Pmax),current at maximum power(Imax),Efficiency(Eff), Fill factor(FF) and module performance Ratio (MPR) was also evaluated using the following expressions:

$$\text{Fill factor (FF)} = I_{max}V_{Max}/I_{SC}\,V_{oc} \quad (3.1)$$

$$\text{Efficiency (Eff)} = {}^{I_{Max}V_{max}}/_{P_{in}} = I_{sc}VocFF/P_{in} = {}^{I_{sc}V_{OC}}/_{AE_e} \quad (3.2)$$

Module performance Ratio, MPR = Effective Efficiency/Efficiency at STC (3.3)

The maximum power (P max) which is the operating point of the module,was recorded by the logger which is expected to corresponds to the largest area of a rectangle that fit inside the I-Vcurve.Thehighest current and voltage at this point are Maximum Current ($I_{\max}$) and voltage maximum ($V_{\max}$) respectively.

Microsoft Excel was used to analyse the data and the hourly averages,monthly averages, and annual averages of the performance variables as against theirambient parameters were calculated and recorded. In the case of the hourly averages, 12 x 20 coulombs per performance variable was recorded by the logger per hour since the logger scanned the load current from 0 to 1 A at an interval of 50mA every five minutes from the hour of9:00am to 6:00pm daily.A mini syntax programme was developed to calculate the hourly, daily, and yearly averages given the enormity of data involved and the resultsare displayed in Table 4.1 to 4.4. The percentage degradation rates of the various electrical parameters like output power,short-circuit current (Isc),open-circuit voltage (Voc), and fill factor (FF) are therefore calculated for the nameplate rating of the module provided by the manufacturer using the following formula (Phinikarides*et al*.,2014;Pramod *et al.*,2016)

$$\text{Rate of degradation (RoD)} = \frac{Initial\ data - Final\ data}{Final\ data} \times 100 \qquad (3.4)$$

Then thereafter, statistical software Minitab version 17 was used for the statistical analysis of the data. Both descriptive and inferential statistics were used for the analysis of the data.Regression model for the prediction of yearly performance status life time of the module was equally carried out.Details are found in section 4.2.

CHAPTER FOUR

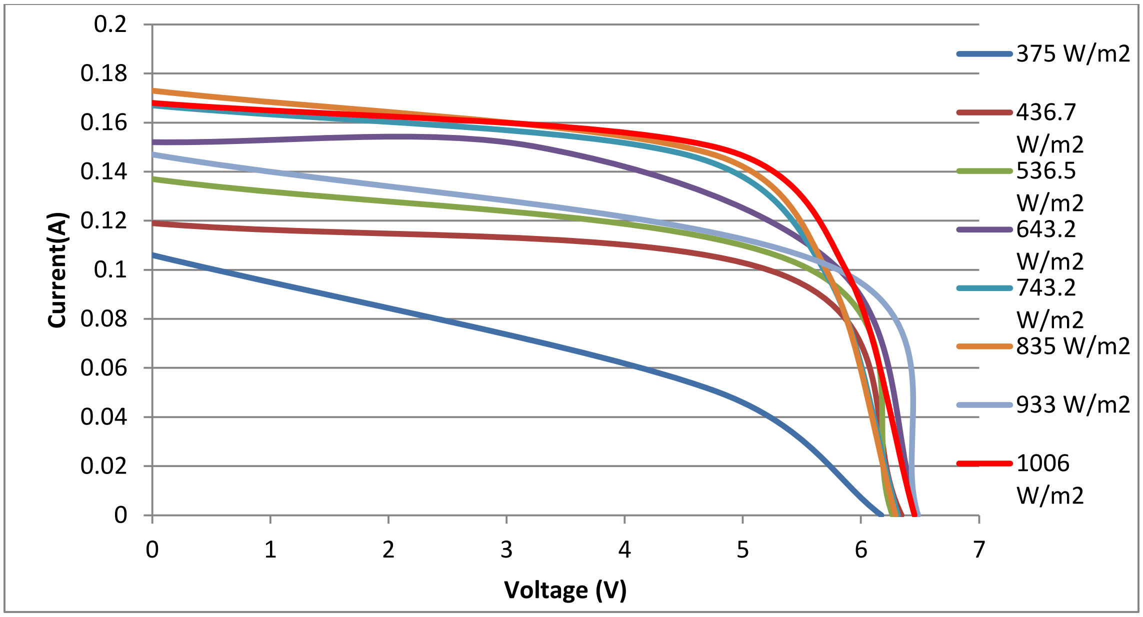
4.0 RESULTS AND DISCUSSION

The result from the characterisation and performance evaluation of the monocrystalline module for the four years data obtained are presented here. The outcome of the comparison of the yearly performance and the degradation rate was deduced for the four years of data studied. Discussion of the results and mathematical modeling used to predict the lifetime of the monocrystalline module is equally being presented.

4.1 Results

The daily hourly data considered were from 9:00a m to 6:00pm local time. However, hourly, daily and yearly averages were computed within these hours. Figures 4.1 to 4.4 show the output characteristics of the monocrystalline PV module as a function of global irradiance using four years of data obtained. These output characteristics are expressed in the form of I-V curves.

In these Figures, it was observed that current is proportional to the irradiance as the current increases with an increasing irradiance while insignificant increases are noticed on the voltage axis showing that there is no regular linear relationship between the voltage and the irradiance. It was also observed that the range of spacing along the current axis witnessed in the first year of operation diminished in subsequent years. The relative bunching of the I-V curves along the voltage axis, which was beyond the 6 volts mark in the first year, also witnessed systematic decreases in subsequent years. This suggests that these electrical parameters are degrading.



4.1:I-V Characteristics of Monocrystalline module as a function of global irradiance for the first year 2015.

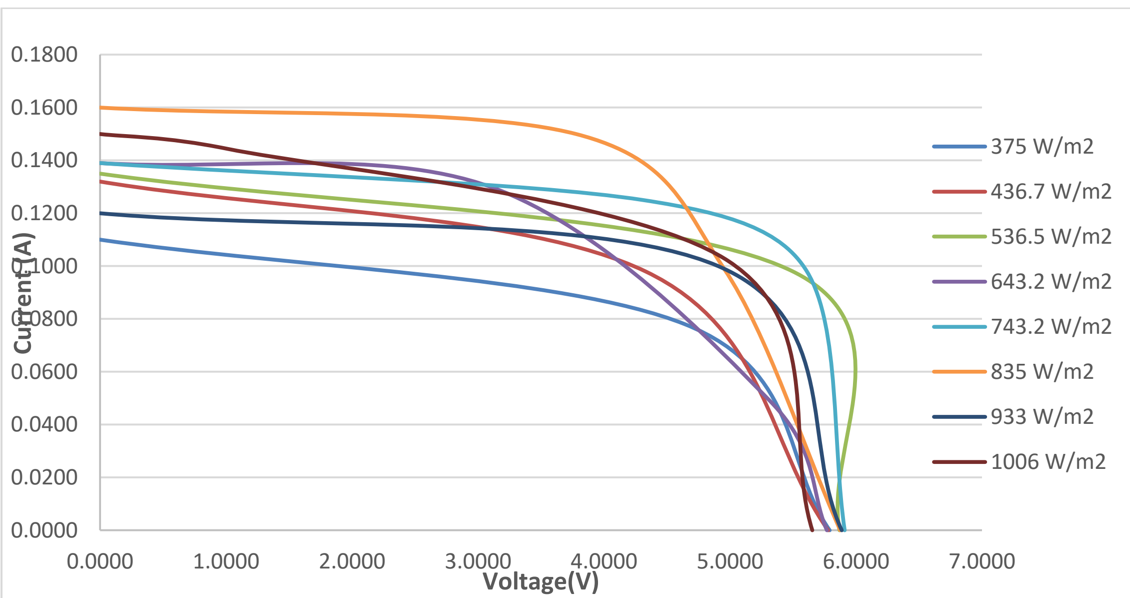


Figure 4.2: I-V Characteristics of the Monocrystalline module as a function of global irradiancefor the second year(2016).

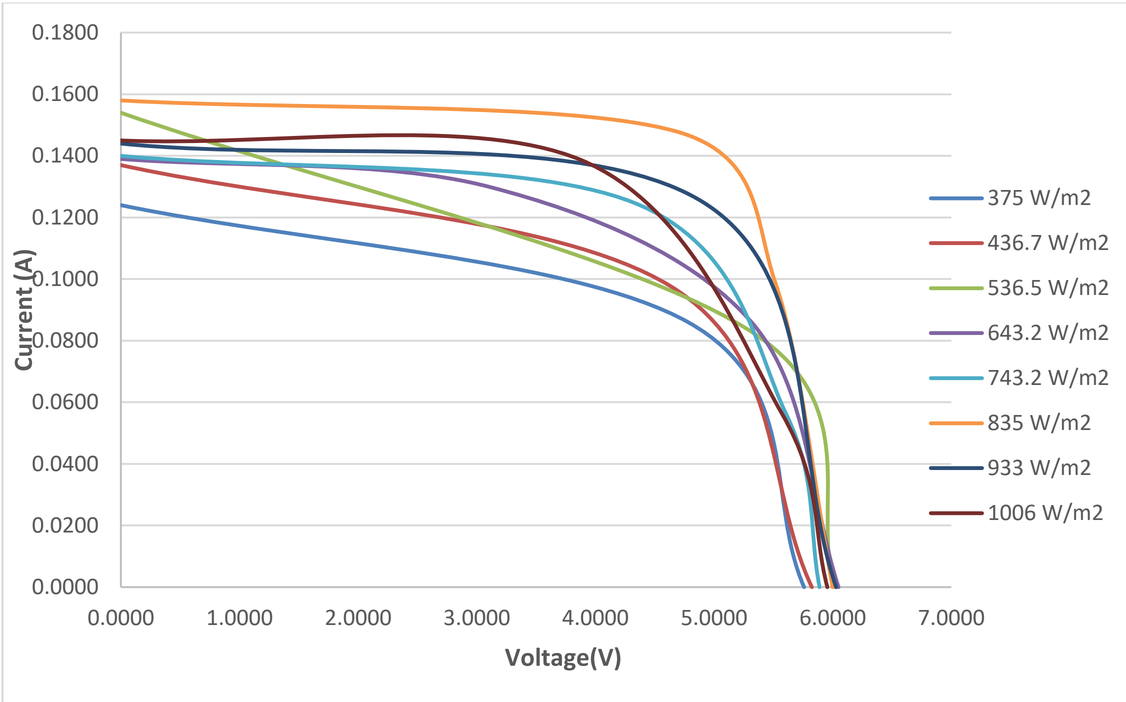


Figure 4.3: I-V Characteristics of the monocrystalline module as a function of irradiance fors the third year (2017).

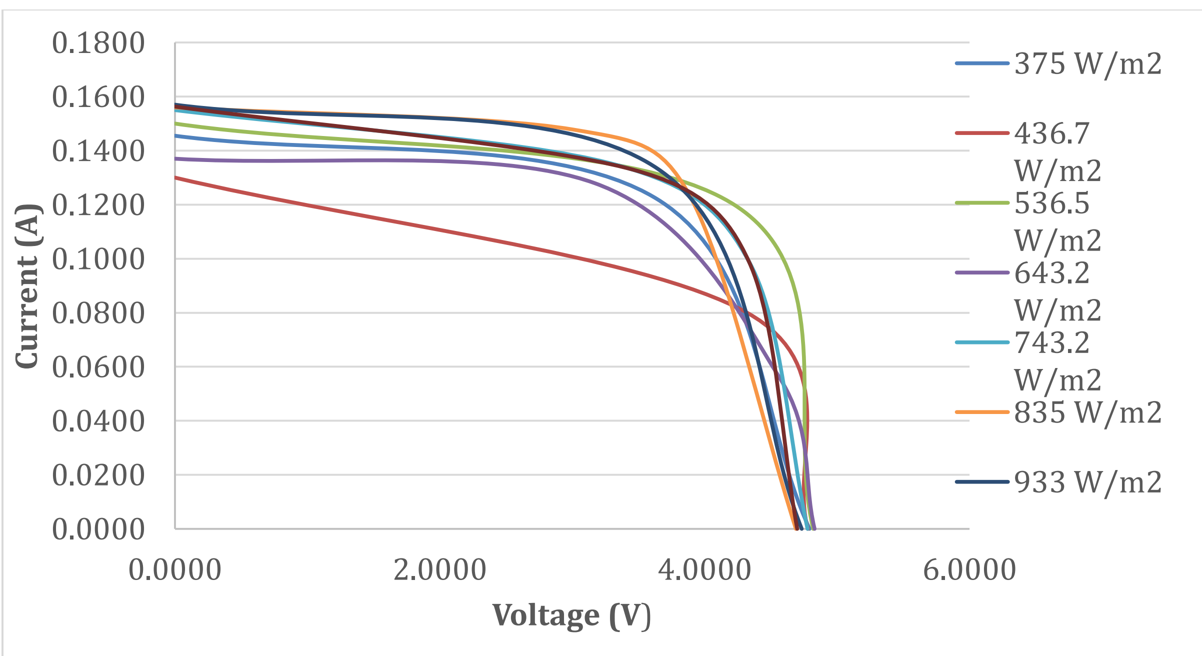


Figure 4. 4: I-V Characteristics of the monocrystalline module as a function of irradiance for the fourth year(2018).

