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INVESTIGATION OF THE IMPACT OF BLACK SOOT DEPOSITION ON PHOTOVOLTAIC (PV) SOLAR PANEL OUTPUT EFFICIENCY IN AGBOR METROPOLIS, DELTA STATE, NIGERIA

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Abstract

The solar photovoltaic (PV) panel is one of the fundamental components that are used to harness the operation of solar power system. However, its performance is dependent greatly on certain environmental factors and location. This research was focused to investigate the effect of black soot on the output efficiency of solar photovoltaic (PV) panel. The basic studies and operational activity was carried out at a building located in Agbor, Delta State, Nigeria (longitude 6.201883 N and latitude 5.6037 E and 86.16m elevations above the sea level). The major materials used for this research include the following; two (2) monocrystalline solar panels (one served as a control 'clean' while the other as a device under test 'sooty' and a multimeter. The multimeter was used to measure parameters like: short-circuit current I_{SC} and open-circuit voltage V_{OC} while the output power and percentage (%) losses were computed using the measured values. This operation was carried out for a period of three (3) months and the mean values were obtained. From the obtained values, the maximum value of V_{OC} for the control module is 35.7V at12 midday while the corresponding value for the sooty module is 34.3V at the same time. Typically, the total daily output power for the control module was 7103.15W while the corresponding value for the sooty solar module was 4827.38W. This presents 32.04% loss in the power output due to black soot on the surface of the solar panel. Cumulatively, the total output power loss daily ranges from 32.04% to 63.90%.

Keywords:

Black Soot, Solar Panel, Short-circuit current, open circuit voltage, Output Power, Efficiency.

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1.0 Introduction

The photovoltaic solar panel is the major component of solar system technology used to harness solar energy. A solar module is made up of cells that systematically arranged and linked to form arrays.

The fundamental principle of this system operation is to convert energy fron sun radiation (solar) into electrical energy. Certain literature has it that photovoltaic solar panel has a lifespan of about twenty-five (25) years. However, the efficiency and lifespan of a solar panel can be affected by a variety of factors, including the module's quality, tilt-angle, fill factor, material deterioration, shading, soiling (soot), parasitic resistances, and other significant parameters, to name a few (Nsasak, W.A., Uhunmwangho, R., Omorogiuwa, E. and Alabo, A.B., 2021).

Another important factor that may determine the efficiency of the photovoltaic solar panel is the geographical location. For example, Warri in Delta State is a major crude oil producing location and has always experienced soot fallout. Soot is a dark, powdery substance composed primarily of amorphous carbon produced by the incomplete combustion of organic matter. This is due to the fact that artisanal (local) refining of crude oil (small-scale, uncontrolled burning of hydrocarbons to produce petrol, diesel, and kerosene) has been proven to have negative environmental effects due to the emission of carbon monoxide, methane, and other gases, which results in soot (Whyte, M., Tamuno-Wari, N.A.K., and Sam, 2020).

The presence of black soot has been observed in localities where environmental activities like bush burning, local crude oil production occurs. It thickly covers surfaces of objects like roofing sheets, tables, water, cars, books, tree leaves, chair, floors, window nets and mainly any object exposed to the outdoor environment. The presence of soot pollution is more prevalent in the oil rich and highly industrialized cities. Soot is the common term for a type of particle pollution known as PM 2.5, which is particulate matter 2.5 micrometers in diameter or smaller (Donev, J.M.K.C., Hanania, J., Sheardown, A. and Stenhouse, K. 2021).

Solar (PV) panel as one of the major source of renewable, clean energy is not an exception for soot accumulation when installed outdoor for power generation (especially on roof top). PV solar cell has the ability to directly convert the solar radiation that shines on its surface to electric current. The solar radiation impinges the solar cells and the electrons are knocked out of the cell, thus creating electron – hole mobility that produces the electricity. The direct current (DC) generated from solar cells can also be converted to alternating current (AC) needed in homes to power appliances.

Types of Solar PV Panels

There are four main types of solar panels that are used for residential homes in Nigeria. These include the following monocrystalline, polycrystalline, thin-film and solar shingles. Table 1 below outline the various characters associated with each of these types based on the chosen parameters for their distinctions.

