PERFORMANCE EVALUATION OF AMORPHOUS SILICON PHOTOVOLTAIC MODULE USING SOLAR LIGHT OF DIFFERENT WAVELENGTHS

BY

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DECLARATION

This dissertation is entirely my own work and has not been submitted to another university for consideration for a similar degree.

Signature: ……………………………. Date: …………………………….

APPROVAL

This is to certify that the research dissertation entitled, "**Performance evaluation of amorphous silicon photovoltaic module using solar light of different wavelengths**" was done by SICHONE SEBA ACKIM under our supervision and is now ready for submission to the Board of the Directorate of Research and Graduate Training and the Senate of Kyambogo University with our approval.

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DEDICATION

This dissertation is dedicated to my beautiful wife (Mrs. Rebecca Sichone) for her affection, tolerance, moral, endless prayers, and best wishes during my studies. May her prayers and wishes continue being the key towards other academic activities and stages.

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LIST OF ACRONYMS

BF	Blue Filter
GF	Green Filter
OF	Orange Filter
RF	Red Filter
YF	Yellow Filter
WF	Without Filter
PV	Photovoltaic
STC	Standard Test Condition
OPC	Operating Condition
I_{sc}	Short circuit current
V_{oc}	Open circuit voltage
I_{mpp}	Current at maximum power point
V_{mpp}	Voltage at maximum power point

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ABSTRACT

The performance of amorphous silicon photovoltaic module was evaluated using solar light of different wavelengths in this study. The different wavelengths of solar light were filtered by use of colour filters. During data collection, the plane of the module was oriented perpendicular to the sun, in order to ensure that module gets the maximum solar irradiance. The I-V tracer was employed to obtain the module I-V curves, P-V curves and subsequently the I-V outputs of the module. The short circuit current and power output of the module varied at different wavelengths of solar light, but the module's open circuit voltage was almost constant at different wavelengths. The highest short circuit current of 0.76 A, maximal power of 9.60 W and efficiency of 3.60 % were obtained when the module was not covered with any colour filter. Among all the used colour filters, the yellow colour of solar light gave the highest short circuit current of 0.68 A, maximal power of 8.89 W and efficiency of 3.29 %. This suggests that the yellow light is highly efficient in the amorphous silicon photovoltaic module power generation compared to the other colours of the visible light. The impact of module temperature on the module's open circuit voltage and short circuit current for different wavelengths of solar light were also investigated. The results showed that the rise in module temperature led to the fall in the open circuit voltage and small increment in short circuit current of the module regardless the wavelength of solar light. Due to the outcomes of this research, it was recommended that more research is needed to be done by filtering solar light into single wavelengths rather than the band of wavelengths. The colours of visible light which were not considered in this study, have to be considered for future work. Manufacturers may use the findings of this study to modify the technological design of the module so as efficiently capture the wavelengths of solar light within the yellow portion of the visible spectrum.

CHAPTER ONE: INTRODUCTION

1.1 Background of the study

Energy is currently mankind's most basic necessity. Uninterrupted energy has become necessary for society in recent years. Electricity is very important to every country's economy. Without electricity, the economy of any country will tremble making it difficult to maintain. One of the most urgent issues in the world is energy, and every nation is on the lookout for new sources of energy as demand rises (Arshad et al., 2014). Non-renewable energy resources are too expensive, unsustainable, and destructive to the environment and are eventually going to be depleted. This is the reason why the world is switching to renewable energy sources that regenerate themselves naturally. Although hydroelectric is the cheapest renewable energy source, it is not accessible everywhere in the world. However, the ubiquity of solar energy makes it more reliable for power generation. Energy from the sun has been freely available as both light and heat. Today, solar energy is applied to deliver electric current by using photovoltaic (PV) modules made from photovoltaic cells. Photovoltaic modules have become the major source of electricity in rural areas. The modules do have potential to transform the solar energy to electric current. Solar energy being a renewable resource, presents a great future for photovoltaic module technologies. The common photovoltaic module technologies, such as, monocrystalline and polycrystalline modules which are currently in use are expensive because of their higher production cost. Thin-film technologies, such as, amorphous silicon are cheaper than crystalline silicon technologies because their production cost is lower.

The conversion of the Photovoltaic energy system from solar to the current has become a popular subject and has been the focus of many engineers and scientists. (Premkumar et al., 2020). As a result of improvements in photovoltaic technology for the past twenty years, the cost of photovoltaic modules and other components has dropped significantly, efficiency has increased, and the system's reliability and yield have improved significantly. As a result, electricity prices have decreased (Benda and Černá, 2020). To be incorporated into the power grid, solar systems must be able to predict how much electricity they will produce. This concerns how the solar module will behave in various climatic situations to which they would be subjected (Moreno-Sáez et al., 2016). The working of photovoltaic modules is mainly dependent upon the irradiance and temperature. The radiation of the sun comprises of light of different wavelengths and therefore, different photon energies. Since photons have different energies, they penetrate the photovoltaic active materials to different depths before generating current in the module. A photon with a higher energy than the active photovoltaic material's bandgap energy is absorbable and produce an electron and a hole (Honsberg and Bowden, 2019, Chen, 2011). Because the electron–hole pair's potential energy equals the band gap value, the optimum material must possess a band gap towards the solar spectrum's center(Chen, 2011). Another aspect that influences the performance of photovoltaic module is energy gap (Chen, 2011). Depending on the relative placements of the valence band's top and bottom. Depending on the thickness of the photovoltaic active material, some photons may even go straight through the material without being absorbed and consequently, generating no current. The current measured at the module output is the combined effect of the absorbed photons from different solar light wavelengths. Therefore, to be able to understand the contribution that each solar light wavelength makes to the overall module output current, there is need to filter the different wavelengths of solar light and study their effect on photovoltaic module performance separately.

1.2 Statement of the problem

Thin-film PV modules are increasingly becoming important for electricity production due to their lower production cost and hence cheaper (Ye et al., 2014, Gottschalg et al., 2004). The generation of electricity in PV module is entirely dependent on the solar radiation. Since the solar radiation spectrum is not monochromatic, the current generated in the module is a function of the different wavelengths constituting the solar light. The impact of solar light wavelengths on the monocrystalline and polycrystalline based photovoltaic modules performance have been investigated (Ramkiran et al., 2020, Njok et al., 2020, Ogherohwo et al., 2015). However, studies on the thin film based photovoltaic modules, particularly amorphous silicon have not been done significantly. In order to critically understand how the irradiance influences the performance of amorphous silicon module, the effects of the different wavelengths of solar light on the thin-film based module performance parameters are probed in this study.

1.3 Main objective of the study

The study's main objective was to evaluate the performance of amorphous Silicon PV module by using solar light of different wavelengths.

1.4 Specific objectives of the study

The study's specific objectives were to;

(i) Determine the short circuit current and open circuit voltage of amorphous silicon PV module under solar light of different wavelengths.

(ii) Determine the maximum power output of amorphous silicon PV module at different wavelengths of solar light.

(iii) Investigate the effect of different wavelengths of solar light on the overall module efficiency.

(iv) Investigate the effects of the module temperature on the short circuit current and open circuit voltage of amorphous silicon PV module at different wavelengths of solar light.

1.5 Scope of the study

This research was performed on amorphous silicon PV module of power rating of $10\,W$ manufactured by Shenzhan Topray Solar Co. Ltd. The following colour filters were employed in this study; red, blue, green, yellow and orange because they are readily available in the market. The experiment was conducted at Kyambogo University.