Generally, open-circuit voltage (Voc)seems to increase slowly with irradiance up to a critical point beyond which there is no more increase.Those increases are not commensurate with the increase in irradiance as earlier stated and this explains the bunching of the I-V characteristics curves along voltage axis compared to relative regular spacing along the current axis throughout the four years as seen in Figures 4.1 – 4.4.This is due to the high temperature associated with an increase in irradiance which does not favourthe open-circuit voltage.In contrast, the short circuit current increased generally with irradiance. This result is in agreement with Ezenwora*etal*. (2010).The area of a rectangle that fits inside the curve is the maximum power and the current and voltage associated with them are the maximum current and maximum voltage. It could be further observed from figures 4.1 to 4.4 that, these graphs depict the diode characteristics which are associated with solar modules

Table 4.1 shows the annual hourly average of the performance variable and the ambient parameters for the year 2015.It could be noticed that the performance variables of the monocrystalline modules are seen to peak between the hours of 12pm and 1 pm local time. The same observation was noticed in Table 4.2 for 2016, Table 4.3 for 2017, and Table 4.4 for the year 2018. In the case of the ambient parameters, solar irradiance (H_g) peak time is at noon, these brought about open-circuit voltage and maximum voltage to peak at noon for the four years of study while ambient temperature (Ta) peaked between 2pm and 4pm local time for the first three years of study but in the fourth year (2018) of study, ambient temperature (Ta)peakedbetween 1pm to 4pm local time. In the same vein, the wind speed (WS) and the relative humidity (RH) peaked at 9am local time and reduces drastically down towards 6pm local time throughout the four years in Minna local environment. They show downwards trends. Similarly, it was observed in Tables 4.1 to 4.4 that the maximum power and maximum current increasewithasteady increase in solar irradiance and module temperature. This explains the inclusion of maximum power point tracker (MPPT) in some PV power components (Ezenwora, 2016).

Table 4.1: Annual hourly average of performance variables and ambient parameters for year one (2015).

T(Hours)	WS(m/s)	T_a(^{0}C)	RH (%)	T_{mod}(^{0}C)	H_g(W/m^2)	V_{oc} (v)	I_{sc} (A)	P(W)	V_{max} (V)	I_{max} (A)	P_{max}
9 AM	1.94	21.3	56.6	32.1	399	2.98	0.035	0.153	2.98	0.057	0.229
10 AM	1.98	23.0	54.5	35.9	533	5.22	0.039	0.306	5.22	0.086	0.503
11 AM	1.88	24.4	51.8	39.3	627	5.65	0.041	0.438	5.65	0.112	0.689
12 PM	1.80	25.5	49.4	41.9	666	5.88	0.043	0.509	5.88	0.130	0.808
1 PM	1.66	26.4	46.7	43.5	656	5.94	0.043	0.532	5.94	0.136	0.849
2 PM	1.61	27.1	45.1	43.2	575	5.64	0.042	0.485	5.65	0.126	0.775
3 PM	1.50	27.3	43.8	41.8	456	5.38	0.041	0.398	5.38	0.107	0.635
4 PM	1.40	27.4	43.4	38.8	293	4.41	0.039	0.243	4.42	0.073	0.387
5 PM	1.15	26.5	44.1	34.2	125	0.86	0.024	0.047	0.87	0.032	0.057
6 PM	0.94	25.3	45.6	31.3	52	0.01	0.009	0.000	0.01	0.012	0.000

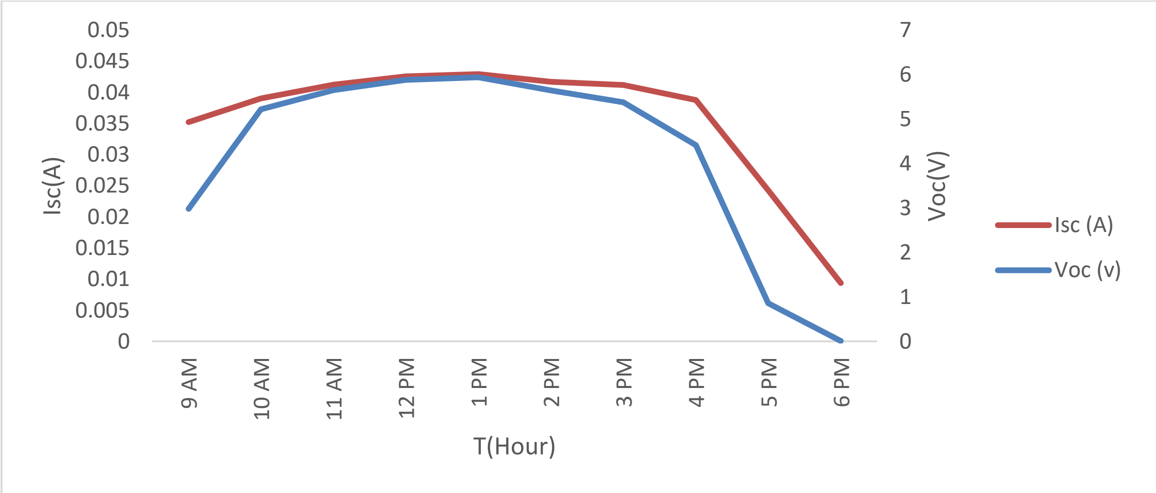


Figure 4.5: Annual hourly average plot of short-circuit current and open-circuitvoltage of the monocrystalline module in the year 2015.

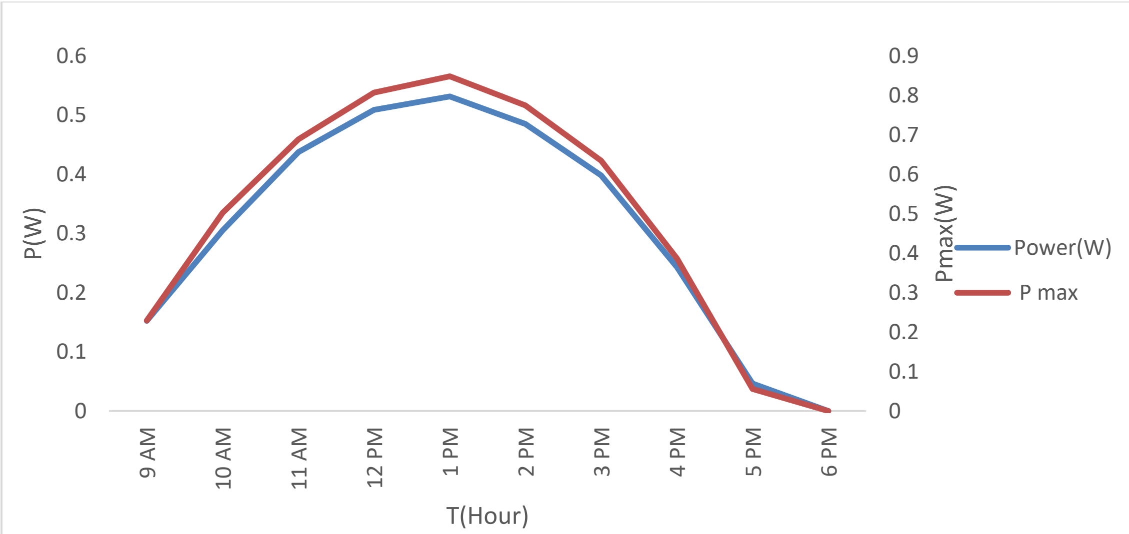


Figure 4.6: Annual hourly average plot of power output and maximum power for the monocrystalline module in the year 2015.

Figure 4.6 shows that power and maximum power peaked at the same time between 12 pm to 2 pm and eventually dropped down as the ambient parameters dropped-down. A slight difference was observed in figure 4.7 where the open-circuit voltage peaked between 12 pm to 1 pm local time while short circuit current peaked from 12 pm to 3 pm local time. The variation is as a result of the long-range high module temperature encountered which affected the early drop-down of the open-circuit voltage. The trend is indicating degrading in the performance variables for the year 2015.

Table 4.2:Annual hourly average of performance variables and ambient parameters for the year (2016).

T(Hours)	WS(m/s)	T_a(°C)	RH (%)	T_{mod}(°C)	H_g(W/m²)	V_{oc}(v)	I_{sc} (A)	P(W)	V_{max}(V)	I_{max}(A)	P_{max}
9 AM	1.86	27.6	60.1	32.1	414	2.41	0.023	0.126	2.41	0.050	0.186
10 AM	1.84	29.1	56.4	36.4	566	3.72	0.036	0.238	3.73	0.077	0.373
11 AM	1.76	30.5	52.9	39.9	663	5.17	0.044	0.376	5.17	0.101	0.580
12 PM	1.71	31.6	49.9	42.6	723	6.00	0.048	0.468	6.00	0.117	0.728
1 PM	1.60	32.4	47.4	43.8	708	5.89	0.050	0.475	5.89	0.121	0.741
2 PM	1.53	32.9	45.4	43.8	641	4.97	0.048	0.395	4.98	0.115	0.627
3 PM	1.45	33.1	44.6	42.2	518	3.75	0.044	0.279	3.75	0.100	0.451
4 PM	1.31	33.0	44.4	39.0	338	2.86	0.038	0.166	2.87	0.072	0.259
5 PM	1.12	32.2	46.6	34.2	148	0.73	0.023	0.037	0.74	0.039	0.048
6 PM	0.92	31.4	49.3	31.0	61	0.01	0.008	0.000	0.02	0.023	0.000

The module temperature (Tmod) was observed to have peaked at 1pm local time for the first year as seen in Table 4.1 and the same observation was noticed throughout the four years of study as shown from Tables 4.1 to 4.4. The performance variables are all showing downwards trends.

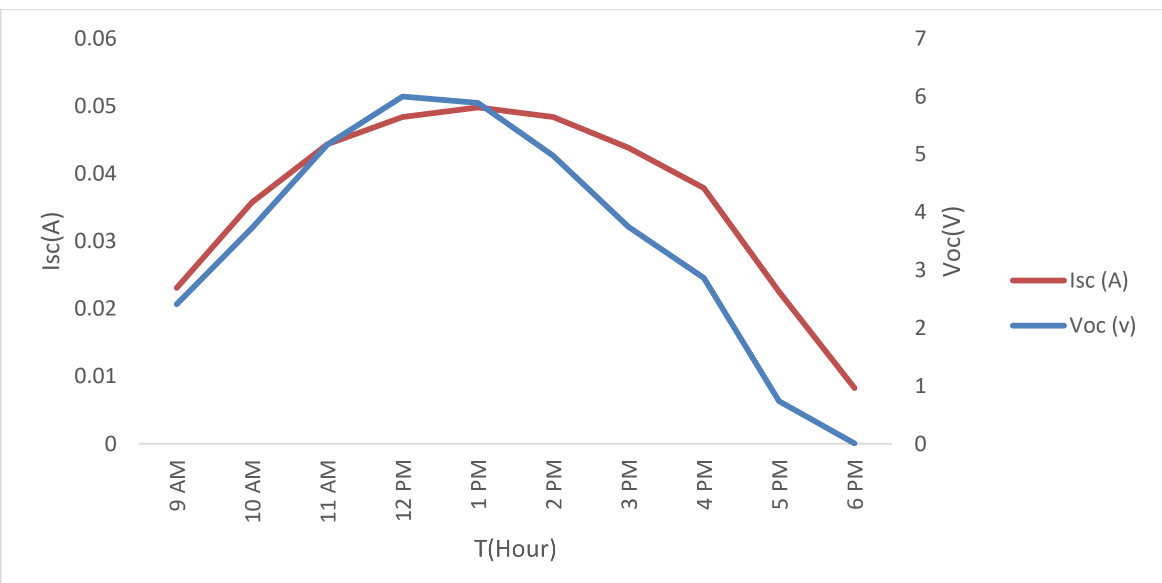


Figure 4.7: Annual hourly average plot of short circuit current and open-circuit voltage for the mono-crystalline module in the year 2016.

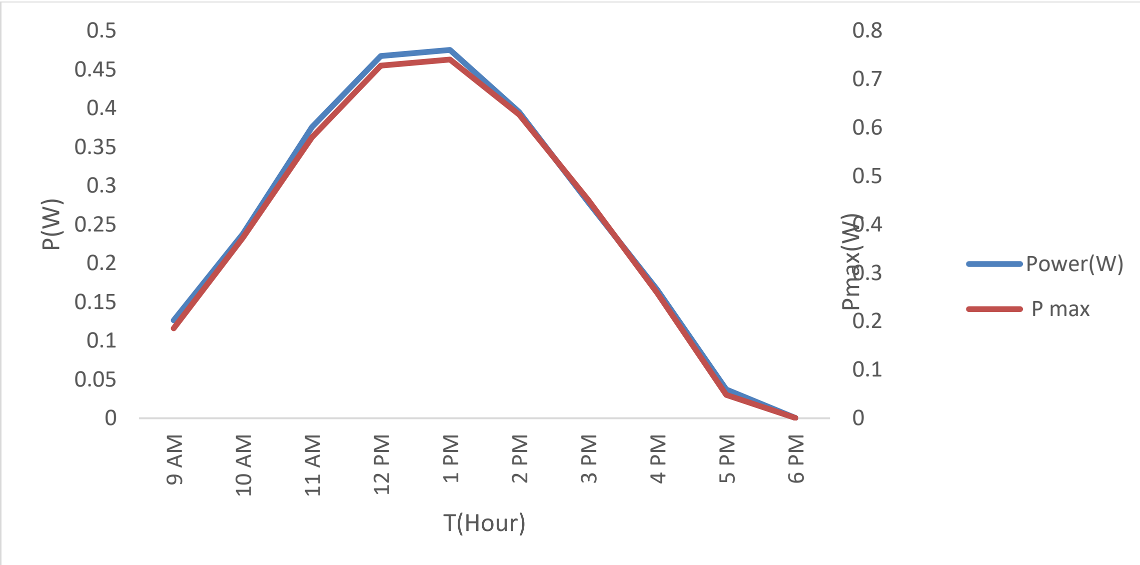


Figure 4.8:Annual hourly average plot of power output and maximum power for the mono-crystalline module in the year (2016).

From Figures 4.7- 4.8,it was observed that the graph is showing a downtrend indicating degradation.It was noticed also that there is a correlation between short circuit currents(Isc) and open-circuit voltage (Voc) in Figure 4.7 also,power and maximum power in Figure 4.8 corralled to confirmed the inclusions of maximum power point tracker which exist in some electronic device that tracks the positioning of maximum power and can also be referred to as the operation point of the module.

Table 4.3: Annual hourly average of performance variables and ambient parameters for year three (2017).