Table 1: Comparative features of different types of Solar Panels

Types	Best For	Average Efficiency	Pros	Cons
Monocrystalline	Efficiency	15 – 20%	Most efficient Modern appearance Good for smaller roofs	Expensive
Polycrystalline	Cost Effectiveness	13 – 16%	Budget-friendly Long lifespan	Lower efficiency than monocrystalline. Require more roof space
Thin-film	Portability	7% - 18%	Flexible and portable Can reach efficiencies similar to polycrystalline	Less durable Shorter lifespan Lower efficiency
Solar shingle	Aesthetics	12% - 14%	Low profile. Impact curb appeal. Efficiency similar to polycrystalline	Expensive

SOURCE: Bopray, A., Downer, R. and McNutt,E. (2024)

2.0 Aim of this Research

This study is necessitated in order to examine the impact of accumulation of black soot on the surface of the installed solar panels and more importantly how it affects its output efficiency. Other factors such as dirt, droppings from birds, shadow, tilt angle, ambient temperature, relative humidity may have been considered by other researcher but they are not within the scope of this study. Figure 1 below shows a photo of typical human feet that was stained by black soot.

Figure 1: Typical Human Palm stained by Black Soot.
Source: Amusan, J.A. (2021)

3.0 Review of Previous Literature

According to El-Shobokshy, M.S. and Hussein F.M. (1993), it was shown that the reduction in PV module conversion efficiency were 10%, 16% and 20% respectively for 12.5 g/m2, 25 g/m2 and 37.5 g/m2 dust deposition on its surface. An experiment was conducted to investigate the impact of wind speed and dust accumulation on the PV cell performance. The results showed that wind speed affects the PV cell performance largely since the output reduction is greater in high winds than in low winds. At the same time, the wind affects the sediment structure of the dust coating on the cell, resulting in a higher transmittance (of light) for coatings created during high winds. The experiment investigated the effect of dust deposition on photovoltaic solar cells (GoossensD. and Van Kerschaever, E., 1999).

In another study, the effect of soot on the transparent cover of solar collectors was discussed. The reduction in glass normal transmittance depends strongly on the dust deposition density in conjunction with plate tilt angle, as well as on the orientation of the surface with respect to the dominant wind direction (Elminir, H.K., 2006).

An analysis on the dust effect on the performance of PV systems in Athens was conducted. The studies were done using three different pollutants, red soil, limestone and carbonaceous fly-ash particles. It was found that there was a 6% reduction on PV performance with carbonaceous fly-ash, 10% with limestone and 19% with red soil (Kaldellis, J.K. and Kapsali, P.M., 2011). In a research report by Jiang, H., Lu, L. and Sun, K. (2011) the impact of airborne dust deposition on the performance of PV module inside the laboratory under the controlled conditions in a test chamber was investigated. Dust was uniformly distributed on the panel surface with the help of a fan. It was concluded that efficiency of PV module reduced to 26 % as mass of dust increased to 22 g/m^2.

In another published research article, a study was carried out on three (3) types of dust pollutants (red soil, ash and sand) on the performance of three (3) different PV panels technologies (mono-c, multi-c and a-Si) was investigated. The authors claimed that ash have the highest effect in comparison with other pollutants. Also, it is found that a-Si is performing better than mono-c and multi-c in dusty environment (Kazem, H.A. 2013).

An experiment to determine the effect of dust physical properties on photovoltaic module in northern Oman was conducted. 64% of the dust particles size ranged from 2 to 63 μm in diameter. There is no significant loss of energy productivity due to the traceability of a little surface of dust (less than 1 g/m^2) on the photovoltaic unit. The daily loss in PV efficiency did not exceed 0.05%. However, after 3 month exposure to outdoor conditions, the efficiency reduced by 30-35% (Kazem, A.A., Chaichan, M.T. and Kazem, H.A. 2014).

Sulaiman, S.A. (2014) revealed that external resistance could reduce PV performance by up to 85%. This study also concluded that water droplet from rain would not affect significantly the performance of PV modules. Fundamental studies on dust fouling effects on PV module glass cover was carried out by Said S.A. and Walwil, H. M. (2014), it was found that the spectral transmittance reduction was around 35% and the overall transmittance was around 20%. It was also observed that the dust particles accumulated were generally spherical in shape.