1.6 Significance of the study

This study presented comprehensive knowledge about effects of the different wavelengths of solar light based on performance parameters of amorphous Silicon PV modules. This information is employable by the PV module manufacturers to select absorber materials with consideration of solar light wavelength which gives optimum efficiency. The information from this study can also be used for further research. The study contributed the body of knowledge and can be applied for educational purpose.

CHAPTER TWO: THEORY AND REVIEW OF RELATED LITERATURE

2.1 Introduction

This chapter reviews the previous writers' conclusions on the relevant study. It features the theory, solar light spectrum, effect of irradiance on the performance of the PV module, effect of temperature on the performance of the PV module, effect of spectral variation on the PV module performance, effect of the wavelengths of solar light on the performance of the PV module and colour filters.

2.2 Theory

The incident light (photons) on the photovoltaic material's surface will either be absorbed or reflected from the photovoltaic material (Honsberg and Bowden, 2019). Failure of any of the two mentioned processes, the photons will be transmitted through the photovoltaic module. In photovoltaic devices, reflections and transmissions are often regarded as losses because the photons which are not absorbed do not generate current in the photovoltaic module. A photon's ability to excite valence band electron into conduction band when it is absorbed. The photon energy plays a crucial role in deciding whether a photon is absorbed or transmitted. The electron will therefore, only be stimulated to the conduction band from the valence band if the photon energy is higher than the band gap energy of photovoltaic material. (Honsberg and Bowden, 2019). The incident radiation of solar light (photons) links with a photovoltaic material in two means; A photon stronger compared to the energy gap of a material can penetrate and bear an electron and a hole (Chen, 2011). In terms of a detailed balance the chances of that two processes should be the same. Because the electron-hole pair's potential energy is equal to the energy of the band gap, good photovoltaic material must possess a band gap close to solar light spectrum's center (Chen, 2011). The process of converting solar light photons into electrical energy needs absorbing substances.

Incident ray of solar light absorbed by the photovoltaic module excites electrons to high energy states, excited electron depletes its energy in the circuit and produces electricity (Pannase and Nanavala, 2017).

The ratio of the input photon flux to the wavelength-dependent photogenerated current density is known as the spectral response (Okullo et al., 2011, Ghitas and Geophysics, 2012). The mathematical expression of SR is

$$SR(\lambda) = \frac{J_{ph}(\lambda)}{G(\lambda)}, \quad (2.1)$$

where $J_{ph}(\lambda)$ is the overall photogenerated current density for a certain solar light wavelength (λ) and $G(\lambda)$ is the solar light's spectrum irradiance as it strikes. Nevertheless, in the status module,

the current density of the short circuit (J_{sc}) measured is approximately to J_{ph} (Silvestre et al., 1999). The wavelength measurement, which measures the spectral reaction of the photovoltaic module signal is very important in assessing the properties of the material of the photovoltaic module (Bell and Freedman, 1978). Most often, quantum efficiency (QE), a measurement of how effectively a device transforms incoming photons to charge carriers in the circuit, is used to report the spectrum reaction of photovoltaic modules. (Shaltout et al., 2000). From the expression (2.1), the short circuit current density can be expressed regarding spectral irradiance $G(\lambda)$ of incident solar light as

$$I_{sc} = \frac{Aq}{hc}\int_{\lambda_0}^{\lambda_c} QE(\lambda)\, G(\lambda)\lambda d\lambda, \quad (2.2)$$

where A is the module's surface area, λ_0 and λ_c are, respectively, the minimum and cut-off wavelengths, q is the electronic charge, h is Planck's constant and c is the velocity of light in vacuum (Singh et al., 2003). The photovoltaic solar cell's capacity, material composition, and structure all affect the spectrum response to capture energy does not depend only on the incident photon energy but also its capacity to detect particular wavelength of solar light (Ogherohwo et al., 2015).

2.3 Solar spectrum

The earth receives solar energy of sun's light with the majority of its spectral components being in the visible, near infrared, and close to ultraviolet (Chen, 2011). The atmosphere of the earth serves as a natural filter for solar radiation. (Ramkiran et al., 2020). The electromagnetic spectrum, from ultraviolet to infrared, is spread out by inbound radiation. Visible light is only a small component of the electromagnetic energy that makes up solar light. (Honsberg and Bowden, 2019). Figure 2.1 indicates the parts of solar energy spectrum.

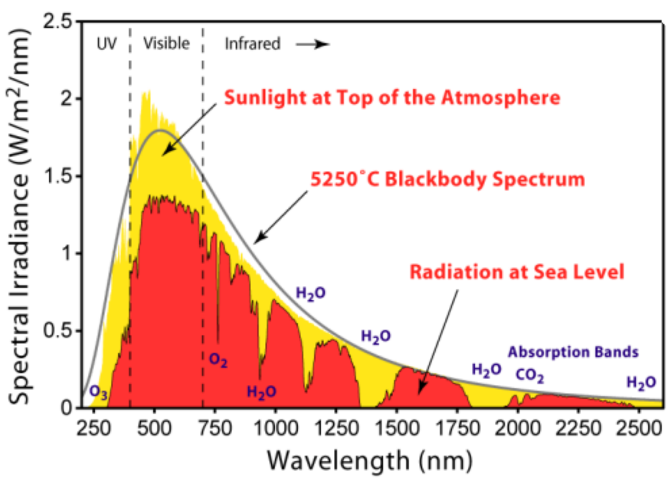

Figure 2.1: Solar energy spectrum (Ramkiran et al., 2020).

2.4 The impact of irradiance on the performance of the module

The output of light energy from the entire sun disc, as measured at the earth, is known as irradiance. Photons which carry this energy have different wavelengths (NASA, 2008). The working of the module is mainly determined by the irradiance (Hishikawa et al., 2013). The current output of the photovoltaic modules increases significantly with the increment in irradiance while with an increase in sun irradiation, the voltage slightly rises. (Irwanto et al., 2010, Rodrigues et al., 2011). Many studies have shown that as irradiance rises, the short circuit current also considerably rises and the open circuit voltage rises just a little with the increase in irradiance (Islam et al., 2014, Xiao et al., 2014, Musanga et al., 2018).The variation of PV module outputs temperature and irradiance was investigated, and shown that the short circuit current varies nonlinearly with irradiance, the open circuit voltage is insignificantly affected by the irradiance, the shunt resistances decreases with increasing solar irradiance while the relationship between series resistance and solar irradiation is logarithmic. (Ibrahim and Anani, 2017). Figure 2.2 indicates the I-V curves of the PV module at various levels of irradiance.

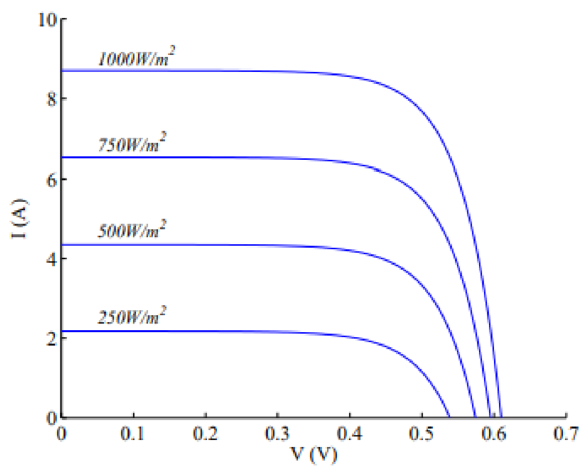

Figure 2.2: The I-V curves at difference irradiance levels (Rodrigues et al., 2011).