T(Hours)	WS(m/s)	T_a(^{0}C)	RH(%)	T_{mod}(^{0}C)	H_g(W/m^2)	V_{oc} (v)	I_{sc} (A)	P (W)	P_{max}
9 AM	1.64	28.5	56.6	33.6	409	2.84	0.041	0.147	0.210
10 AM	1.63	30.1	53.2	38.0	552	4.64	0.046	0.273	0.442
11 AM	1.54	31.5	50.0	41.7	648	5.11	0.048	0.363	0.606
12 PM	1.48	32.6	47.4	44.5	694	5.24	0.051	0.407	0.699
1 PM	1.41	33.3	45.0	45.8	684	5.10	0.050	0.401	0.705
2 PM	1.27	33.7	43.2	45.4	614	4.87	0.049	0.367	0.631
3 PM	1.17	33.9	42.1	43.6	492	4.56	0.047	0.307	0.504
4 PM	1.07	33.7	42.3	40.1	322	3.55	0.045	0.192	0.292
5 PM	0.89	33.0	44.3	34.9	144	0.62	0.028	0.032	0.039

6 PM	0.75	32.2	47.0	31.6	62	0.01	0.013	0.000	0.000

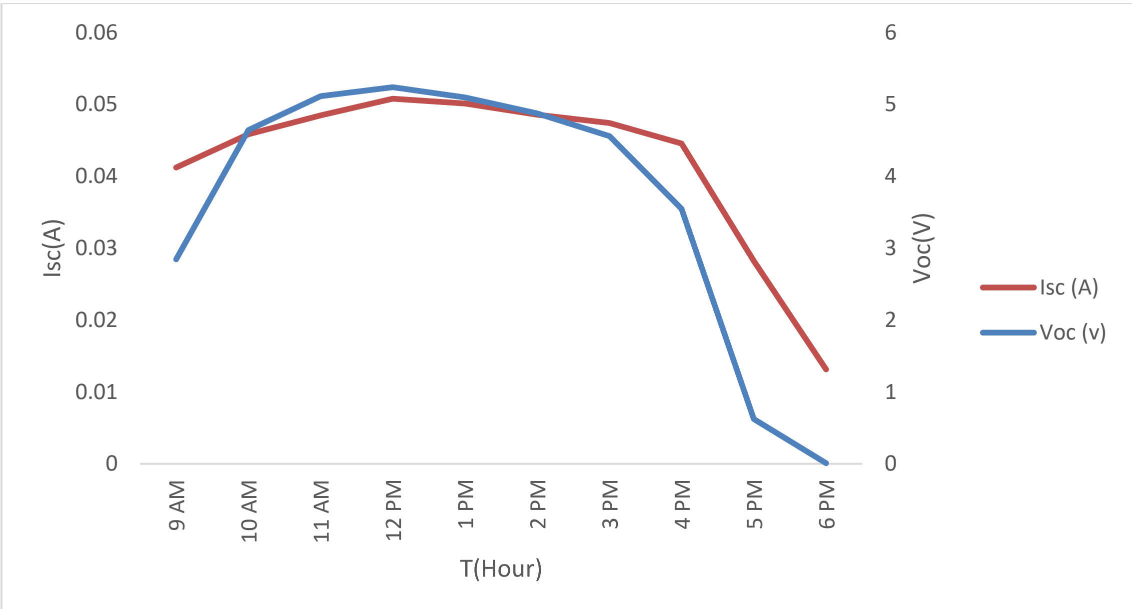


Figure 4.9: Annual hourly average plot of short circuit current and open-circuit voltage for the mono-crystalline module in the year 2017.

In figure 4.9, the open-circuit voltage moves steadily before short circuit current and they both intercepted at 10 am local time, open circuit current peaked at 12noon and immediately declined at 2 pm while the short circuit current declined by 4 pm.This resulted from high module temperature that went beyond 2 pm which favours short circuit current since short circuit current is proportional to the module temperature. Both the short circuit current (Isc) and open circuit voltage move towards the zero indicating degradation.

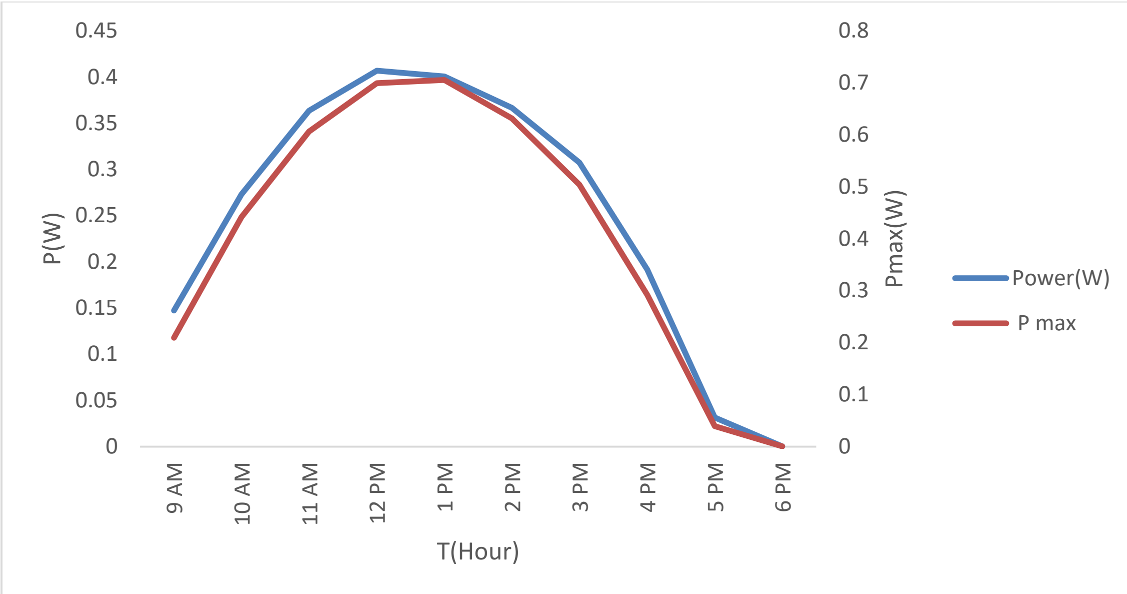


Figure 4.10:Annual hourly average plot of power output and maximum power for the monocrystalline module in the year (2017).

Figure 4.10 shows that power and maximum power peaked at 12noon to 2 pm which corresponds to power of 0.4 W and voltage of 0.71 V and the trends moved sharply downwards around 5 pm to 6 pm in the year 2017 showing a degradations trends.

Table 4.4: Annual hourly average of performance variables and ambient parameters for the fourth year (2018).

T(Hours)	WS(m/s)	T_a(^{0}C)	RH(%)	T_{mod}(^{0}C)	H_g(W/m^2)	V_{oc} (v)	I_{sc} (A)	P (W)	P_{max}
9 AM	1.31	28.9	64.8	33.4	380	0.76	0.020	0.038	0.051
10 AM	1.37	30.5	60.8	38.0	519	1.76	0.030	0.088	0.137
11 AM	1.21	32.1	56.9	42.1	624	2.49	0.039	0.126	0.217
12 PM	1.15	33.3	53.7	44.8	670	2.70	0.044	0.164	0.269
1 PM	1.07	34.0	50.7	46.2	674	2.58	0.045	0.174	0.284
2 PM	0.97	34.3	48.3	45.9	603	2.15	0.042	0.136	0.229
3 PM	0.89	34.3	47.2	43.8	474	1.42	0.035	0.075	0.135
4 PM	0.72	34.0	46.8	40.3	316	0.86	0.031	0.043	0.066
5 PM	0.61	33.3	48.7	34.8	143	0.19	0.018	0.009	0.012
6 PM	0.48	32.5	51.0	31.2	62	0.01	0.005	0.000	0.000

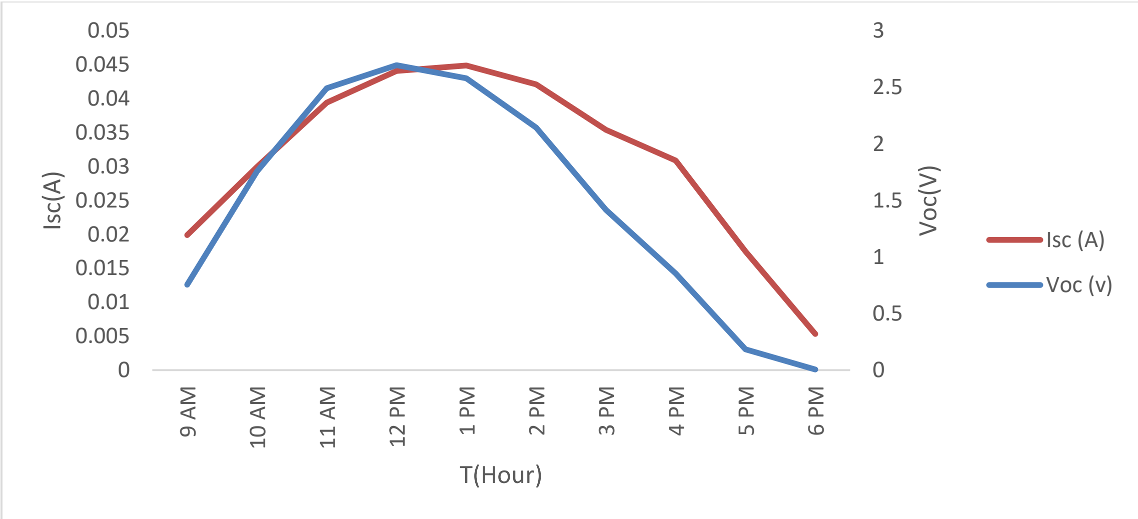


Figure 4.11: Annual hourly average plot of short circuit current and open-circuit voltage for the mono-crystalline module in the year 2018.

Figure 4.11 indicates a correlation between open-circuit voltage and short circuit current at 10 am and at 12noon, this is attributed to the steady increase of irradiance and open-circuit voltage and finally moved downwards indicating degradation.

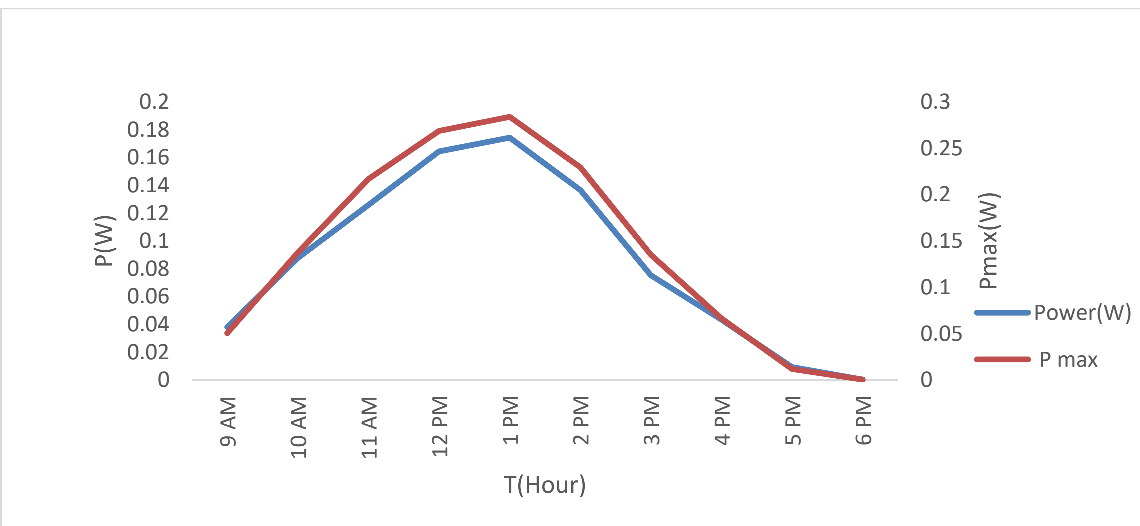


Figure 4.12:Annual hourly average plot of power output and maximum power for the mono-crystalline module in the year (2018).

Figure 4.12 furtherindicated that both power and maximum power peaked at 1pm, this is as a result of the highest module temperature recorded $(46.2^{c}C)$ at this time.The monthly hourlyaverages of the performance variables (open-circuitvoltage, short-circuit current, power output, maximum power) were equally investigated using four years data obtained and the plots for atypical dry season,the month of January,and a typical rainy season forAugust for the four years studied (2015 -2018) are shown in Figures 4.13 – 4.28.

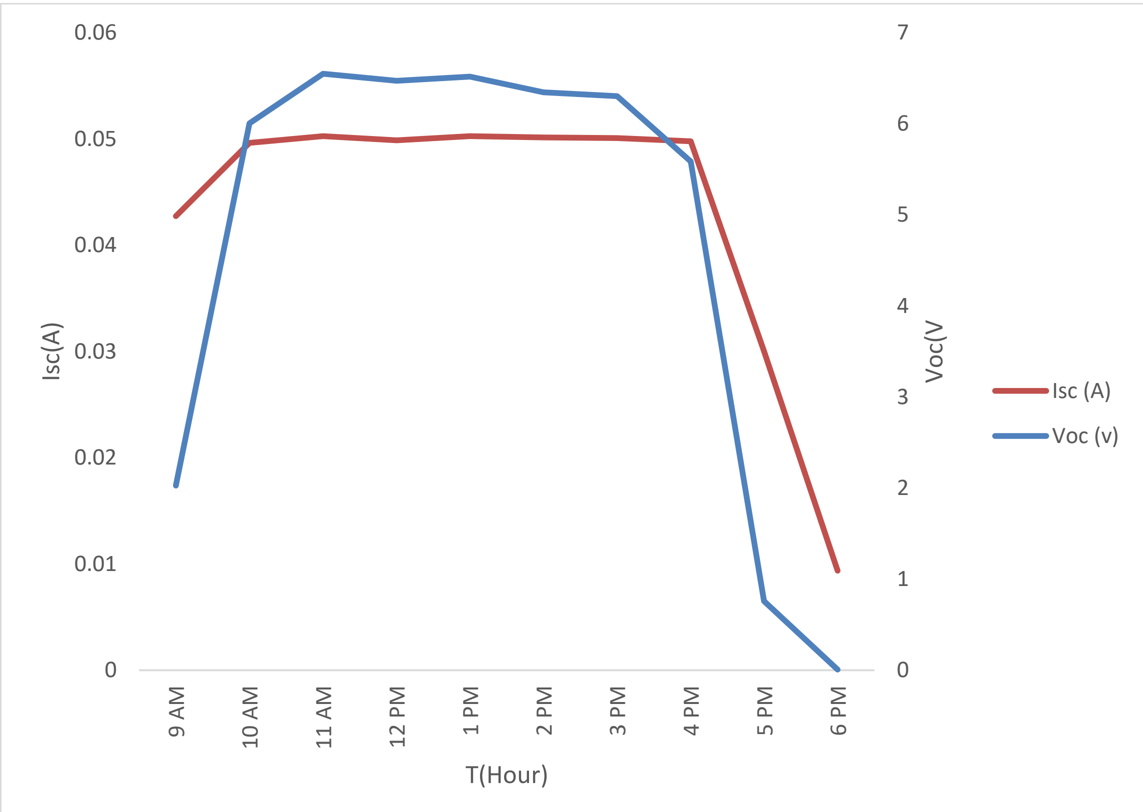


Figure 4.13: Hourly average variation of short-circuit current and open-circuit voltage of the mono-crystalline module as a function of time for January 2015.