An experiment using two panels of 10W capacity, mounted on a stand was conducted. The two PV systems are of polycrystalline type. One has carbon particles (grinded charcoal) as black soot debris on the panel while the other has none. They inclined both panel at an optimal angle of 15o facing the northern hemisphere. From their experiment, they came up with the conclusion that "the highest voltage is produced when the panel is not covered by layer of black soot". They observed that the voltage and power for the panel with black soot is low compared to the panel without soot (Emmanuel, C.O. and Tamuno-omie, J.A., 2018).

According to a publication by Amusan, J.A. and Otokunefor, E.B. (2019), the effect of shadow on output performance of solar module in a series-parallel solar cell array was studied andmmeasurements of the degradation of the power curve with time, current-voltage characteristics as function of total and partial shade were made on 250W monocrystalline silicon solar modules. The results show that the power loss for partially shaded solar modules ranges between 12%-40% when compared with the fully illuminated solar module. So, the power loss for partially shaded solar module can be as high as approximately 40%.

The effects of solid dirt accumulation on the solar panel's surface was investigated and quantified. Typically, a total daily power output for control solar module was 1758.487W while the corresponding value for dirty (mixture of algae, sand, dust and moist air) solar module was found to be 1286.813W at the instance of time and same insolation. The study shows that the solid dirt affects the output power of the solar module and consequently reduces the efficiency of the solar module (Amusan, J.A. and Igwe, C.E., 2020).

This paper thus reports the output performance of two (2) identical pairs of solar photovoltaic (PV) panels in a specific geographical location with black soot deposited on one of the pairs and the other is left clean. The direct impact of black soot deposition on the solar panel performance can be gauged by a comparison of the current-voltage (I-V) characteristics of the panels with and without black soot settlement on their surfaces.

4.0 Materials and Methodology

The following items were used to carry out this research.

1. Two solar panels of 300W capacity set up on the ground as illustrated in Figure 2 and Figure 3. The two solar panels are of monocrystalline type. One of the panels served as clean (without soot on the surface) and the other as soot (with soot spread on the surface).
2. A digital multimeter (Figure 2) which was used to measure the short circuit current, I_{SC} and open circuit voltage V_{OC}.
3. Carbon particles extracted from car and generator exhaust.

4. A clock

Figure 2: Employed Digital Multimeter

Table 1: Specifications of the employed solar panel(s)

MODEL TYPE	**HU250**
Peak Power	250W
Short Circuit Current (Isc)	8.60A
Open Circuit Voltage (Voc)	38.0Volts
System Voltage	1000Volts
Insulation	≥100MW
Peak Power Tolerance	±20%

The Table 2 shows the specifications of the employed digital multimeter for the experiment.

Table 2: Specifications of the employed digital multimeter

Model Number	**DT9205A**
DC Voltage	200Mv – 1000V
AC Voltage	200Mv – 700V
DC Current	2mA – 20A
AC Current	2mA – 20A
Net Weight	280g

This research field studies was conducted by using two 300W solar PV panels inclined at an angle of 145^{O}to the ground mount. During this operation, the set of equipment used to obtain some of the required data include two (2) monocrystallinesolar panels and a digital multimeter used to measure electrical parameters like current and voltage. One of the solar panels had black soot deposited on its surface (soot panel) while the other panel was without soot (clean panel).

Also, the output power Pdc for the clean and soot panel were calculated. Parameters like short circuit current Isc and open circuit voltage Voc needed for the evaluation of the systemperformance were measured at an interval of one hour between 8:00am and 6:00pm daily. This experimental study was carried out for seven (7) consecutive days at a location close to College of Education Agbor, Delta State, Nigeria. The latitude, longitude and elevation (above sea level) of the location are: 6.264092N, 6.201883E and 155.82m respectively (www.latlong.net and www.aititude-maps.com).

