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The Impact of Air Mass on the Performance of a Monocrystalline Silicon Solar Module in Kakamega

Ligavo Margdaline Musanga[1*], Mageto Maxwell[1], Wafula Henry Barasa[1] and Emmanuel Yeri Kombe[2]

[1]Department of Physics, School of Natural Sciences, Masinde Muliro University of Science and Technology, Kenya.
[2]Department of Energy Technology, School of Engineering and Technology, Kenyatta University, Kenya.

Authors' contributions

This work was carried out in collaboration among all authors. Author LMM designed the study, performed the statistical analysis, wrote the protocol. Author EYK wrote the first draft of the manuscript. Authors MM and WHB managed the analyses of the study.
All authors read and approved the final manuscript.

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ABSTRACT

This paper investigates the outdoor performance of a 20 W monocrystalline silicon solar module in relation to air mass (AM) in Kakamega. Direct measurement of air mass and module output parameters from experimental setup was done in Kakamega at a location 0.2827^0 N and 34.7519 E. Experimental results showed a decrease in I_{SC} and V_{OC} with increasing AM. The maximum output power produced by the module reduced with an increase in AM. Maximum power was therefore seen to be produced at noon in this region. V_{OC} increased from 19.47 to 20.04 then decreased to 19.49 V while I_{SC} increased from 0.36 to 1.19 then decreased to 0.48A. It was observed that both the FF and η of a monocrystalline solar module increase with increase in air mass. The module performed better during the afternoon than morning and evening hours with the peak performance observed close to AM 1.

**Corresponding author: E-mail: musanga1989@gmail.com;*

Keywords: Solar module; air mass; outdoor performance; renewable energy; peak performance.

ABBREVIATIONS

FF : Fill factor
NASA : National Aeronautic Space Administration
V_{OC} *: Open Circuit Voltage*
I_{SC} *: Short Circuit Current*
P_{MAX} *: Maximum Power*
V_{MP} *: Voltage at Maximum Power*
I_{MP} *: Current at Maximum Power*

1. INTRODUCTION

In modern world today, much of the energy is generated in power plants from fossil fuels which are naturally exhaustive, thus the need to switch to the use of renewable energy is increasing worldwide.

In Kenya, renewable energy sources include hydro, wind, solar, biomass and geothermal. Currently, Kenya heavily depends on hydro as the main source of electricity averaging as high as 70% [1]. Due to persistent droughts, electricity generation has been affected. This forces the country to ration the energy generated in most of its industrial zones, where continous power supply is vital. Therefore, there is need to generate clean and reliable energy from solar energy sources. Kenya sits astride the equator hence it receives abundant amount of solar radiation in a year.

The performance characterization of a photovoltaic module does not take into consideration the impact of ecological factors such as solar spectrum, the level of insulation, and other climatic conditions. Solar cell devices are natural spectral sensitive, therefore solar spectrum is among the environmental factors which strongly affect the performance of a solar cell module.

This paper sought to determine the effect of air mass on the performance of mono-crystalline silicon solar module whose characterization will provide sufficient information for PV system design in the Kakamega.

2. THEORY OF PHOTOVOLTAICS

The air mass is the path length which light takes through the atmosphere normalized to the shortest possible path length (that is, when the sun is directly overhead) [2]. It quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust.

$$\text{Air mass, A.M} = \frac{1}{\cos\theta} \tag{1}$$

The actual solar spectrum is commonly quantified using air mass factor which describes the shape of solar spectrum [3]. Air mass shows the effect of wavelength distribution on the flow of photons which varies depending on weather conditions such as water vapour and dust hence it affects transfer intensity of electron flow in the PV module [4]. AM at 1.01 corresponds to shortwalength radiation of high intensity resulting to high photon flow leading to high voltage registered as well as current. Increasing AM leads to increasing wavelength of radiation hence reduction of photon transfer intensity that causes voltage and current to reduce as indicated in this study. Climatic or seasonal variations shifts the air mass spectral profile [3,4] and impose variations in the spectrum & light intensity, reflection of unpolarized light, polarization and the temperature [5]. Since, the solar illumination serves as the input to the solar module operation, any variation in the solar illumination due to geographical location results in a profound output change [5].