From figure 4.13 above, short circuit currents at 0.05 A had a steady linear trend from 10 am to 5 pm at short circuit current of 0.049 A and open-circuit voltage of 5.9 V and finally drop down while open-circuit voltage (Voc) maintains unstable trends downwards after the peak at 4 pm with the voltage of 5.5 V.The downwardtrends isan indication of low performance as the time counts down.

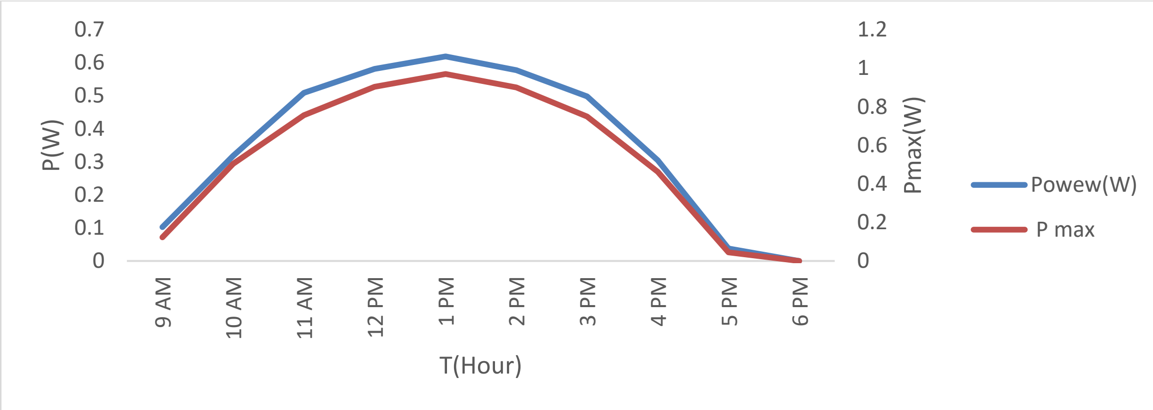


Figure 4.14: Hourly average variation of power output and the maximum power of as a function of time for January 2015

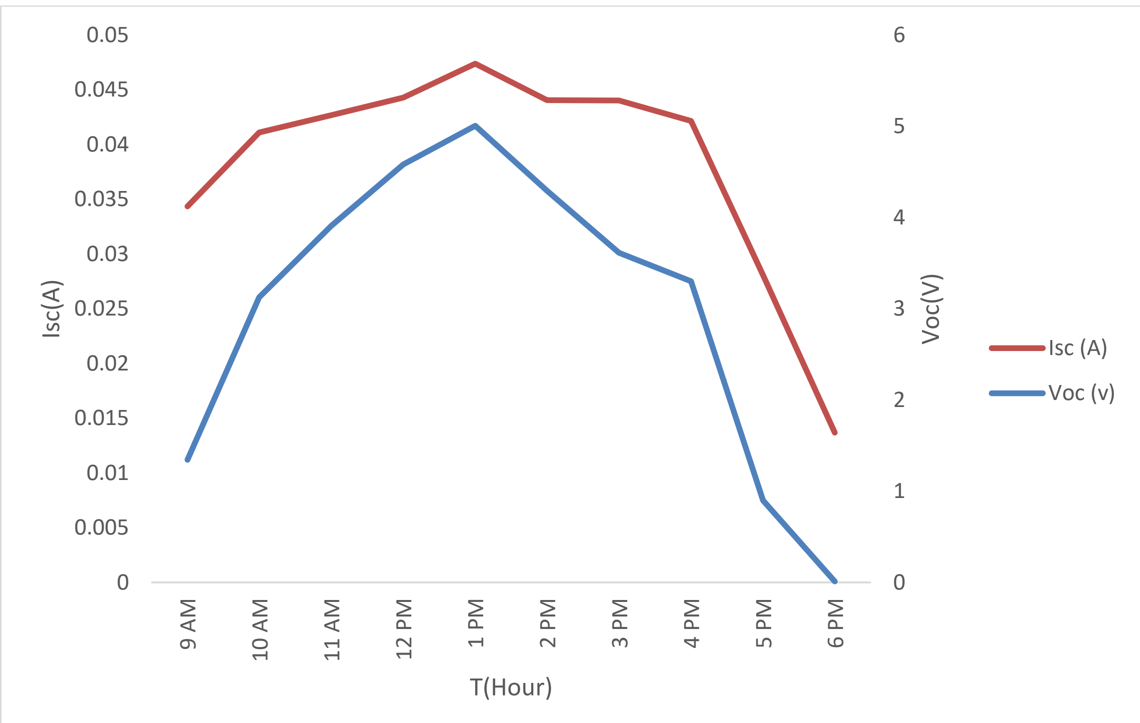


Figure 4.15: Hourly average variation of short-circuit current and open-circuit voltage of the mono-crystalline module as a function of time for August 2015.

From Table 4.14, both Maximum power and power peaks by 1 pm at 0.058 W and 0.8 W, the trends all moved downwards to indicatedegradation. Figure 4.15 witnessed the same trends and moved downwards as well.

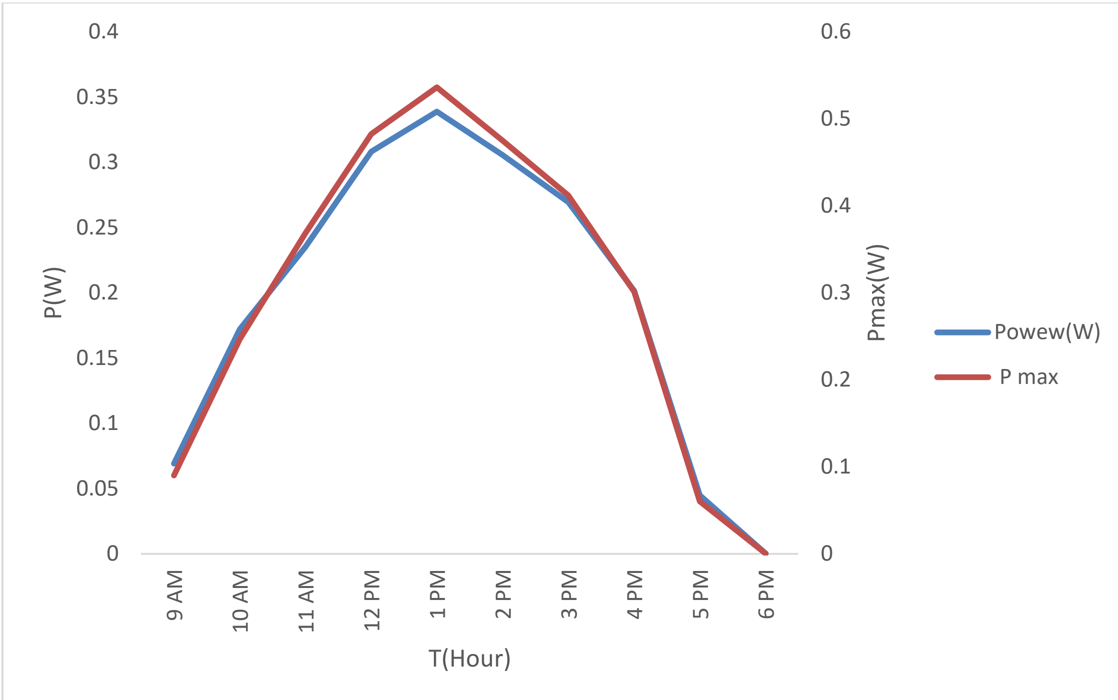


Figure 4.16: Hourly average variation of power output and the maximum power of the mono-crystalline module as a function of time for August 2015.

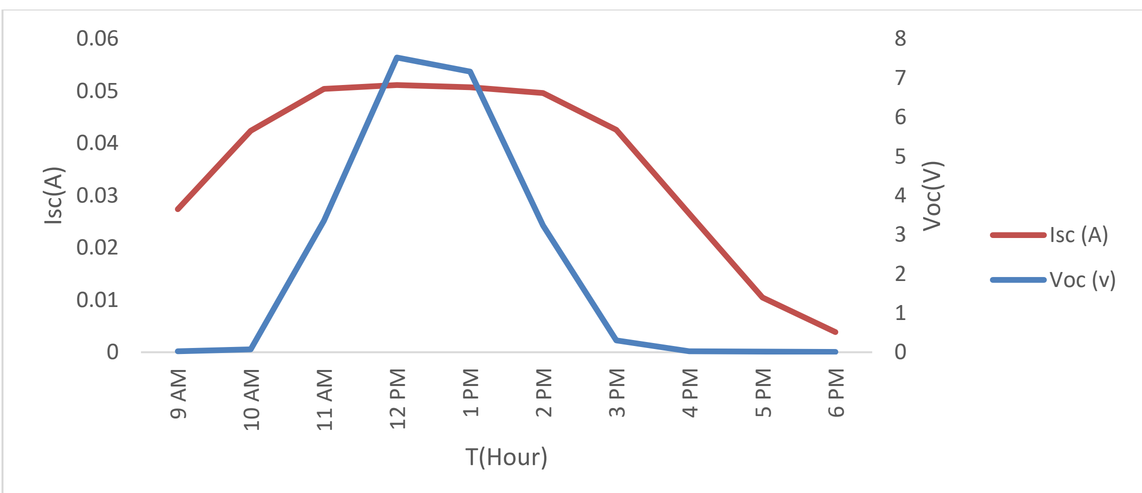


Figure 4.17: Hourly average variation of short-circuit current and open-circuit voltage of mono-crystalline module as a function of time for January 2016.

Figure 4.16 and 4.17 are showings the downward trend. At 1 pm, Power (W) and Power maximum are 0.3 W and 0.5 W while in figure 41.7,open-circuit voltage peak at 6 V and short circuit currents peaked at 0.05 A. Both are showing a downward trend as an indication of low performance as the time go up.The same trends are witnessed in Figures 4.18 – 4.28.

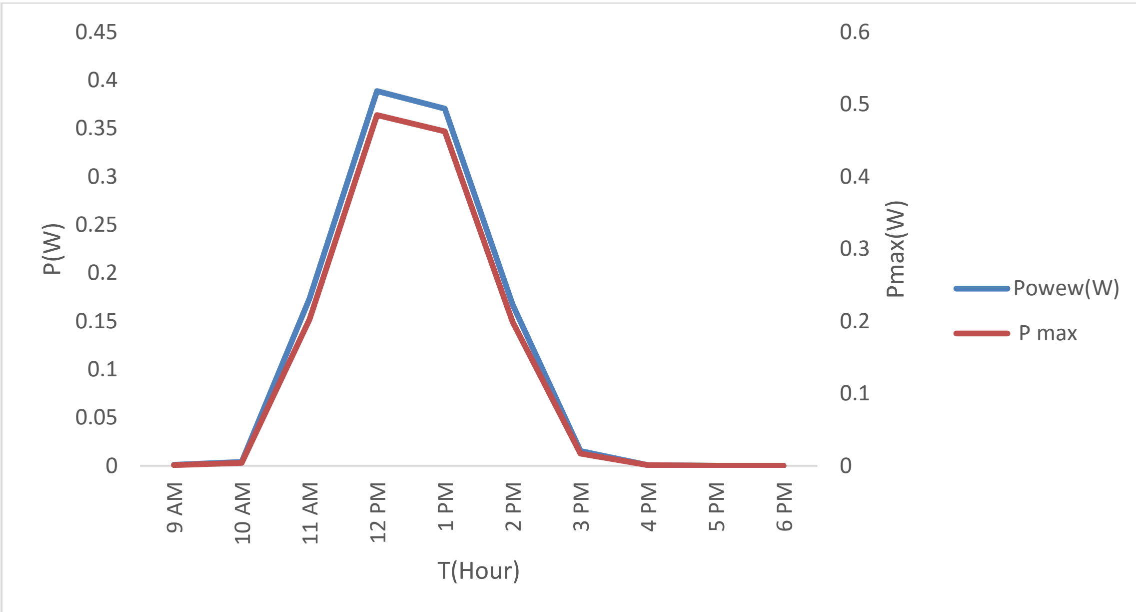


Figure 4.18: Hourly average variation of power output and power of the monocrystalline module as a function of time for January2016.