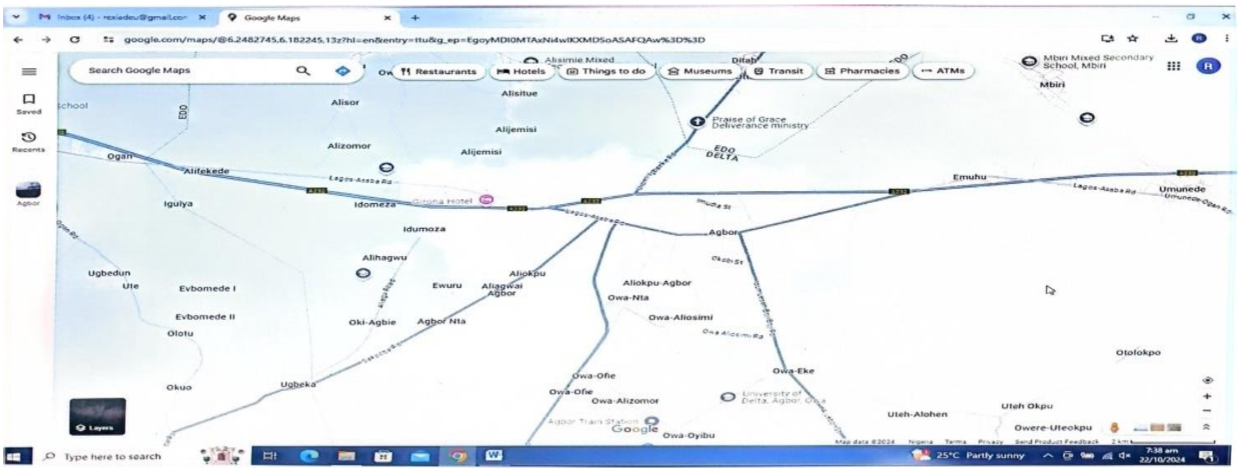


Figure 3: Google Map of Agbor, Nigeria

Source: www.latlong.net

The governing equations for calculating the average power (Pdc) for the clean and soot panels, is highlighted below. Percentage loss in output voltage and percentage loss in output power can be obtained via these equations.

$$\text{Average Power } P_{dc} = I_{sc} \times V_{oc} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 1$$

Where

: I_{sc} = short circuit current of the solar panel

V_{oc} = Open circuit voltage of the solar panel

Percentage loss in output voltage is given as:

$$V_{out} = (V_w - V_b)/V_w \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2$$

Where:

V_w= Voltage without black soot

V_b = Voltage with black soot

Percentage loss in output power is given as:

$$P_{out} = (P_w - P_b)/P_w \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 3$$

Where

Pw = Power output without black soot

Pb = Power output with black soot

From the measured values, graphs are plotted for Isc against time (for clean and soot), Voc (for clean and soot) against time and Pdc (for clean and soot) against time. Then, the percentage loss in output power are calculated (for clean and soot) to determine the efficiency of the solar panel with soot deposited on its surface (sooty) and compare its result with the panel without soot (clean).

5.0 Results and Discussions

The typical measured values obtained during the period of the experiment are shown in Table 3.

Table 3: Average Measured Values

Time (Hours)	**I_{sc} (short circuit current) for Clean (Amperes)**	**V_{oc} (open circuit voltage) for Clean (volts)**	**Average Power P_{dc} for Clean (watts)**	**I_{sc} (short circuit current) for Soot (Amperes)**	**V_{oc} (open circuit voltage) for Soot (volts)**	**Average Power P_{dc} for Soot (watts)**
8:00AM	**5.82**	**32.4**	**188.57**	**3.48**	**30.4**	**105.79**
9:00AM	**6.88**	**33.6**	**231.17**	**3.64**	**31.0**	**112.84**
10:00AM	**7.46**	**34.4**	**256.62**	**3.95**	**32.2**	**127.19**
11:00AM	**8.45**	**35.8**	**302.51**	**4.22**	**33.0**	**139.26**
12NOON	**7.44**	**35.2**	**261.89**	**4.14**	**32.2**	**133.31**
1:00PM	**6.88**	**34.8**	**239.42**	**4.08**	**31.5**	**128.52**
2:00PM	**6.02**	**34.2**	**205.88**	**3.65**	**31.2**	**113.88**
3:00PM	**4.94**	**33.7**	**166.48**	**3.40**	**31.0**	**105.4**
4:00PM	**3.66**	**33.5**	**122.61**	**2.88**	**30.6**	**88.13**
5:00PM	**2.48**	**32.0**	**79.36**	**1.20**	**30.4**	**36.48**
6:00PM	**1.85**	**31.5**	**58.28**	**0.68**	**30.1**	**20.47**

Figures 4 shows the graph of I_{sc} verses Time for clean and sooty panel for the average measured values of short-circuit current I_{SC}. The maximum values of I_{SC} for the clean and sooty panels are 8.45A and 4.22A at 11amrespectively.