The module conversion efficiency (η), fill factor (*FF*), maximum power (P_{max}), short circuit current (I_{sc}) and open circuit voltage (V_{oc}) are the key parameters used in characterising the perfomance of a solar module. These parameters are obtained from the I-V characteristic curve. I_{sc} is the current generated when the circuit load is zero [6]. It is mathematically expressed as:

$$I_{sc} = I_{sp} - I_0 \left[e^{\frac{q(R_S I_{SC})}{mkT}} - 1 \right] for\ V = 0 \tag{2}$$

Where *q* represents an electron charge, *m* denotes the diode quality factor [7].

The PV voltage measured when the device terminals are isolated is called the open circuit voltage (V_{oc}). It correlates to the voltage occurring when no current is passing through the solar cell [6,7]. It is mathematically expressed as:

$$V_{oc} = \frac{mkT}{q} \ln\left(\frac{I_{sc}}{I_0} + 1\right) \ \text{for} \ \ I = 0 \tag{3}$$

Where T is the temperature, I_o denotes the dark saturated current, k represents the Boltzmann constant and I_{sc} denotes the current generated [2].

FF determines the quality of the solar cell with the range 0.7 to 0.8 representing a good panel and 0.4 representing a bad panel [8].

$$FF = \frac{P_{max}}{V_{oc} * I_{sc}} = \frac{I_{max} * V_{max}}{V_{oc} * I_{sc}} \tag{4}$$

The ratio of electrical output power and solar input power is called the efficiency [6]. The solar module efficiency is mathematically expressed as

$$\eta = \frac{P_{out}}{P_{in}} \rightarrow \eta_{max} = \frac{P_{max}}{P_{in}} = \frac{V_{oc} * I_{sc} * FF}{I_t * A_c} \tag{5}$$

Where power input, P_{in} = Irradiance (W/m^2) * cross-sectional area of solar cell (m^2).

3. MATERIALS AND METHODS

3.1 Materials

The module parameters used in this study are illustrated in Table 1. In addition to the module, the following equipment and apparatus were used in this study: a straight metal post of length 2.8 m, a meter rule, two digital multimeters, and a 50 Ω variable resistor.

3.2 Methodology

Outdoor performance characterization was carried out at Kakamega located 0.2827^0 N and longitude 34.7519^0 E. Air mass was determined using the shadow method. An upright post was erected on a suitable flat surface in an open field at the site as illustrated in Fig. 2. The length of the post was measured using a meter rule. The length of the shadow cast by the post was measured using the metre rule from 9 a.m. to 3 p.m. at an interval of one hour. From the values obtained, the zenith angle, Θ was obtained from trigonometric ratios and the air mass calculated using equation 1.

To obtain short circuit current at given values of air mass the module was connected directly to the multimeter and the pointer adjusted to read the corresponding value of current. The same procedure was used to obtain open circuit voltage. For I-V characterization, a 50 Ω variable resistor was connected in series with the module and values of current and voltage obtained in steps of 10 Ω as illustrated in Fig. 1. This study was conducted over a period of six months and the average data used for analysis.

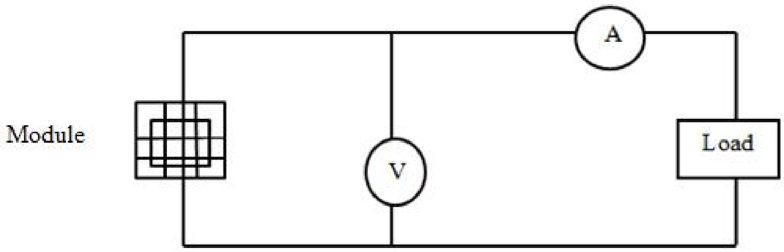

Fig. 1. Block diagram for I-V measurement

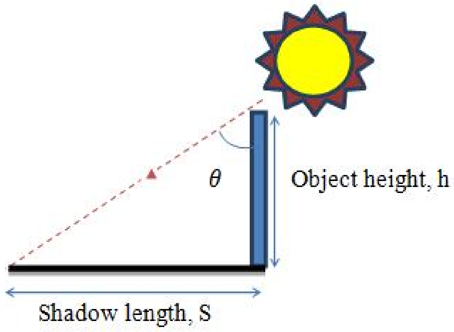

Fig. 2. Air mass measurement

Table 1. Module parameters

Module parameters						
V_{oc} [V]	I_{sc} [A]	V_{mp} [V]	I_{mp} [A]	P_{mp} [W]	Fill Factor	Efficiency
21.6	1.2	18	1.1	20	0.764	14.69%