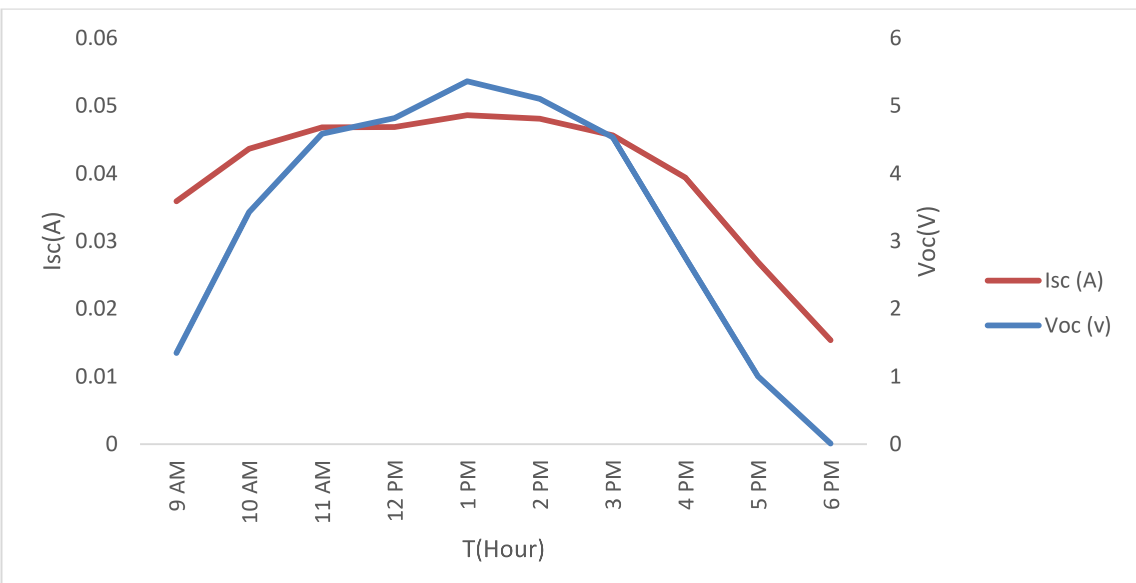


Figure 4.19: Hourly average variation of short-circuit current and open-circuit voltage of the mono-crystalline module as a function of time for August 2016.

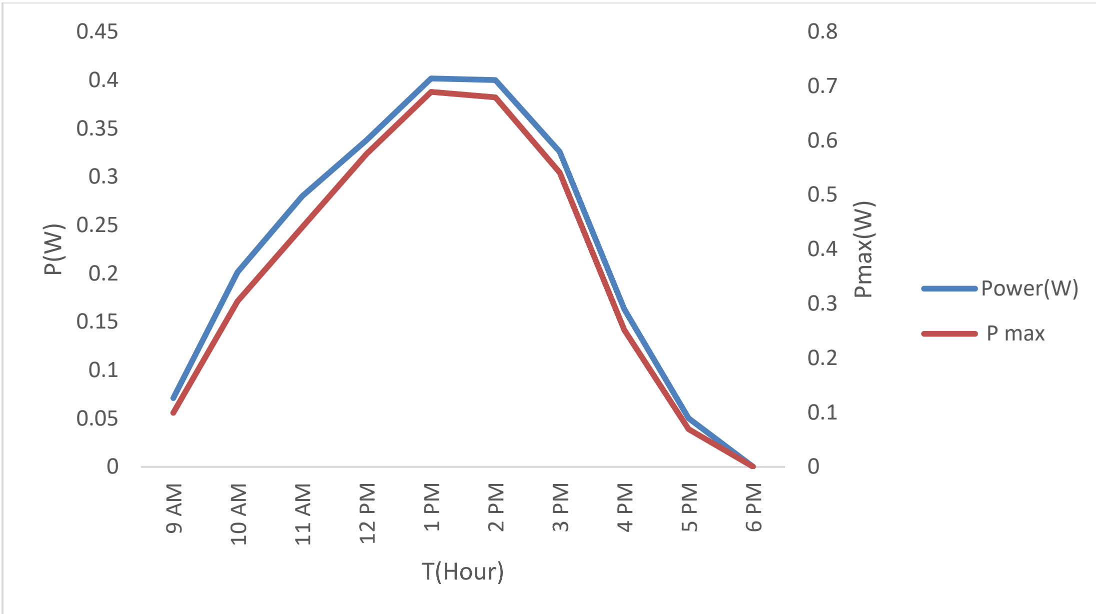


Figure 4.20: Hourly average variation of power output and the maximum power of the mono-crystalline module as a function of time for August 2016.

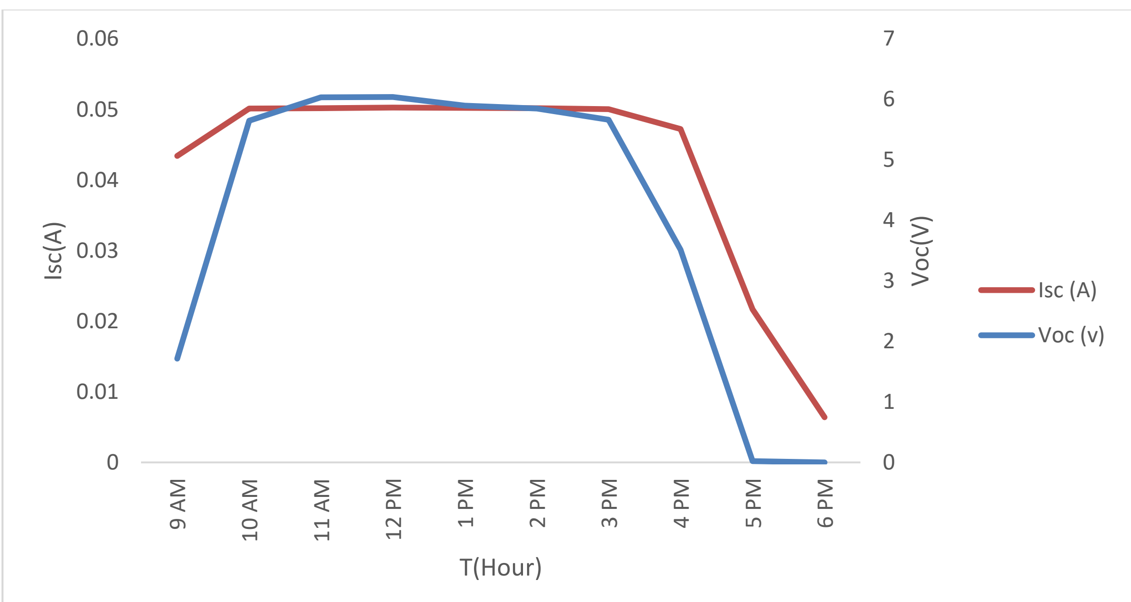


Figure 4.21: Hourly average variation of short circuit current and open-circuit voltage of mono-crystalline module as a function of time for January 2017.

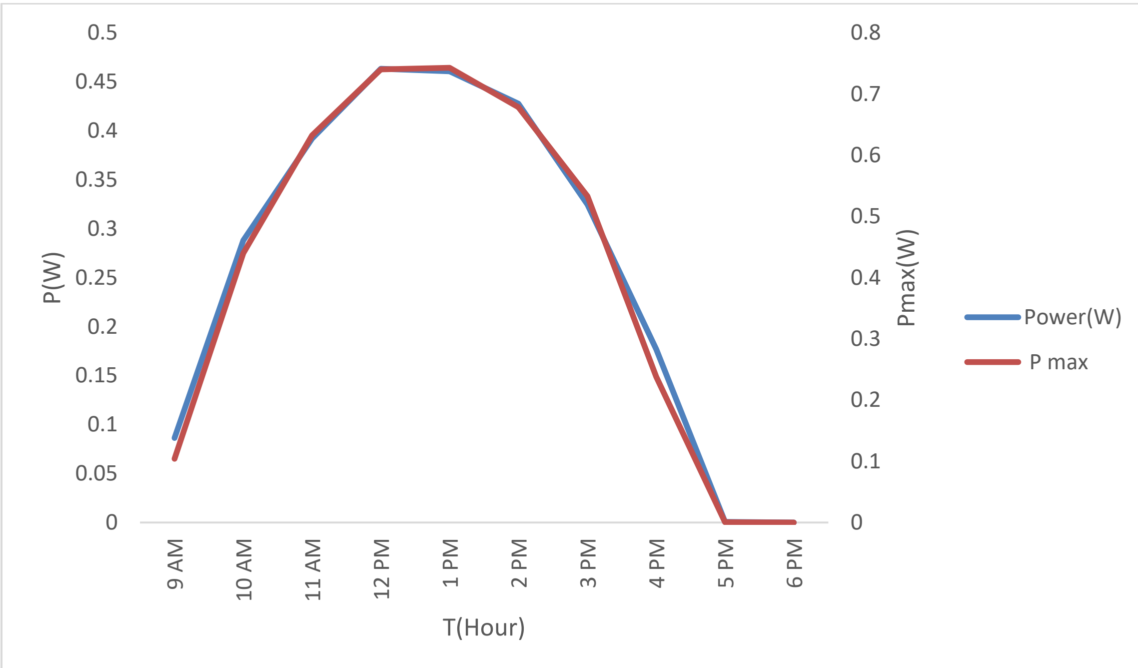


Figure 4.22: Hourly average variation of power output and the maximum power of monocrystalline module as a function of time for January 2017.

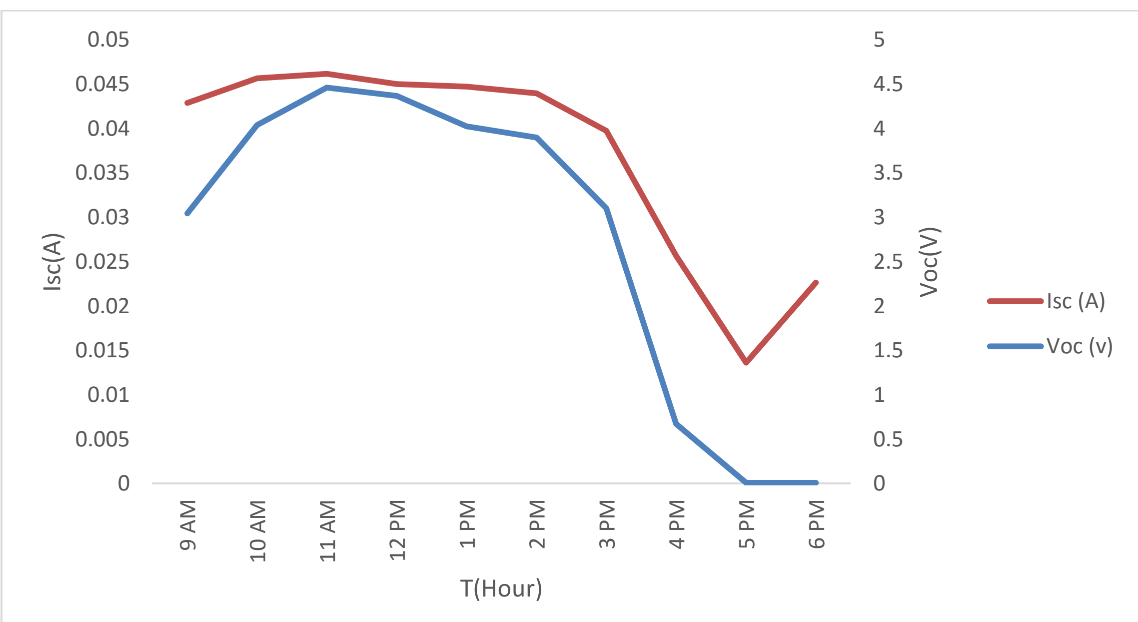


Figure 4.23: Hourly average variation of short circuit current and open-circuit voltage of mono-crystalline module as a function of time for August 2017.

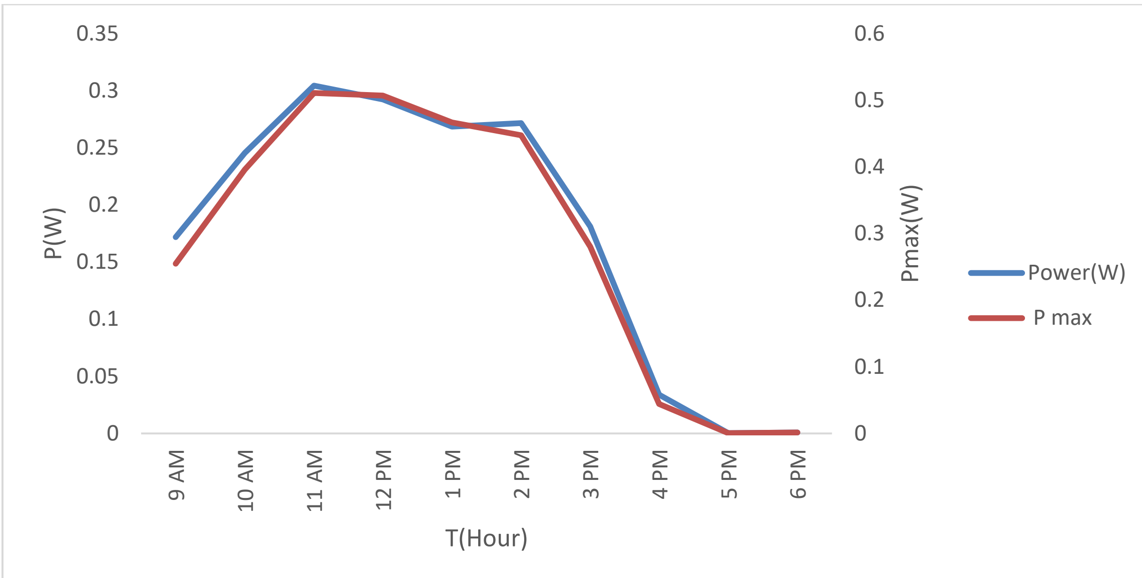


Figure 4.24: Hourly average variation of power output and the maximum power of mono-crystalline module as a function of time for August 2017.