2.5 The impact of temperature on the module performance

The performance of the module varies with temperature, the change in temperature distorts the module's power output. The voltage output of the photovoltaic module is greatly influenced by temperature and decreases with increasing temperature (Fesharaki et al., 2011). The module temperature is the result of the absorption of solar irradiance and, is the critical issue when predicting the energy production of the module (Amelia et al., 2016). The raising of the temperature causes the efficiency of the PV module to decrease gradually and thus, negatively affects the module's performance (Amelia et al., 2016). The photovoltaic conversion processes depend significantly on the operating temperature of the module, which also has a direct relationship with the efficiency and power output of the module. (Dubey et al., 2013). The impact of the experimental study of temperature and irradiance on photovoltaic modules was conducted, and revealed that the module’s efficiency is highly depends upon the temperature and decrease energy output (Zaoui et al., 2015). It has been found that amorphous silicon PV modules perform better in areas with higher temperatures compared to traditional crystalline silicon PV modules (Ruther et al., 2008).

2.6 Effect of spectral fluctuation on the PV module performance

Spectral variation is a crucial element that affects how well PV modules function. (Gottschalg et al., 2005). The working of polycrystalline silicon modules and thin film modules was examined experimentally for the effects of the daily spectrum change. The outcomes demonstrated that the visible spectral bands create greater short circuit current than the infrared and ultraviolet spectral bands. (Okullo et al., 2011). It has been shown that the afternoon spectra have more infrared radiations than morning spectra and shifting of spectra to infrared has negative impact on the working of the thin film modules (Okullo et al., 2011). The performance of single and double amorphous silicon modules under the influence of spectrum changes was studied, where the outcomes gave the evidence that spectral variations of the solar irradiance cause significant changes in the PV module performance parameters (Gottschalg et al., 2005). Comparative study on the effect of seasonal spectral variations on the performance of amorphous silicon, thin film and polycrystalline silicon modules was conducted and revealed that spectral variation has additional influence on the amorphous PV modules' performance parameters (Magare et al., 2016).

2.7 Impact of Solar light wavelength on the PV module operation

The wavelengths of solar light affect the photovoltaic module's operation. The investigation on the results of solar light's wavelengths on the working of monocrystalline photovoltaic module was done, and concluded that compared to other colors, magenta light induces more electricity. (Ramkiran et al., 2020). Another study on the impact of light wavelength on the functionality of monocrystalline silicon photovoltaic modules discovered that red colour induces more energy than any other colour (Ogherohwo et al., 2015). The experimental study on how polycrystalline photovoltaic module respond to different wavelengths of light was done and found that yellow light produced best efficiency, while blue light generated the PV module's lowest efficiency (Njok et al., 2020). The research on the implications of solar light's wavelengths on the operation of amorphous silicon photovoltaic module are not significantly done.

2.8 Colour filters

Colour filters are transparent materials to solar light, with the wavelength having an influence on the amount of light passed. Selective absorption underlies how color filters work. More spectral components are absorbed than are transmitted, in other words. (Gunther, 2012). A filter of a specific colour allows its own colour to pass through and absorbs the remaining colours as illustrated in Figure 2.3. The spectral colours and their respective wavelength ranges have been indicated in Table 2.1.

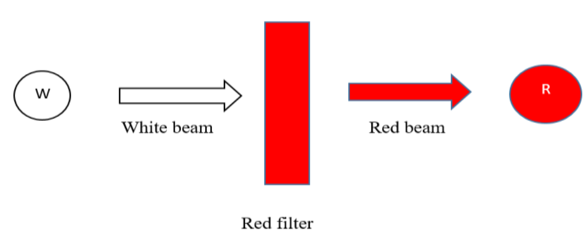

Figure 2.3: Filtering of white light using red colour filter.

Table 2. 1: Spectral colours with their corresponding wavelengths (Gunther, 2012).

Spectral colour	**Wavelength (nm)**
Violet	400 - 420
Indigo	420 – 455
Blue	455 - 490
Green	490 - 575
Yellow	575 - 585
Orange	585 - 650
Red	650 - 720

2.9 Normalization of the experimental I-V data

The literature has employed techniques for rectification of the real operating conditions (OPC) experimental I-V data to Standard Test Conditions (STC) values (Atsu et al., 2020, Seapan et al., 2020, Chamberlin et al., 1995, Spataru et al., 2015, Golive et al., 2021).The normalization of the experimental data to STC values examine the impacts of varying sun irradiation levels and module temperature. The photovoltaic module's short circuit current is potently depends on the incident solar irradiance level (G_m) and the open circuit voltage is strongly depends on both the module temperature (T_m) and incident solar irradiance level (G_m) (Chamberlin et al., 1995).The measured data are corrected to STC values by using the following mathematical relations which were developed using multiple linear regression (Chamberlin et al., 1995).

$$V = V_m \left(\frac{V_{oc;r}}{V_{oc;m}}\right), \tag{2.3}$$

where V is the module's voltage corrected to STC, V_m is the measured module's voltage, $V_{oc;m}$ is the measured module's open circuit voltage and $V_{oc;r}$ is the module's reference open circuit voltage.

$$V_{oc;r} = V_{oc;m} + a(T_r - T_m) + b(G_r - G_m), \tag{2.4}$$

where T_r is the reference temperature, T_m is the temperature measured, a is coefficient of the module's temperature and b is an insolation coefficient

$$I = I_m \left(\frac{G_r}{G_m}\right), \tag{2.5}$$

where I is the current of the module corrected to STC, I_m is the measured current of the module, G_m is the mensurable irradiance and G_r is the reference irradiance.

2.10 Basic working principle of the Photovoltaic module

Photovoltaic module is the collection of solar cells joined in a framework for installation (Chen, 2011). In essence, a photovoltaic solar cell is a semiconductor diode. (Shah et al., 1999). The module works based on the photovoltaic effect (Bahrami et al., 2013). The active photovoltaic material absorbs the incident photons and transforms them into pairs of electron-holes (Shah et al., 1999). The bandgap energy of the semiconductor is the key factor in this photogeneration process (Chen, 2011, Shah et al., 1999). In an abstract condition, only photons having energy equal to or greater than bandgap energy will contribute to photogeneration. These photons provide their energy to the photogenerated electron-hole pair, with any extra energy being thermalized away very quickly (Shah et al., 1999). The flux of photons with an energy greater than bandgap, provides the upper bound for the photogenerated electric current density. Consequently, the electric current density diminishes when the bandgap widens (Roger and Jerry, 2005, Shah et al., 1999).

CHAPTER THREE: METHODOLOGY

3.1 Introduction

In this chapter, the research approach is explained. It indicates the research design, determination of the module's short circuit current and open circuit voltage, determination of the maximum power output of the amorphous module, investigation of the impact of different wavelengths of solar light on the overall module's efficiency and examination of the relationship between the module's temperature and the module's open circuit voltage and short circuit current at different wavelengths of solar light.

The experiments were done at Physics laboratory compound of Kyambogo University in Uganda. The instruments and material used during the experimental study were amorphous silicon PV module of power rating of 10 W, I-V tracer, pyranometer, thermocouple, stand and colour filters. Origin 6.0 software was used for analyzing data including plotting the graphs.

3.2 Research design

This study involved experimental method of data collection and quantitative analysis of data. The data were obtained through experimental measurements and analyzed using the Origin 6.0 software. The rectification of measured experimental data to STC values was automatically done by the I-V tracer by normalizing the measured data to the STC values.