4. RESULTS AND DISCUSSION

Fig. 3 reports the I-V characteristic of a mono-crystalline solar module obtained between AM 1.04 and AM 1.85. Fig. 3 reports a decrease in open circuit voltage and short circuit current as the AM is increased. The reduction in both open circuit voltage and short circuit current is attributed to the decrease in photo-generation at higher AM resulting from attenuation of the active component of the incident radiation which is vital for PV effect. The atmospheric attenuation is mainly due to scattering and absorption of incident radiation by aerosols and constituent gases such as carbon dioxide, water vapor, ozone and oxygen [3]. This causes the reduction in power of the incident radiation [9]. Therefore, the photon transfer intensity reduces at higher AM, leading to lower open circuit voltage and and short circuit current. This result agrees with those obtained by Rida KS et al. [4].

Fig. 4 reports a decrease of maximum output power produced with increase in AM. This reduction in maximum power produced is attributed to the increase in scattering by air pollutants like aerosols and clouds when AM increases leading to a reduction in the intensity of the incident radiation [10]. This result is in agreement with those obtained by Shnishil AH et al. [11].

From Table 2, on average, it can be deduced that FF of a monocrystalline solar module increase with an increase in air mass. This indicates that monocrystalline solar module responds favorably to short wavelength radiation. The fill factor depends on both the Isc and Voc, and as they both reduce with air mass increase, this result is acceptable. This result is in agreement with those obtained by [4,12].

Closely related to FF, Isc and Voc is module efficiency, η. The efficiency of a monocrystalline solar module increases by 30.78% as air mass increase from 1.04 to 1.32. This behavior is caused by the good response of monocrystalline solar module to short wavelength radiation as well as increase in FF. Studies by Otakwa [12] have also reported similar behavior.

From Fig. 5 it was observed that the module performs better during the afternoon than morning and evening hours. This is attributed to the presence of more atmospheric gaseous absorbers such as water vapor, oxygen and carbon dioxide during the morning and evening hours [13]. The presence of these gaseous absorbers increases the Rayleigh scattering and atmospheric turbidity, leading to the extinction of solar beam [14], which influence the values of air mass by varying the active component of the incident radiation reaching the surface of the earth [9].