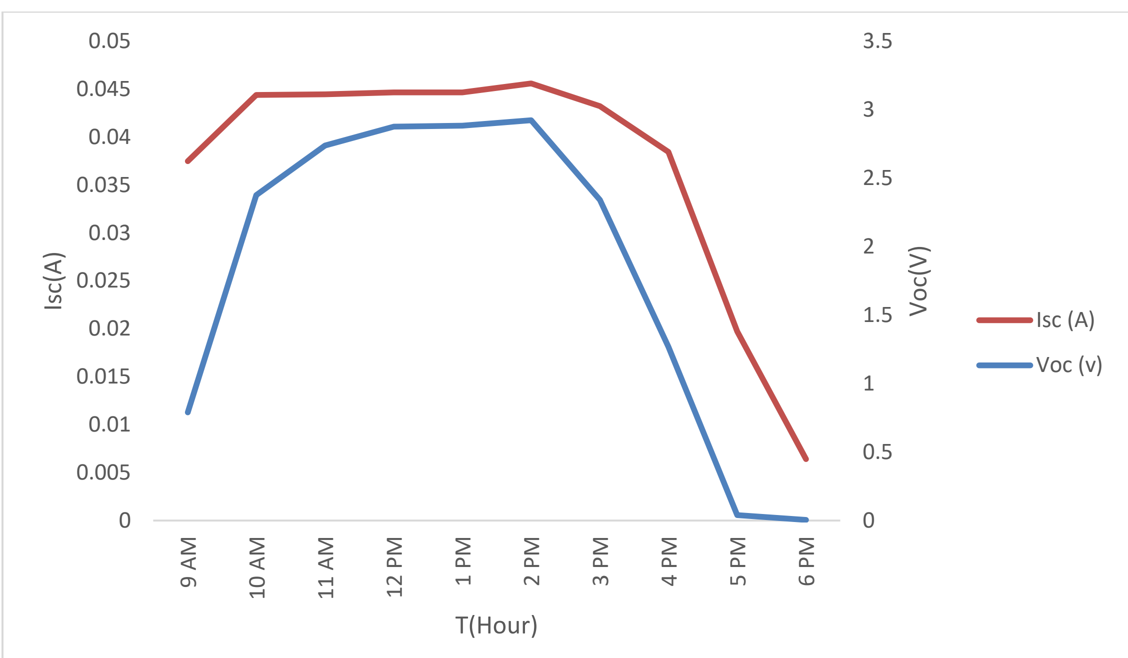


Figure 4.25: Hourly average variation of short circuit current and open-circuit voltage of mono-crystalline module as a function of time for August 2018.

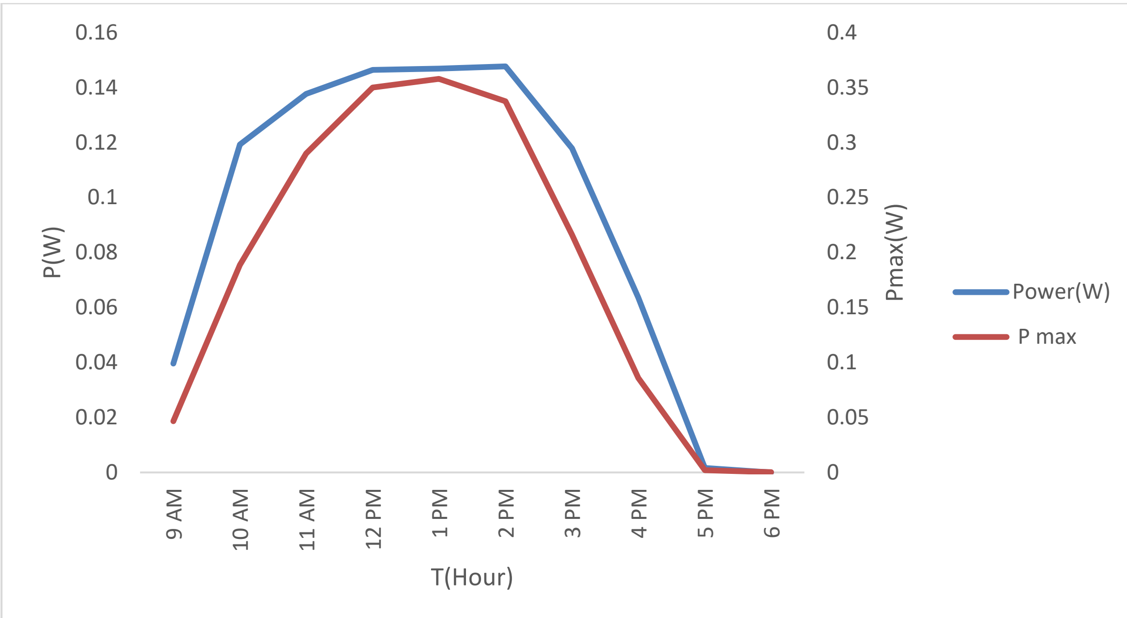


Figure 4.26: Hourly average variation of power output and the maximum power of the mono-crystalline module as a function of time for August 2018.

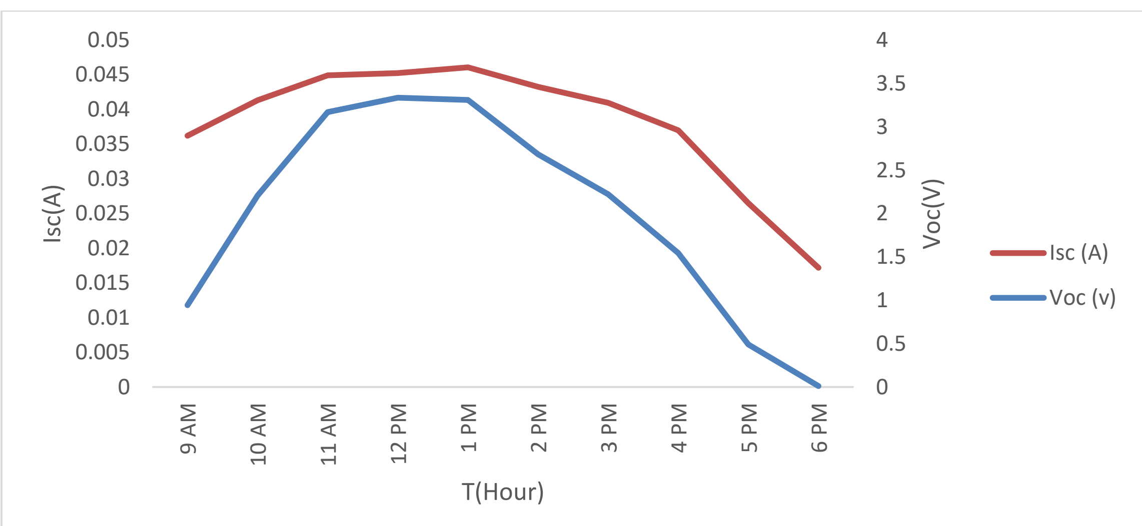


Figure 4.27: Hourly average variation of short circuit current and open-circuit voltage of mono-crystalline module as a function of time for August 2018.

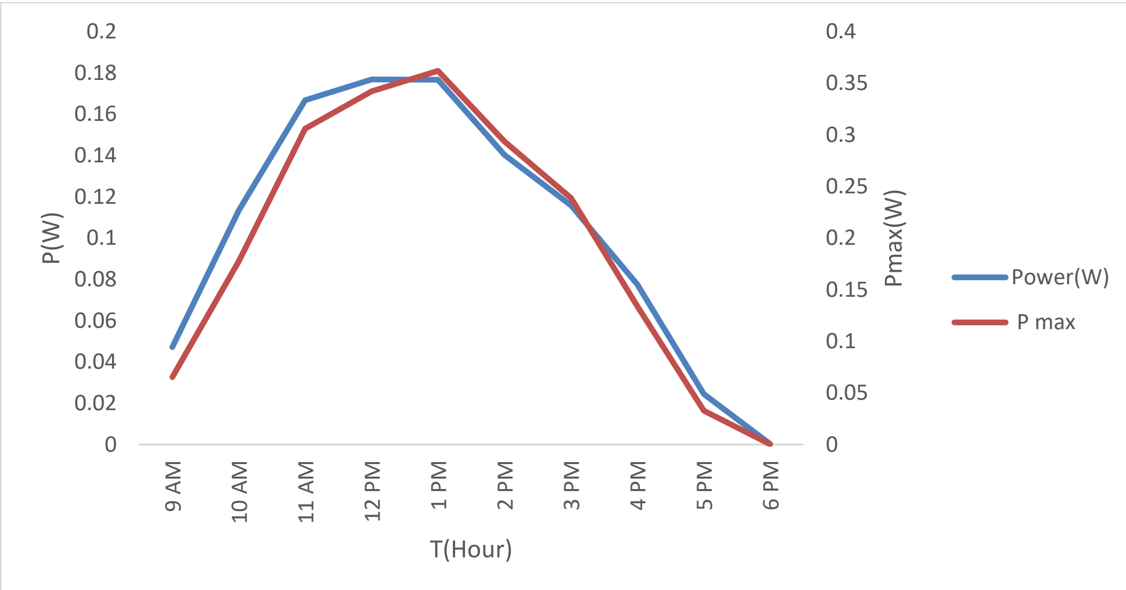


Figure 4.28: Hourly average variation of power output and the maximum power of the mono-crystalline module as a function of time for August 2018.

Generally, the electrical parametersof photovoltaic modules respond differently to insolationdepending on the seasons which bring about the degradations in their performance as witnessed by their trend sloping down.In 2015, Figure 4.13 to 4.16 shows the responses of the electrical parameters as a function of time in the typical rainy season and typical dry season and the effects of each wave formed have been duly explained earlier using Table 4.1 to 4.4. They all depict a graph of degradation.

In 2016, It was observed from Figures 4.17 to 4.20 that open-circuit voltage peaks earlier in the day than short circuit current in both seasons for the year and they all show a downwards trend towards zero levels indicating degradation.

In 2017, the trend from Figures 4.21- 4.24 all showed a downward trend but in Figure 4.23 short circuit currents raise but the open-circuit voltage for the year depicts degradation trends.

In 2018,Figures 4.25 – 4.28 demonstrates degradation in the performance variables through the trends they exhibit. Short circuits currents, open-circuit voltage, power, power maximum in both dry and wets seasons in the year degraded more compared to the previous year meaning that atmospheric parameters do not favour the variables parameters in the year 2018.The output voltage and power of crystalline silicon photovoltaic modules decreased at high temperatures as their module temperature increases.This gives further confirmations by the shapes of the curves of those performance variables as seen in figures4.5 – 4.28 with their trends moving downwards after the peak points to indicate degradations.

Hourly average values of the module's performance variables and ambient parameters for the four years of study at different irradiance levels were summarized in Table 4.5.The Fill factor and efficiency at different irradiance levels of the monocrystalline modules were computed appropriately.

Table 4.5:Summary of performance response for four years at different irradiance Level

2015

$Hg(W/m^2)$	Voc	Isc	Pmax	Vmax	Imax	FF	Eff %
276	6.12	0.08	0.311	6.12	0.051	0.614	5.24
375	6.17	0.11	0.475	4.74	0.100	0.725	5.85
437	6.34	0.12	0.523	5.33	0.098	0.692	5.53
537	6.27	0.14	0.558	5.49	0.102	0.652	4.83
643	6.48	0.15	0.583	5.83	0.100	0.592	4.20
743	6.31	0.17	0.663	4.51	0.147	0.629	4.13
835	6.29	0.17	0.694	4.68	0.148	0.637	3.84
912	6.26	0.16	0.636	4.27	0.149	0.643	3.23
933	6.48	0.15	0.578	5.81	0.100	0.610	2.88
1000	6.51	0.16	0.711	4.69	0.152	0.684	3.30

Tmod = 38.9^o

MPR= 0.075
Pmax (%) = 7.11%

2016

Voc	Isc	Pmax	Vmax	Imax	FF	Eff %
5.56	0.049	0.275	5.564	0.062	1.265	5.79
5.79	0.049	0.287	5.792	0.064	1.306	4.58
5.98	0.33	0.001	0.025	0.033	0.000	0.01
6.16	0.072	0.004	0.025	0.186	0.010	0.04
6.26	0.049	0.002	0.04	0.049	0.006	0.01
6.37	0.051	0.559	6.373	0.144	2.824	5.72
11.3	0.051	0.581	11.28	0.077	1.510	4.82
6.31	0.051	0.669	6.18	0.168	3.226	5.27
6.22	0.052	0.308	6.227	0.182	3.504	5.62
11.8	0.157	1.839	11.75	0.186	1.185	10.12

Tmod =39.3^o

MPR= 0.22
Pmax (%) = 18.39%

2017

2018

Hg(W/m^2)	Voc	Isc	Pmax	Vmax	Imax	FF	Eff %
276	5.062	0.051	0.257	5.062	0.056	1.098	4.755
375	5.634	0.049	0.279	5.634	0.066	1.347	4.591
437	5.825	0.032	0.275	5.489	0.07	2.061	4.071
537	6.041	0.031	0.004	0.03	0.131	0.021	0.034
643	6.135	0.139	0.005	0.04	0.169	0.008	0.049
743	6.135	0.14	0.102	1.843	0.177	0.380	2.033
835	6.001	0.148	0.52	6.122	0.144	0.993	4.888
912	6.207	0.051	0.584	6.021	0.159	3.024	4.860
933	6.037	0.049	0.516	6.047	0.142	2.903	4.261
1000	5.956	0.056	0.503	5.956	0.145	2.589	3.998

Tmod = 40.8^o
MPR= 0.082
Pmax (%) = 5.03%

Voc	Isc	Pmax	Vmax	Imax	FF	Eff %
4.49	0.049	0.222	4.49	0.062	1.265	4.67
4.792	0.455	0.237	4.72	0.054	0.117	3.15
4.919	0.049	0.243	4.919	0.078	1.592	4.06
4.881	0.051	0.109	2.151	0.087	0.752	1.61
5.003	0.056	0.398	5.835	0.111	2.312	4.66
4.776	0.051	0.307	4.776	0.155	3.039	4.61
4.417	0.051	0.225	4.417	0.139	2.725	3.40
4.262	0.05	0.214	4.262	0.129	2.580	2.79
3.875	0.051	0.197	3.875	0.119	2.333	2.29
4.468	0.05	0.225	4.483	0.136	2.729	2.82

Tmod = 41.0^o
MPR= 0.061
Pmax (%) =2.25%

In Figure 4.5, it was observed that the peak hour for short circuit current and open-circuit voltage is between 12 pm to 4 pm with a correlation between 11:00 am to 1 pm. This correlation observed was premised to the high module temperature.This increase in module temperature arises due to high insolation heating, low wind speed with the consequent low heat transfer from the module to ambient temperature which resulted to high ambient temperature.The module performance for the four years of study was compared with other literature. The maximum power achieved at 1000W/m^2 for the four years of studies are 0.711W,1.839W,0.503W and 0.225W representing 7.11%,18.39%,5.03%and 2.25%.Modules efficiency at 1000W/m^2 for the four years of study are 3.30%,10.0%,3.99%, and 2.82% respectively which showing reduction in value.