3.3 Determination of the short circuit current and open circuit voltage of amorphous silicon module

To be able to determine the module's short circuit current and the open circuit voltage, an amorphous silicon module was inclined at 90 degrees to the sun, to ensure that it receives the maximum irradiance. This was accurately done by use of an inclinometer as indicated in Figure 3.1.

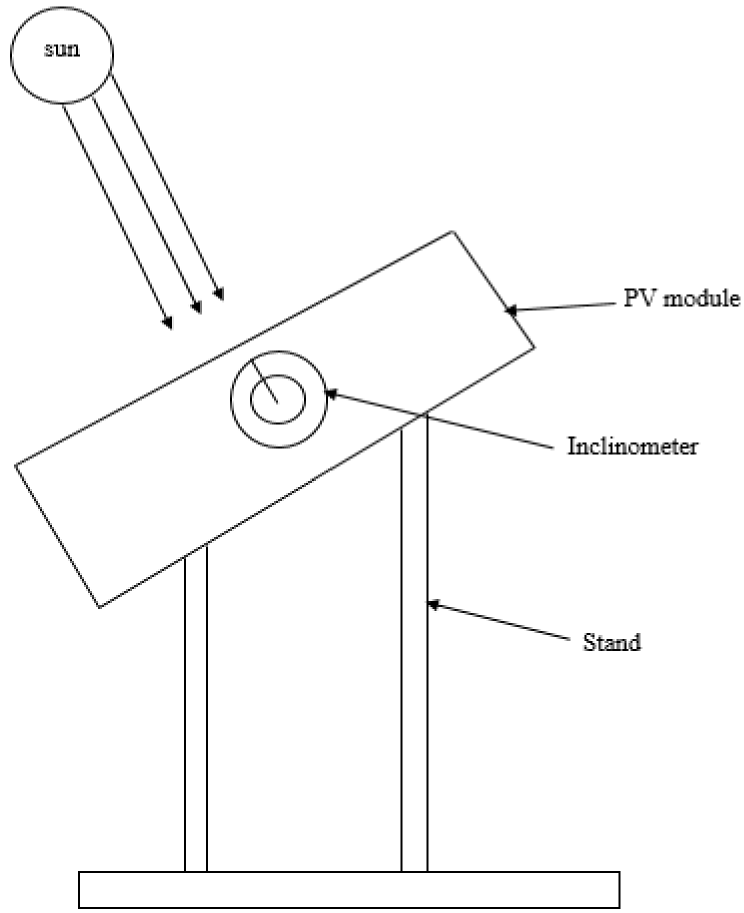

Figure 3. 1: Schematic diagram of experimental setup during measurements.

To ensure that the PV module was at right angle to the incident irradiance, the shadow of the stem of the inclinometer lied inside the inner circle of the inclinometer base. The glass side of the module was covered with a colour filter in order to induce the wavelength of solar light strikes on the module. The colour filter absorbed all the wavelengths of solar light except that of their own colour. In this study, red, blue, yellow, green and orange colour filters were employed. The PV module outputs, pyranometer and temperature probe were connected to the I-V tracer as depicted in Figure 3.2.

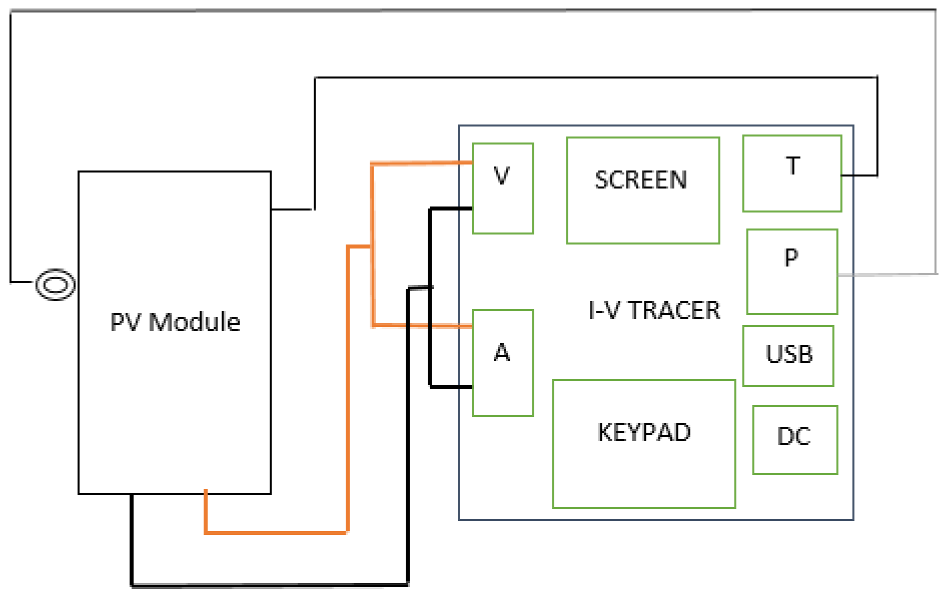

Figure 3. 2: The diagram for experimental set up.

The I-V curves of amorphous module were extracted using the I-V tracer and the module's electrical performance parameters were gotten from the module I-V curve. The experiment was repeated for blue, green, yellow, orange and red colour filters, and the performance outputs of the amorphous PV module were recorded. Three experimental measurements for each particular colour filter were carried out for three days consecutively.

Figure 3. 3: The I-V tracer and amorphous module with red filter.

Figure 3. 4: Different colour filters used during the experimental study.

3.4. Determination of the maximum power output of amorphous silicon PV module at different wavelengths of solar light.

The PV module's maximum power is granted by the expression in equation (3.1),

$$P_{max} = V_{max} \times I_{max} \tag{3.1}$$

where V_{max} and I_{max} represents the maximum voltage and current of the module respectively. The same experimental set up in Figure 3.2, was employed for determination of the module's maximum power for different wavelengths of solar light. The P-V curve of the module was extracted using I-V tracer, from which the P_{max} was determined. The experiment was repeated for blue, green, yellow, orange and red colour filters, the module's maximal power was recorded. Three experimental measurements for each particular colour filter were carried out for three days consecutively.

Table 3. 1: Specifications of amorphous silicon PV module at STC.

Specification	**Parameter**
Short circuit current (A)	0.95
Open circuit voltage (V)	23
Maximum current (A)	0.572
Maximum voltage (V)	17.5
Maximum power (W)	10

3.5 Investigation of the effect of different wavelengths of solar light on the overall module efficiency.

The module's maximum efficiency is calculated by using the expression (3.2),

$$\eta_m = \frac{Maximum\ power\ output}{Incident\ radiation \times area\ of\ collector} \times 100\ \% = \frac{P_{max}}{G \times A} \times 100\ \% \qquad (3.2)$$

Where G is the encountered solar irradiance and A is the module's surface area.

The same experimental set up in Figure 3.2, was employed. The module's length and width were measured and its area calculated. The value of the maximum power at particular wavelength of solar light was determined from the extracted P-V curve using I-V tracer and the efficiency of the PV module was calculated. The experiment was repeated for blue, green, yellow, orange and red colour filters. Three experimental measurements for each particular colour filter were carried out for three days consecutively.

3.6 Investigation of the effects of the module temperature on the short circuit current and open circuit voltage of amorphous silicon PV module at different wavelengths of solar light.