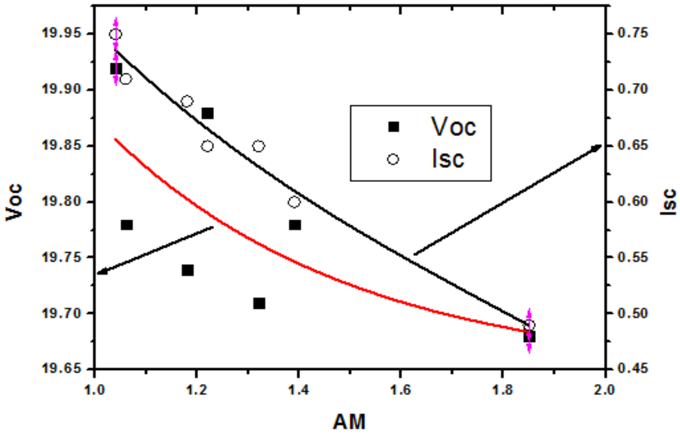

Fig. 3. Variation in I-V characteristics with air mass

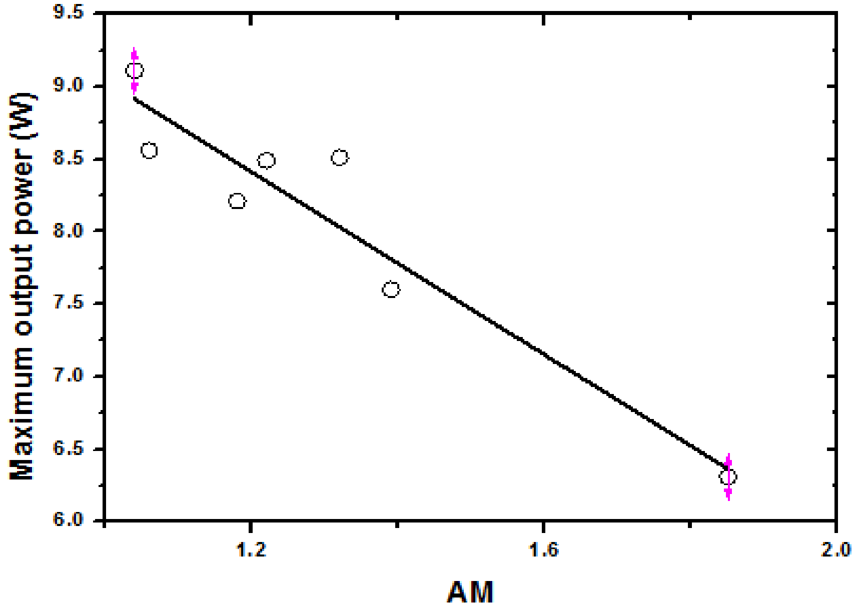

Fig. 4. Maximum output power variation with air mass

Table 2. Effect of air mass on the efficiency and FF of a monocrystalline module

AM	**1.04**	**1.06**	**1.18**	**1.22**	**1.32**	**1.39**	**1.85**
η	8.78	9.07	9.67	9.69	11.48	10.64	11.43
FF	0.61	0.61	0.60	0.65	0.66	0.64	0.65

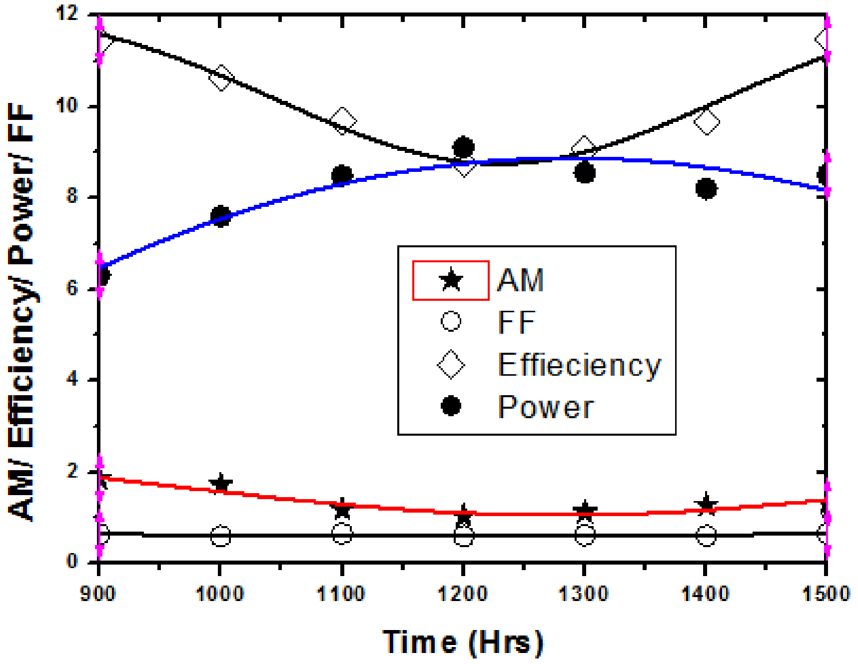

Fig. 5. Effect of AM on efficiency and power produced by the module

In the morning, the radiation from the sun strikes the earths surface at an oblique angle, the irradiance is of low intensity, hence the path lenghth is longer which is the reason for the larger value of A.M recorded. At around 12.30 p.m the sun rays are overhead, the irradiance is of highest intensity, the solar hour angle is close to zero and the path length for the radiation is short, hence the lowest value of AM recorded. Beyond noon, the solar hour angle increases hence the irradiance strikes the surface at an oblique angle with low intensity, therefore the higher path length recorded. The peak performance was observed at 12.30 PM where AM is the shortest [10].

5. CONCLUSION

The performance of a monocrystalline solar module was evaluated in terms of its output variables (V_{OC}, I_{SC}, FF, and η) as a function of A.M. The following is the summary of the key observations:

1. Experimental results showed a decrease in I_{SC} and V_{OC} with increasing AM. This reduction is caused by a decrease in photo-generation at higher AM resulting from attenuation of the active component of the incident radiation by aerosols and constituent gases such as carbon dioxide, water vapor, ozone and oxygen.
2. The maximum output power produced by the module decreased with an increase in AM due to the increase in scattering by air pollutants like aerosols and clouds. Maximum power was therefore seen to be produced at noon in this region.
3. It was observed that both the FF and η of a monocrystalline solar module increase with an increase in air mass. The efficiency of a monocrystalline solar module increases by 30.78% as air mass increase from 1.04 to 1.32. This indicates that monocrystalline solar module responds favorably to short wavelength radiation.
4. The module performs better during the afternoon than morning and evening hours with the peak performance observed close to AM 1.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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