The open-circuit voltage at 1000V recorded degrades to 6.50V, 11.75V, 5.956V, and 4.468Vin 2015, 2016,2017, and 2018 respectively for the four years of study while the short circuit current degrades to 0.16A, 0.157A, 0.056A, and 0.050A in 2015,2016, 2017 and 2018 respectively.

Similarly, the maximum voltage(Vmax) with an initial value of 17.4 V at 1000W/m^2, degrades to 4.69V, 11.75V, 5.956V, and 4.483V for the year, 2015, 2016, 2017, and 2018 respectively. The maximum current (Imax) degraded from 0.57 A to 0.152A, 0.186A, 0.145A, and 0.136A for the four years of study. The module performance ratio also reduces from 0.57A to 0.072A,0.22A,0.087A, and 0.061A respectively for 2015,2016,2017 and 2018. It was noted that no years recorded module temperature of 25^{O}C at 1000W/ m^2 solar irradiance as usually assumed for STC as seen in Table 4.5 for the four years of study as they all recorded module temperature(Tmod) beyond 25^{O}C in the local environment.

This has clearly shown that there are degradations in the values obtained in the variables parameters as compared to their initial values. The difference in the monocrystalline module values obtained in the four years of study is due to variance in the ambient parameters and meteorological conditions of the environment which bring about the degradations.

An annual yearly average of performance variable and ambient parameters are shown in Table 4.6 for the monocrystalline module to ascertain the average annual Rate of Degradation(RoD).

Table 4.6: Annual yearly averages of performance variables and ambient parameters for the monocrystalline module.

T(Years)	WS(m/s)	T_a(^{0}C)	RH (%)	T_{mod}(^{0}C)	H_g(W/m^2)	Voc(v)	I_{sc}(A)	P(W)	P_{max}
YEAR 1 (2015)	1.65	25.4	48.3	38.9	477	4.62	0.038	0.342	0.543
YEAR 2 (2016)	1.57	31.4	49.7	39.3	520	3.91	0.039	0.282	0.439
YEAR 3 (2017)	1.34	32.3	47.1	40.8	502	4.02	0.045	0.274	0.455
YEAR 4 (2018)	1.03	32.7	53.1	41.0	485	1.64	0.034	0.094	0.154

The ambient parameters are responsible for the degradation of the variable electrical parameters and as such, there is a need to ascertain the annual yearly averages of the performance variables to know the effect and rate of degradations of the electrical parameters. From Table4.6,it was observed that the module temperature increases $from\ 38.9^{o}$,39.8^{o} 40.8^{o} and 41.0^{o} for 2015,2016, 2017, and 2018 respectively, and also short circuit current increased from 0.038 A,0.039 A,0.045Afrom 2015,2016 and 2017 but decreases to 0.034 A in 2018.In the same vein, the output power decreases steadily to 0.342 W, 0.282 W, 0.274 W, and 0.094 W for theyears 2015,2016,2017 and 2018 respectively.

The maximum power also was observed to decreases from 0.543 W to 0.439,2015 to 2016 but slightly increasedto 0.455 W in 2017 and decreased to 0.154 W in 2018.

The annual average rate of degradation of the performance variables is presented in Table 4.7

Table 4.7: Annual average rate of degradation (RoD)

T(YEAR)	Voc(V)	Isc(A)	P(W)	Pmax(W)
2015 to 2016	0.71	0.001	0.060	0.104
2016 to 2017	0.11	0.006	0.008	0.016
2017 to 2018	2.38	0.011	0.180	0.301
ROD	**1.06**	**0.002**	**0.082**	**0.140**

From Table 4.7, it was observed that Voc and Isc has a yearly degradation rate of 0.71 V and 0.001 A from 2015 to 2016, slightly increased to 0.11V and 0.006A from 2016 to 2017 and further increased to 2.38V and 0.011A from 2017 to 2018. The increases noticed in short circuit current is believed to have been as a result of the continuous increases in module temperature from 38.9^{o} in the first year up to 41^{o} in the fourth year as indicated in Table 4.6. Meanwhile, the power (W) has a yearly decrease of 0.06W fortheyear 2015 to 2016, 0.008W for the year 2016 to

2017 and 0.18Wfor the year 2017 to 2018, while the maximum power has a slight decrease from0.104W to0.016W in 2016 to 2017 and finally increased to 0.301 Win 2017 to 2018.The Annual Average Rate of Degradation (RoD) for the four years was calculated on the performance variables which indicates that open-circuit voltage (Voc),short circuit current (Isc),power (P) and maximum power (P_{max}) has an annual average(RoD) of 1.06V,0.002A,0.082W and 0.140 W respectively for the four years of study as seen in Table 4.7.

Annual yearly average plots of performance variables are shown in Figures 4.29 – 4.30.Figure 4.29 shows the degradation rate for the performance variables being investigated in Minna, North central Nigeria. It was discovered that the open-circuit voltage (Voc) decreases drastically from the year 2015 to 2018.However,a slight increase was observed by the short circuit current (Isc)from 2015 to 2016. The increase in module temperature arises due to high insolation heating, low wind speed with the consequence to low heat transfer from the module to high ambient temperature. The rise in short-circuit current during this increase in temperature could be attributed to the fact that the band-gap of silicon material decreased as the temperature increases and the saturation current (I_o) of the silicon material also increases with temperature accordingto equation 2.3 thereby leading to an increase in short-circuit current.

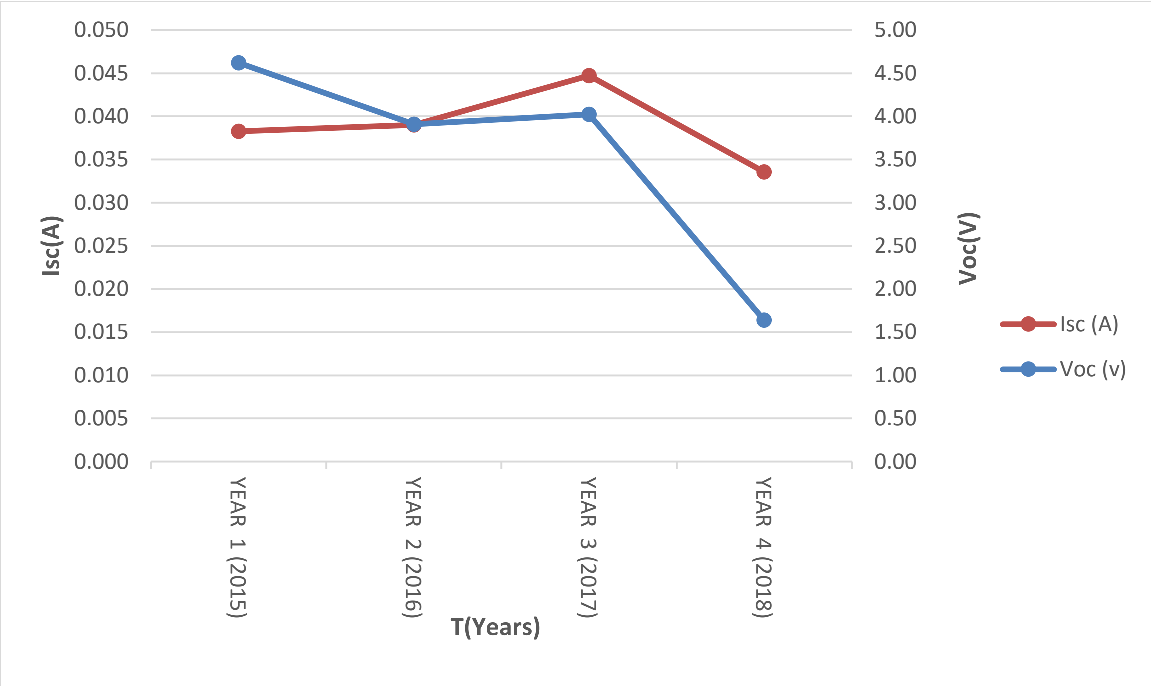


Figure 4.29: Variation of short circuit current and open-circuit voltage as a function of years.

From Figure 4.29,it was observed that open-circuit voltage decreased drastically from the first year to the last year of study while the short circuit current experience a slight rise in the second year but degrade from the third year downwards. The slight rise in the short circuit current in the second year (2016)does not imply degradation were not taking place but further confirmed a decreased in the band-gap of silicon as the temperature increases and the saturation current (I_o) of the silicon material also increased leading to an increased in the short circuit current.

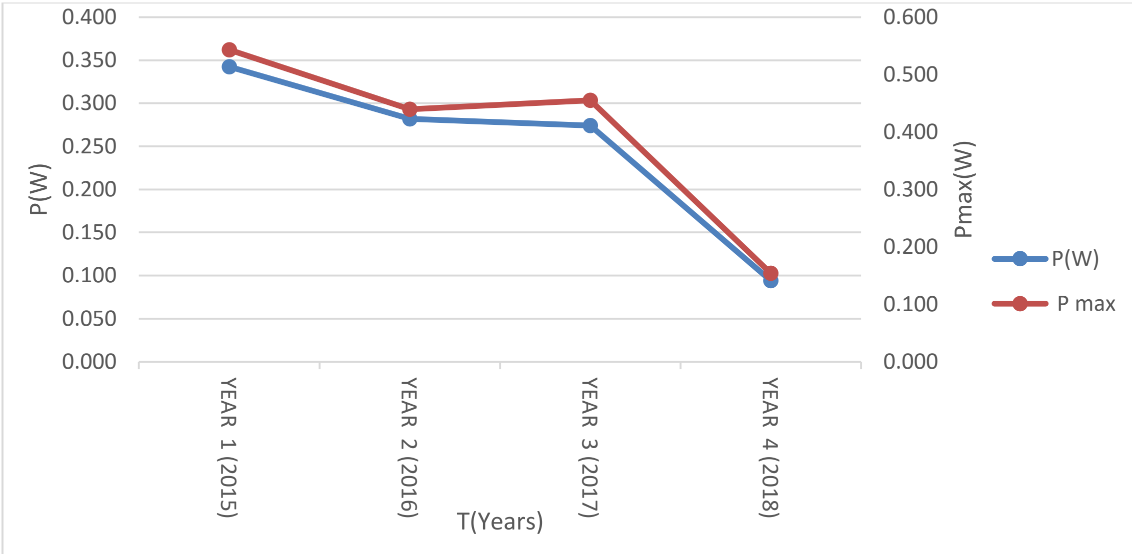


Figure 4.30: Variation of power output and maximum power as a function of years.

In Figure 4.30,It was observed that the power (W) and maximum power(W) decreased steadily from 2015 down to 2018 which correspond to the investigation and performance evaluation of monocrystalline photovoltaic panels in Funaab, Alabata, Ogun State by Kifilideen*et al.*, (2018) and that of the result from three different types of commercially available silicon PV module of monocrystalline that were simultaneously characterised with their performance evaluation by Ugwuoke and Okeke (2012)at Energy Research Center, University of Nigeria, Nsukka,Southeast Nigeria.

4.2.0 Statistical Analysis and Models

The regression model of three variables which include Voc(V), Isc(A), and Power (W*)* was doneoverthe years. 20 years forecast from the model was driven to determine whether there is a downward or upward trend of the experimental data.

4.2.1 Descriptive statistics: Voc (v), Isc (A), power(W)

The Mean, Standard Error Mean(SE, Mean), Standard deviation (St.Dev), Variance and Sum and Sumof squares of the variables were obtained as in Table 4.7 below.

Table 4.8: Mean, SE. Mean, Standard deviation and Variance

Variable	Mean	SE Mean	St.Dev	Variance	Sum Squares	
Voc (v)	3.8020	0.2840	1.9670	3.870018	2.4970	875.7570
Isc (A)	0.04298	0.00212	0.01469	0.000216	2.06318	0.09883
Power (W)	0.2760	0.0243	0.1683	0.0281	3.2459	4.9868

Table 4.7 shows thatthe mean of Voc (V) was 3.8020 which was higher than the mean of Isc (A) and Power (W) with a variance of 3.8700 and Standard Error of 0.2840, Isc (A) has mean of 0.04298 with a variance of 0.0002 and standard error of 0.0021, while, Power (W) has the mean of 0.2760, variance of 0.0281and Standard Error of 0.0243, respectively.

4.2.2. Inferential statistics

A multiple regression model was developed with the three independent variables which include Voc(V), Isc (A) and Power (W) and one dependent variable (Years). The Regression equation model for the research work is**:**

YEAR = 4.60 - 0.603 Voc (v) - 6.83 Isc (A) + 1.75 Power (W)(4.1)

From equation 4.1, per unit increase in Voc (V) there is 0.603, decrease in the Years value keeping Isc (A) and Power (W) constant, per unit increase in Isc (A) there is 6.83 decrease in the Years value keeping Voc (V) and Power (W) constant which shows the very fast downward trend of the values than the Voc (V)and also per unit increase in Power (W) there is 1.75, increase in the Year'svalue keeping Voc(v) and Isc (A) constant.

Thepercentage decrease of Isc (A) contributed to the fast decrease in the values as Years increases.The coefficients of the variable (Coef),T-test, and P-value are shown in Table 4.9.

Table 4 .9 Coefficients of variables (Coef); T-test and P-value

Predictor	Coef	SECoef	T-test	P-test
Constant	4.6042	0.3139	14.67	0.000
Voc (v)	-0.6031	0.1206	-5.00	0.000
Isc (A)	-6.833	7.173	-0.95	0.346
Power(W)	1.748	1.496	1.17	0.249

From Table 4.9, since P-vales for Voc (v)= 0.000 is less than 0. 05 (5%) the variable contribute significantly to the model, while Isc (A) and Power(W) with P-value = 0.346 and 0.249 are greater than 0.05 (5%) does not contribute significantly to the model. Further, the analysis of variance explained the significant difference in the contribution of the variables to the model as shown in Table 4.10.