The experimental set up in Figure 3.2, was employed and for particular colour filter covering the PV module, module temperature measurements were recorded and the I-V curves were extracted from the module with help of I-V tracer at each temperature. This experiment was repeated for blue, green, yellow, orange and red colour filters. Three experimental measurements for each particular colour filter were carried out for three days consecutively.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Introduction

This chapter includes the discussion of the obtained experimental results. The short circuit current, open circuit voltage, maximum power, efficiency of the amorphous silicon PV module under different wavelengths of solar light and the effects of temperature on the short circuit current and open circuit voltage of amorphous silicon PV module at different wavelengths of solar light have been presented and discussed.

4.2 Short circuit current and Open circuit voltage of amorphous silicon PV module under solar light of different wavelengths.

The extracted I-V curves of amorphous silicon module from which short circuit currents and open circuit voltages were determined are indicated in Figure 4.1.

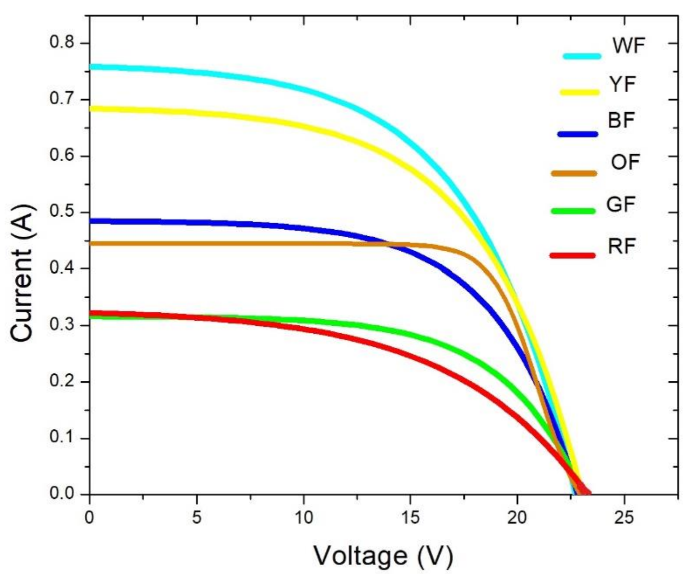

Figure 4. 1: The normalized I-V curves of amorphous silicon PV module under different wavelengths of solar light.

The I-V curves shown in Figure 4.1 were used to obtain the values of short circuit currents and open circuit voltages of the module at different wavelengths of solar light. The obtained values of short circuit currents and open circuit voltages are tabulated as seen in Table 4.1.

Table 4. 1: The values of the short circuit current and open circuit voltage at different wavelengths of solar light.

Colour	Wavelength (nm)	Short circuit current (A)	Open circuit voltage (V)
Whole solar spectrum	300-2500	0.76	22.72
Blue	455-490	0.48	22.72
Green	490-575	0.31	22.71
Yellow	575-585	0.68	22.72
Orange	585-650	0.44	22.71
Red	650-720	0.32	22.73

The Table 4.1 shows the extracted values of short circuit current and open circuit voltage of PV module at different wavelengths of solar light. The Figure 4.1 shows an insignificant change in the module's open circuit voltage compared to the short circuit current at different wavelengths of solar light. Many studies have shown that both open circuit voltage and short circuit current changes with variation of the incident radiation (Suman et al., 2021, Ibrahim and Anani, 2017, Tsuno et al., 2005, Islam et al., 2014, Musanga et al., 2018, Honsberg and Bowden, 2019, Gxasheka et al., 2005, Hishikawa et al., 2013, Macháček et al., 2007, Rani et al., 2018, Rodrigues et al., 2011, Okullo et al., 2011, Irwanto et al., 2010, Premkumar et al., 2020, Agroui, 2012, Vidyanandan, 2017, Nadia et al., 2020, Al-Bashir et al., 2020, Ogbulezie et al., 2020, Golive et al., 2021). The dependence of short circuit current on the incident solar radiation is higher compared to the open circuit voltage because the increment in the intensity of solar irradiance increases the photocurrent produced and hence, increased short circuit current (Musanga et al., 2018). Many studies have revealed that short circuit current largely change with change in irradiance level and there is very small change in open circuit voltage with change in irradiance level (Suman et al., 2021, Honsberg and Bowden, 2019, Islam et al., 2014, Rodrigues et al., 2011, Okullo et al., 2011, Agroui, 2012, Irwanto et al., 2010, Abdulrazzaq et al., 2020, Vidyanandan, 2017, Wi et al., 2014, Nadia et al., 2020, Islam et al., 2018).

Colour filters were employed in this study in order to filter unwanted wavelengths and allow only light corresponding to the wavelength of the colour of particular filter (Gunther, 2012, Tay et al., 2021, Ramkiran et al., 2020) to reach the photovoltaic material of the PV module. Different wavelengths possess different photon energies (Honsberg and Bowden, 2019, Ramkiran et al., 2020) and hence, different irradiance levels. These photons, therefore, penetrates the photovoltaic material at different depths before generating current in the module (longer wavelengths penetrate deeper compared to short wavelengths) (Honsberg and Bowden, 2019). The PV module has a specific spectral reaction and the depth of absorption (how wavelengths can penetrate without much deviation). Different depths of absorption and spectral responses depend on the various materials applied to make the cells of the PV module (Bankson et al., 2016).

An insignificant change in open circuit voltage with change in irradiance levels (different wavelengths of solar light) is due to its logarithmic dependence on the ratio between reverse saturation current and short circuit current (Irwanto et al., 2010, Broderick et al., 2015). The results in Figure 4.1 shows that the module's open circuit voltage output was almost constant at different wavelengths of solar light.

The significant fluctuation in short circuit current with fluctuation in irradiance levels (different wavelengths of solar light) is resulting from the fact that, the short circuit current is directly proportional to irradiance level received by the module. Similar studies have been reported by other researchers (Chen, 2011, Pandiarajan and Muthu, 2011). In this study, the highest short circuit current of 0.76 A was gotten when the PV module was not wrapped with any colour filter. This is so because all wavelengths of photons are present in the white solar light (Ramkiran et al., 2020). With colour filters, the highest short circuit current of 0.68 A was gotten when PV module covered with a yellow colour filter. This was followed by blue, orange, red and green colour filters which gave 0.48 A, 0.44 A, 0.32 A and 0.31 A respectively. Apart from yellow and green colours filters used, as solar light's wavelength increased, the short circuit current decreased. (from blue, orange to red) as shown in Figure 4.1. Other studies done by (Njok et al., 2020, Ramkiran et al., 2020) on the consequence of colour filters on the operation of Polycrystalline and monocrystalline modules respectively, revealed that yellow colour performed better than other colour filters used during the experiment.

Probably, that is to say, the spectral response of the module has its peak response at wavelengths corresponding to yellow colour of solar light than other colours of solar light (Ogherohwo et al., 2015, Berwal et al., 2016b, Peng et al., 2019, Honsberg and Bowden, 2019, Minemoto et al., 2007, Dirnberger et al., 2015, Betts et al., 2003, Rüther et al., 2002). The spectral response of photovoltaic modules changes with change in wavelength and depends upon the PV technology, material and structure of the solar cells used to make the module (Tsutsui et al., 2008, Minemoto et al., 2007, Okullo et al., 2011, Berwal et al., 2016a, Dirnberger et al., 2015). This shows that material and structure of amorphous PV module are more sensitive to the wavelengths corresponding to yellow colour of solar light. Probably, yellow colour of light gave the highest short circuit current than other colour filters, due to the fact that, yellow colour is secondary colour, a combination of red and green colours. Probably, the yellow light wavelengths possess more energetic photons, which can produce more output current (Ramkiran et al., 2020).

4.3 Maximum power output of amorphous silicon PV module at different wavelengths of solar light.

The P-V curves of amorphous silicon PV module from which maximum power was determined at different wavelengths of solar light are presented in Figure 4.2.

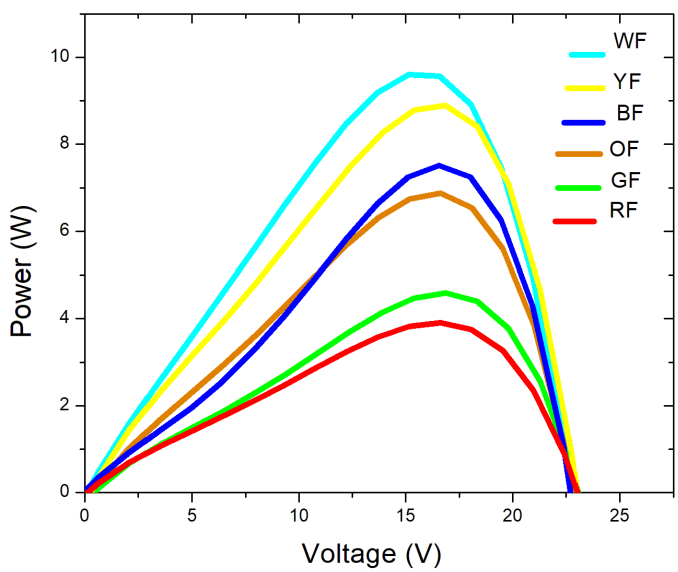

Figure 4. 2: The normalized P-V curves of amorphous silicon PV module at different wavelengths of solar light.

The P-V curves in Figure 4.2 were used to obtain values of the module's maximal power at different wavelengths of solar light and the values were presented in Table 4.2.

Table 4. 2: The values of the normalized maximum power at different wavelengths of solar light

Colour	**Wavelength (nm)**	**Maximum power (W)**
Whole solar spectrum	300-2500	9.60
Blue	455-490	7.50
Green	490-575	4.60
Yellow	575-585	8.89
Orange	585-650	6.87
Red	650-720	3.91

The module's power output varies with changes in the solar radiation (Rani et al., 2018, He et al., 2011, Vidyanandan, 2017, Nadia et al., 2020, Pandiarajan and Muthu, 2011). The Figure 4.2 shows that the maximum power of 9.60 W of the PV module was obtained when the PV module was not covered with any colour filter. With colour filters, the maximum power of 8.89 W of the module was obtained when the PV module was covered with a yellow filter. It was followed by the blue, orange, green and red colour filters which gave 7.50 W, 6.87 W, 4.60 W and 3.91 W respectively. Similarly, apart from yellow and green colour filters used, there was decrease in power with increase in wavelength of solar light (see Figure 4.2). Among the applied colour filters, yellow colour filter gave the maximum power, this is because, from the I-V curves in Figure 4.1, yellow colour gave highest product of current and voltage comparatively than other colour filters. Probably yellow light gave maximum power than other colour filters, because of high penetrating power of the photons in yellow part of the solar light spectrum. The maximum power of the module increases as the short circuit current and open circuit voltage increase (Honsberg and Bowden, 2019). Probably, the red light gave low power output because red light is close to infrared part of the spectrum of solar light (longer wavelengths) which mostly gets converted to heat and transmitted through the photovoltaic material of the module. The fact that different wavelengths (colours) of solar light carry different photon energies (thus different irradiance levels) cause variations in power output by the module (Musanga et al., 2018, Ramkiran et al., 2020).

4.4 Efficiency of amorphous silicon PV module at different wavelengths of solar light.

The efficiency of the module at various wavelengths of solar light were calculated as indicated in an appendix 1. The efficiencies were calculated using the normalized power outputs of the PV module.

Table 4. 3: The efficiencies of amorphous silicon PV module at different wavelengths of solar light

Colour	**Wavelength (nm)**	I_{mpp} **(A)**	V_{mpp} **(V)**	P_{max} **(W)**	**Efficiency (%)**
Whole solar spectrum	300-2500	0.58	16.59	9.60	3.60
Blue	455-490	0.45	16.57	7.50	2.78
Green	490-575	0.27	16.86	4.60	1.70
Yellow	575-585	0.53	16.86	8.89	3.29
Orange	585-650	0.41	16.63	6.87	2.54
Red	650-720	0.24	16.62	3.91	1.45

The module's efficiency depends on the maximum power output, photovoltaic module's area and irradiance level (Topi et al., 2007, Honsberg and Bowden, 2019, Chen, 2011, Vidyanandan, 2017). The calculated value of the module's efficiency was changing as the maximum power changes at different wavelengths of solar light. This is because each wavelength (colour filter) carry different photon energies. The Table 4.3 displays the values of efficiency of amorphous silicon PV module under solar light of different wavelengths, as were calculated using the equation 3.2 of the efficiency of solar cell. The highest efficiency of 3.60 % was obtained when the PV module was not covered with any colour filter. With colour filters, the highest efficiency of 3.29 % was obtained when the module was covered with a yellow colour filter. Research done (Njok et al.,

2020) on the colour filters' effect on a polycrystalline photovoltaic module's performance reported that, yellow colour produced the higher efficiency compared to other colour filters. In this study, yellow colour was followed by blue, Orange, Green and Red colour filters with efficiency of 2.78 %, 2.54 %, 1.70 % and 1.45 % respectively. Apart from yellow and green colours of solar light, the module's efficiency falls with increment in wavelength of solar light as displayed in Figure 4.2. Among the applied colour filters, yellow colour filter gave maximum efficiency than other colours of solar light, this is because, yellow colour produced the highest power output as shown in Figure 4.2. Additionally, when short circuit current and open circuit voltage rise, so does the module's efficiency (Honsberg and Bowden, 2019).

4.5 Effect of module temperature on the short circuit current and open circuit voltage of amorphous silicon PV module at different wavelengths of solar light.

The I-V curves of amorphous silicon PV module at different module temperatures under different wavelengths of solar light were extracted as shown in Figures 4.3, 4.4, 4.5, 4.6 and 4.7. Under different operating conditions, the increment in the module temperature reduces the open circuit voltage while linearly increasing the short circuit current (Dhass et al., 2016, Musanga et al., 2018, Gxasheka et al., 2005, Macháček et al., 2007, Rani et al., 2018, Amelia et al., 2016, Zaoui et al., 2015, Irwanto et al., 2010, Pandiarajan and Muthu, 2011). Similar phenomenon has been exhibited in this study for all the wavelengths of solar light used during the experimental study.

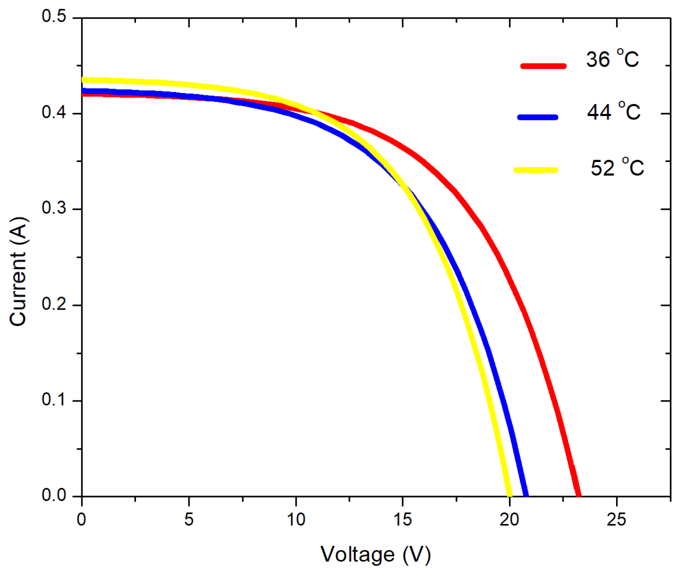

Figure 4. 3: The I-V curves of amorphous silicon PV at different module temperatures under blue colour filter.