Table 4.10: Analysis of variance (ANOVA) for the regression equation

Source of Variance	Degree of Freedom	Sum of Squares	Mean Squares	F-value	P-value
Regression	3	43.368	14.456	38.24	0.000
Residual Error	4416.632	0.378			
Total	47	60.000			

S = 0.614811   R-Sq = 72.3%   R-Sq(adj) = 70.4%

From Table 4.10, since the P-value = 0.000 is less than 0.05 (5%) level of significance, we shall conclude that there is a statistically significant difference in the contributions of the variables to the model with 72.3% explaining the difference and 26.7% unexplained. The implication is the downward trend of the yearly values, showing that there is a significant yearly Rate of Degradation (RoD) of the mono-crystalline module

4.3 Forecasting

A 20 years forecasting using the model developed was tabulated with the predicted values as in Table 4.11

Table 4.11: 20 Years Forecasting

Years	2019	2020	2021	2022	2023	2024	2025	2026	202	2028
Predicted Values	8.117	2.434	-3.249	-8.932	-14.615	-20.298	-25.981	-31.664	-37.347	-43.030
Years	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
Predicted Values	-48.713	-54.396	-60.079	-65.762	-71.445	-77.128	-82.811	--88.494	-94.177	-99.860

The line graph in Table 4.11show diagrammatically the downward trend of the predicted values over 20 years using the Regression equation model for the research in equation 4.1

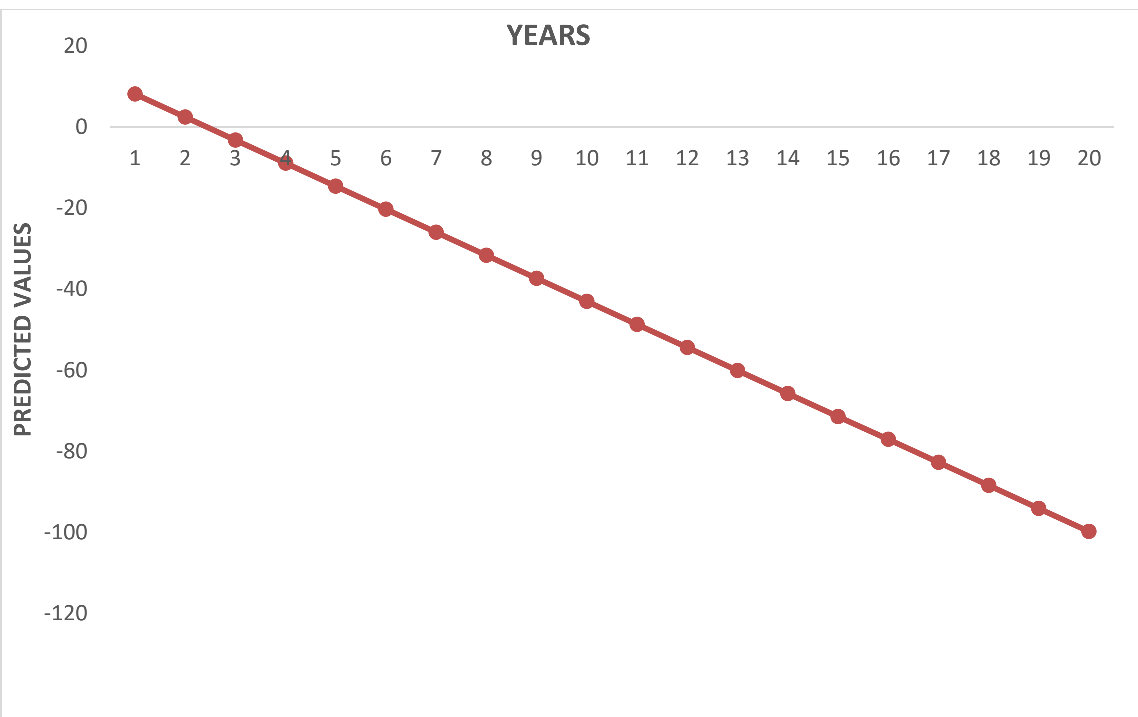


Figure 4.31: Line graph of the predicted values

The statistical mathematical modeling for the graph is

YEAR = 4.60 - 0.603 Voc (v) - 6.83 Isc (A) + 1.75 Power (W)

The key represented in Figure 4.31 line graph of the predicted values in years are:

1= 2019 6= 2024 11= 2029 16 =2034

2= 2020 7= 2025 12= 2030 17= 2035

3=2021 8= 2026 13=2031 18= 2036

4= 2022 9 = 2027 14=2032 19= 2037

5=2023 10 = 2028 15 = 203320= 2038

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The determination of yearly performance and degradation rate of electrical parameters of themonocrystalline photovoltaic module in Minna local environment for the four years of study indicated that the electrical parameters degrade accordingly.The maximum power achieved at 1000W/m^2 for the four years of study are 0.711W,1.839W,0.503W and 0.225 W representing 7.11%,18.39%,5.03% and 2.25% of the initial value of 10 W for 2015,2016 2017 and 2018. Modules efficiency at 1000W/m^2 for the four years of study degrades to 3.30%,10.0%,3.99%, and 2.82% for the years 2015, 2016, 2017, and 2018 respectively from the initial value of 46%. All the temperature recorded by the module for the four years of study were all beyond 25^0C at 1000W/m^2 irradiance.This further proves that there is a degradation in the values of the electrical parameters

The yearly Rate of Degradation (RoD) of monocrystalline photovoltaic modules in Minna local environment shows that all the electrical performance variables of the module degraded significantly from year to year for the four years of study. It was discovered that Voc, Isc, P and Pmax has an annual average RoD of 1.06 V, 0.002 A, 0.082W and 0.142W respectively for the four years of study. Similarly, it was observed that Voc and Isc reduced to 0.71 V and 0.001A from 2015 to 2016, decreased by 0.11V and 0.006A from 2016 to 2017 and further decreased with 2.38V and 0.011A from 2017 to 2018. Meanwhile, power and power at maximum have a yearly decrease of 0.06W and 0.104W from the year 2015 to 2016, 0.008W 2016 to 2017 for power (W) but power at maximum has a slight increase of 0.016W and finally,0.18W and 0.301W of P(W) and P(max) decreased from 2017 to 2018.

The Annual Average Rate of Degradation (RoD) for the four years was calculated only for the performance variables which indicates that Voc, Isc, P and Pmax has an annual average (RoD) of 1.06V,0.002A,0.082 W and 0.142 W respectively for the four years of study as seen in Table 4.7

Finally, a multiple regression model was developed with three independent variables which include Voc (V), Isc (A), and Power (W) and one dependent variable (years).The regression equation model for the research work is

$$\textbf{YEAR = 4.60 - 0.603 Voc (v) - 6.83 Isc (A) + 1.75 Power (W)} \qquad \textbf{(4.1)}$$

From equation 4.1, for every unit increase in the year there is 0.603 decrease of Voc in the Years value keeping Isc(A) and Power (W) constant, per unit increase in Isc(A) there is 6.83 decrease in the Years value keeping Voc(V) and Power (W) constant which shows the very fast downward trend of the values than the Voc (V)and also per unit increase in Power W there is 1.75, increase in the Year'svalue keeping Voc(v) and Isc(A)constant. The percentage decrease of Isc(A) contributed to the fast decrease in the values as Years increased.

5.2 Recommendations

Despite that the yearly performance and Rate of Degradation (RoD) has been extensively carried out under Minna prevailing meteorological parameters, however, there are still areas where work needs to be carried out in Minna local environment.

(i) A reflective loss as a result of module encapsulation was not accounted for in this work, therefore, it is recommended that the optical performance of modules encapsulations be further carried out in Minna Environment.

(ii) Photovoltaic modules respond differently to the different spectral regions of the sun's radiation and this is an important aspect of characterisation and performance evaluation of the monocrystalline module. Unfortunately, this was not considered in this work due to a lack of a spectrometer in Minna at the time of this investigation.It is therefore recommended that the performance response of PV modules to spectral regions of the sun be investigated in Minna.

(iii) It is equally recommended that outdoor yearly degradation studies be carried out in all commercially available PV module in every location of Nigeria and a database should be kept in other to furnish the policy marker, designers, and PV power installers the necessary information on the degradation rate and lifespan of those commercially available PV modules in each region for an effective and reliable PV power system.

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APPENDIX A

Descriptive Statistics: Voc (v), Isc (A), Power(W)

```
                                                               Sum of
Variable      Mean  SE Mean    StDev  Variance       Sum  Squares
Voc (v)      3.802    0.284    1.967     3.870  182.497  875.757
Isc (A)    0.04298  0.00212  0.014690.000216 2.06318  0.09883
Power(W)    0.2760   0.0243   0.1683    0.0283  13.2459   4.9868
```

Regression Analysis: YEAR versus Voc (v), Isc (A), Power(W)

```
The regression equation is
YEAR = 4.60 - 0.603 Voc (v) - 6.83 Isc (A) + 1.75 Power (W)

Predictor      Coef  SECoef      T      P
Constant     4.6042  0.3139  14.67  0.000
Voc (v)     -0.6031  0.1206  -5.00  0.000
Isc (A)      -6.833   7.173  -0.95  0.346
Power(W)      1.748   1.496   1.17  0.249

S = 0.614811   R-Sq = 72.3%   R-Sq(adj) = 70.4%

Analysis of Variance
Source          DF      SS      MS      F      P
Regression       3  43.368  14.456  38.24  0.000
Residual Error  44  16.632   0.378
Total           47  60.000
```

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.8502
R Square	0.7228
Adjusted R Square	0.7039
Standard Error	0.6148
Observations	48.0000

ANOVA

	df	SS	MS	F	ignificance F
Regression	3	43.3683	14.4561	38.2443	2.54E-12
Residual	44	16.6317	0.3780		
Total	47	60			

	Coefficients	andard Errc	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	4.6042	0.3139	14.6672	1.5E-18	3.9715	5.2368	3.9715	5.2368
X Variable 1	-0.6031	0.1206	-5.0003	9.6E-06	-0.8461	-0.3600	-0.8461	-0.3600
X Variable 2	-6.8327	7.1727	-0.9526	3.5E-01	-21.2883	7.6228	-21.2883	7.6228
X Variable 3	1.7479	1.4956	1.1687	2.5E-01	-1.2662	4.7620	-1.2662	4.7620

YEAR = 4.60 - 0.603 Voc (v) - 6.83 Isc (A) + 1.75 Power

YAER	Voc (v)	isc	Power	Total	
1	3.997	-2.23	6.35	8.117	
2	3.394	-9.06	8.1	2.434	
3	2.791	-15.89	9.85	-3.249	
4	2.188	-22.72	11.6	-8.932	
5	1.585	-29.55	13.35	-14.615	
6	0.982	-36.38	15.1	-20.298	
7	0.379	-43.21	16.85	-25.981	
8	-0.224	-50.04	18.6	-31.664	
9	-0.827	-56.87	20.35	-37.347	
10	-1.43	-63.7	22.1	-43.03	
11	-2.033	-70.53	23.85	-48.713	
12	-2.636	-77.36	25.6	-54.396	
13	-3.239	-84.19	27.35	-60.079	
14	-3.842	-91.02	29.1	-65.762	
15	-4.445	-97.85	30.85	-71.445	
16	-5.048	-104.68	32.6	-77.128	
17	-5.651	-111.51	34.35	-82.811	
18	-6.254	-118.34	36.1	-88.494	
19	-6.857	-125.17	37.85	-94.177	
20	-7.46	-132	39.6	-99.86	

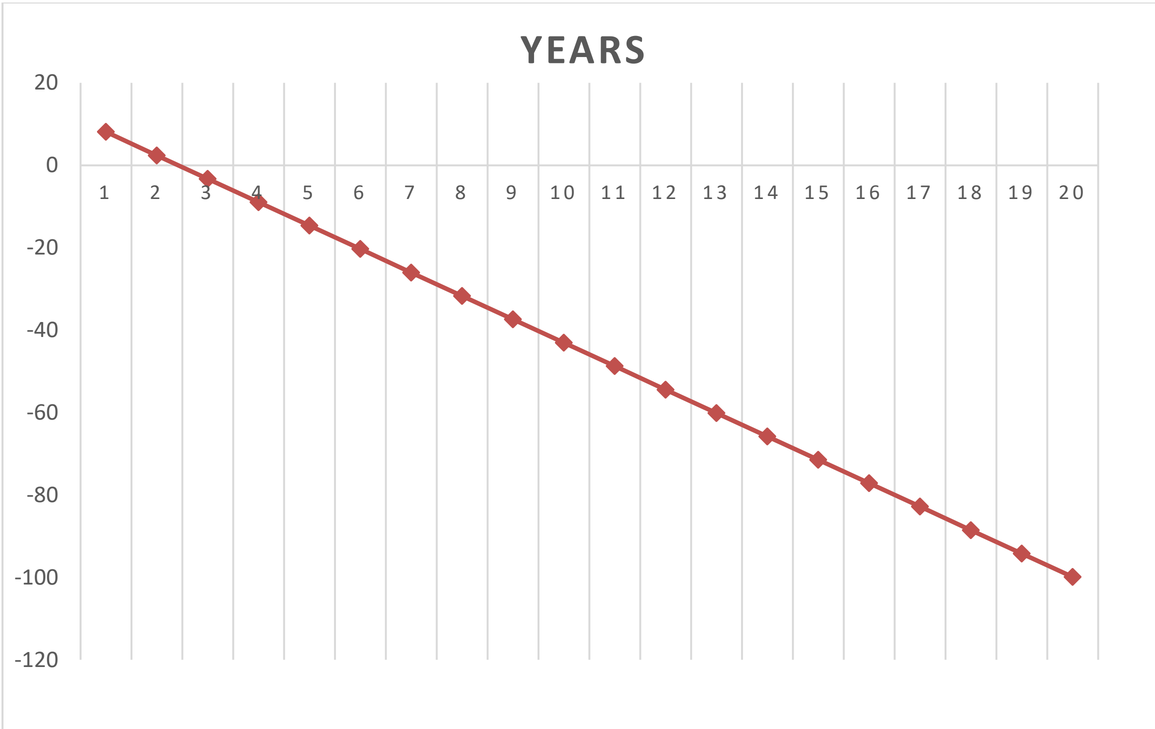

Figure 4.32 Graph of predicted value against years.