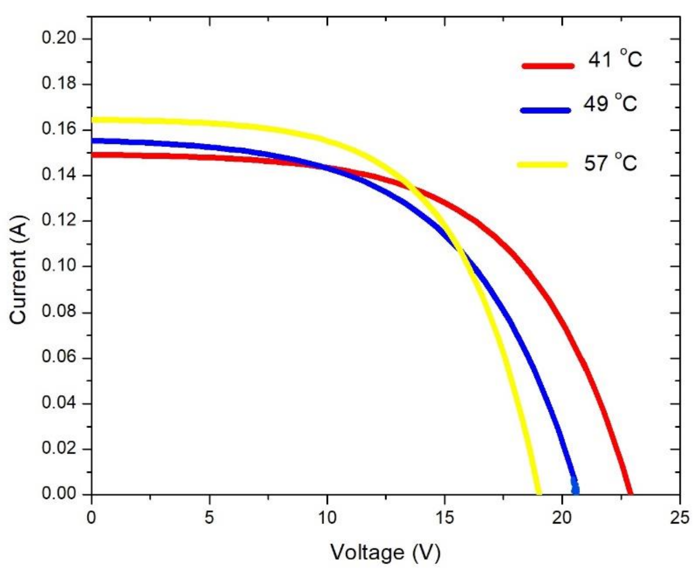

Figure 4. 4: The I-V curves of amorphous silicon PV module at different module temperatures under green colour filter.

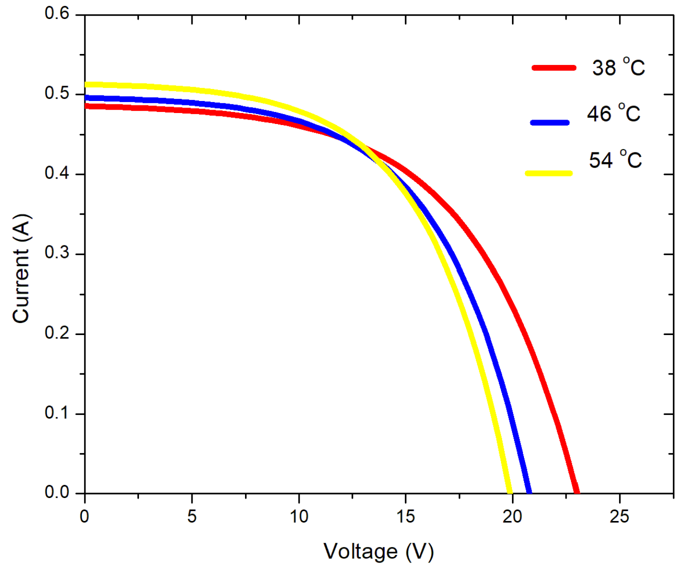

Figure 4. 5: The I-V curves of amorphous silicon PV module at different module temperatures under yellow colour filter.

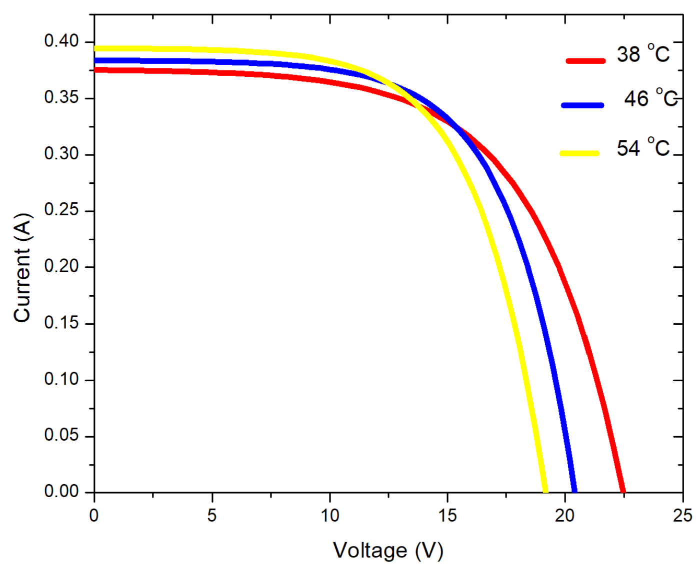

Figure 4. 6: The I-V curves of amorphous silicon PV module at different module temperatures under orange colour filter.

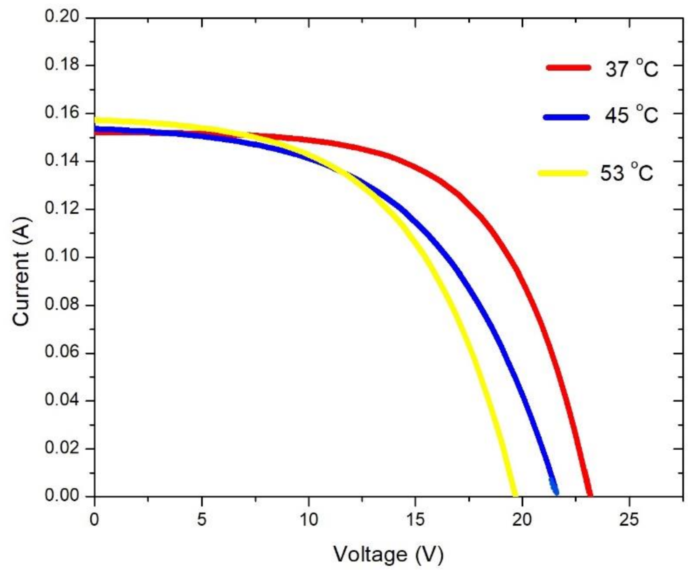

Figure 4. 7: The I-V curves of amorphous silicon PV module at different module temperatures under red colour filter.

The I-V curves were extracted at an interval of 8^{o}C increase in the module temperature for particular wavelength of solar light at a time. The module temperature varies with the change in incident solar radiation as well as ambient temperature (Amelia et al., 2016, Rani et al., 2018, Nasrin et al., 2018). Many previous studies done by (Li et al., 2021, Ibrahim and Anani, 2017, Amelia et al., 2016, Zaoui et al., 2015, Hishikawa et al., 2013, Macháček et al., 2007) on the impact of solar radiation and temperature on different PV technologies, have found that the changes in temperature affects all solar parameters including short circuit current and open circuit voltage. The open circuit voltage significantly falls and the short circuit current somewhat increases as the temperature rises. (Irwanto et al., 2010, Vidyanandan, 2017, Fuke et al., 2020, Van Dyk and Leitch, 2000). In this study, the results showed that there was an increment in the module's short circuit current and diminish in open circuit voltage with increased module temperature for all wavelengths of solar light used during the study as shown in Figures 4.3, 4.4, 4.5, 4.6 and 4.7.

The increment in reverse saturation current, which rises with intrinsic carrier concentration and increases exponentially with temperature, was the cause of the drop in the module's open circuit voltage as the temperature rose. (Singh et al., 2012, Elminir et al., 2001). The open circuit voltage diminishes as reverse saturation current increases. (Irwanto et al., 2010, Singh et al., 2012). The increment in short circuit current with increasing module temperature for all wavelengths of solar light used, was due to the fact that when temperature increase, the diffusion coefficient, minority life time, intrinsic carrier density and diffusion length increases (Irwanto et al., 2010).The generation of photocurrent by the PV module is a combination of the dominant generation current, electron diffusion current and hole diffusion current in the depletion layer (Irwanto et al., 2010). The generation current in the ideal depletion layer, does not depend on temperature. This means that the photocurrent increase as result of the increase of diffusion (Irwanto et al., 2010). The change in short circuit current depends more upon the design of solar cells and on the properties of the material of the semiconductors used (Honsberg and Bowden, 2019), the solar cell with a high sensitivity near the band gap will cause much alteration in short circuit current as the module temperature changes.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The conclusions and recommendations about the results of this research are presented in this chapter.

5.2 Conclusions

Performance of amorphous silicon photovoltaic module using solar light of different wavelengths was evaluated. Amorphous silicon PV module of power rating of 10 W manufactured by Shenzhan Topray Solar Co.Ltd was employed in this study. The solar light was filtered by using colour filters, so that particular wavelengths reach the photovoltaic material of the module at a time. Five different colour filters (blue, green, yellow, orange and red) were used during the experimental study. The experimental measurements were taken for two hours between 10: 30 am to 12:30 pm with an interval of 30 minutes for each colour filter used. The module responded differently to different colour filters and the outcomes of this research are as follows;

The module's short circuit current was changing significantly at various wavelengths of solar light, this is because different wavelengths have different photon energies and therefore different irradiance levels. The highest short circuit current of 0.76 A was generated when PV module was not covered with any colour filter. Among all the colour filters used, yellow light gave the highest short circuit current of 0.68 A and green light gave the least short circuit current of 0.31 A.

The open circuit voltage of the module was changing slightly at different wavelengths of solar light. This is because the change in irradiance levels has a smaller impact on the open circuit voltage. The highest open circuit voltage of 22.73 V was obtained when red colour filter was used, this was followed by green and orange colour filters which gave 22.71 V.

The power of the module varied at different wavelengths of solar light. The maximum power of 9.60 W was obtained when the module was not covered with any filter. With colour filters, the maximum power of 8.89 W was obtained when the module was covered with yellow colour filter. This is because the product of current and voltage produced by the module was comparatively higher for yellow colour filter than other filters used, this was followed by blue light which gave power output of 7.50 W.

The efficiency of the module was changing as the power changes at different wavelengths of solar light. The highest efficiency of 3.60 % was obtained when the module was not covered with any colour filter. With colour filters, the highest efficiency of 3.29 % was obtained when the module was covered with a yellow colour filter. This was followed by blue colour filter which gave an efficiency of 2.78 %. The lowest efficiency of 1.45 % of the module was obtained when red colour filter was used. This is attributed to low photon energies of the wavelengths corresponding to red solar light.

Additionally, the impact of module temperature on the short circuit current and open circuit voltage of the module at various solar light wavelengths was examined. Under all the wavelengths of solar light, the increment in module temperature has consequence on both the open circuit voltage and the short circuit current. The short circuit current was increasing slightly provided that the module temperature rises while the open circuit voltage was decreasing drastically. This is due to the increment in temperature increases saturation current more than the photocurrent, which in turn makes the open circuit voltage to decrease quickly.

5.2 Limitations of the study

The constraints of this research includes continuous change of weather conditions such as rains which extended the time for data collection, since for such conditions the irradiance was insufficient to operate the I-V tracer.

COVID-19 pandemic that caused the closure of the University for quite long led to the delay in completion of the program as scheduled.

5.3 Recommendations

The performance of amorphous silicon photovoltaic module using solar light of different wavelengths was evaluated with the help of colour filters. These colour filters allows only certain range of wavelengths of solar light corresponding to their own colour to reach the active photovoltaic material of the module. More research work needs to be done by filtering solar light into single wavelengths rather than the band of wavelengths in order to comprehend the effects of various solar light wavelengths on the functionality of an amorphous silicon photovoltaic module. In this study, violet and indigo colours of visible solar light spectrum were not considered because of the limited supply of the colour filters. Therefore, they are recommended to be considered for future work because they are part of solar light spectrum, to investigate their implications on an amorphous silicon photovoltaic module's performance.

This study has shown that yellow light generates the highest power in the module compared to the other visible light colours considered. Manufacturers may use the findings of this study to modify their technological designs, select efficient absorber materials and tune the band gap energies of solar cells of amorphous silicon photovoltaic module, so that the wavelengths of solar light which gives the optimal performance of the module can be efficiently captured.

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APPENDICES

Appendix 1: Calculation of the module's efficiency and surface area

(a) Calculation of the module's surface area.

The module's length (L) and width (W) were measured using a tape measure as follows; the length of the module was found to be 0.9 m and the width was found to be 0.3 m. The module's surface area was then calculated as shown below

Area of the PV module $A = L \times W = 0.9 \times 0.3 = 0.27\ m^2$

(b) Calculation of the module's efficiency.

The module's efficiency was calculated as follows;

Efficiency $\eta = \frac{Maximum\ Power}{Incident\ solar\ radiation \times area\ of\ the\ module} \times 100\%$

$$\eta = \frac{P_{max}}{1000\ Wm^{-2} \times 0.27\ m^2} \times 100\%$$

When the module was covered with yellow colour filter, the maximum power obtained was 8.89 W, therefore, the efficiency is;

$$\eta = \frac{P_{max}}{1000\ Wm^{-2} \times 0.27\ m^2} \times 100\% = \frac{8.89\ W}{1000\ Wm^{-2} \times 0.27\ m^2} \times 100\ \% = 3.29\ \%$$

When the module was covered with blue colour filter, the maximum power obtained was 7.50 W, the efficiency is;

$$\eta = \frac{P_{max}}{1000\ Wm^{-2} \times 0.27\ m^2} \times 100\% = \frac{7.50\ W}{1000\ Wm^{-2} \times 0.27\ m^2} \times 100\ \% = 2.78\ \%$$

When the module was covered with orange colour filter, the maximum power obtained was 6.87 W, the efficiency is;

$$ŋ = \frac{P_{max}}{1000\ Wm^{-2} \times 0.27\ m^2} \times 100\% = \frac{6.87\ W}{1000\ Wm^{-2} \times 0.27\ m^2} \times 100\ \% = 2.54\ \%$$

When the module was covered with green colour filter, the maximum power obtained was 4.60 W, the efficiency is;

$$ŋ = \frac{P_{max}}{1000\ Wm^{-2} \times 0.27\ m^2} \times 100\% = \frac{4.60\ W}{1000\ Wm^{-2} \times 0.27\ m^2} \times 100\ \% = 1.70\ \%$$

When the module was covered with red colour filter, the maximum power obtained was 3.91 W, the efficiency is;

$$ŋ = \frac{P_{max}}{1000\ Wm^{-2} \times 0.27\ m^2} \times 100\% = \frac{3.91\ W}{1000\ Wm^{-2} \times 0.27\ m^2} \times 100\ \% = 1.45\ \%$$

When the module was not covered with a filter, the maximum power obtained was 10.36 W

$$ŋ = \frac{P_{max}}{1000\ Wm^{-2} \times 0.27\ m^2} \times 100\% = \frac{9.60\ W}{1000\ Wm^{-2} \times 0.27\ m^2} \times 100\ \% = 3.60\ \%$$

The values of maximum power at different wavelengths of solar light were applied to estimate the efficiency of the module as indicated in Table 4.3.