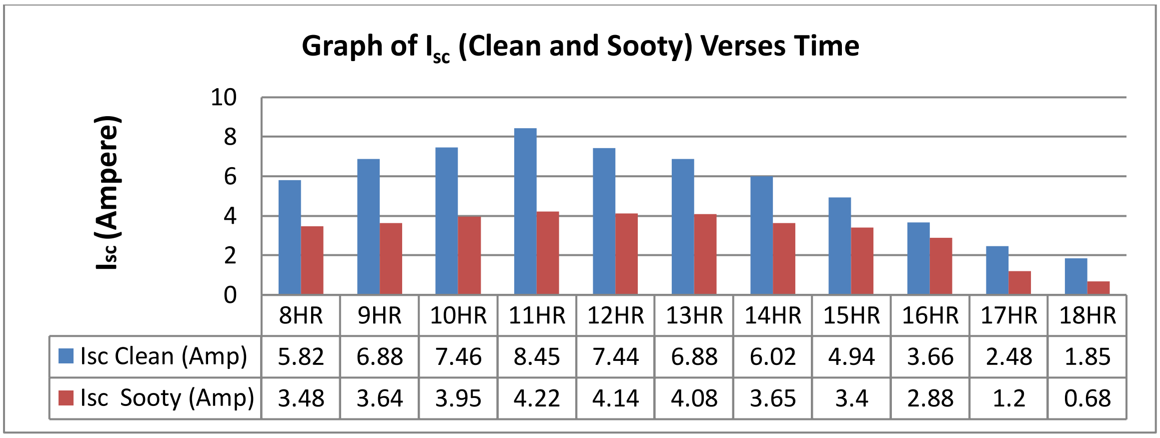


Figure 4: Graph of I_{sc} Verses Time for Clean and Sooty Panel Day 1

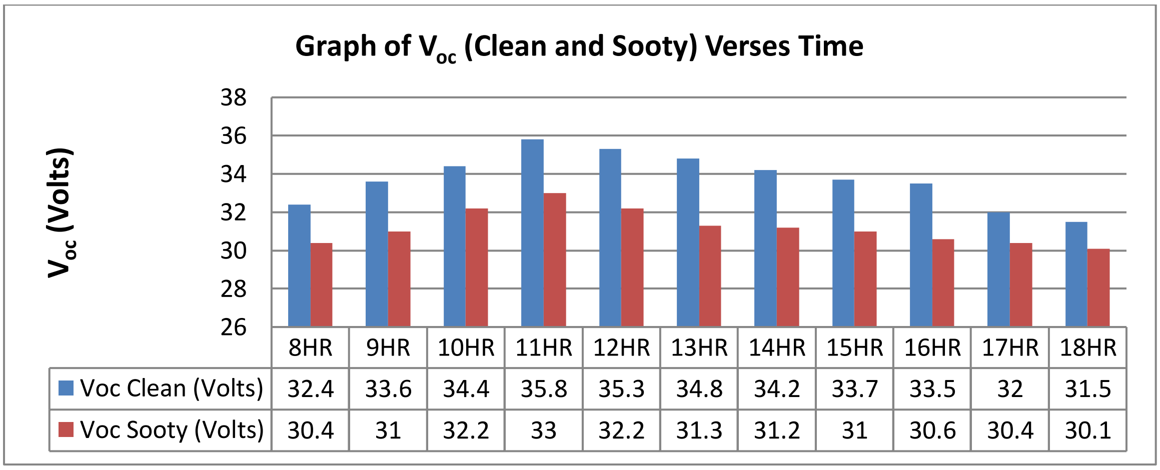


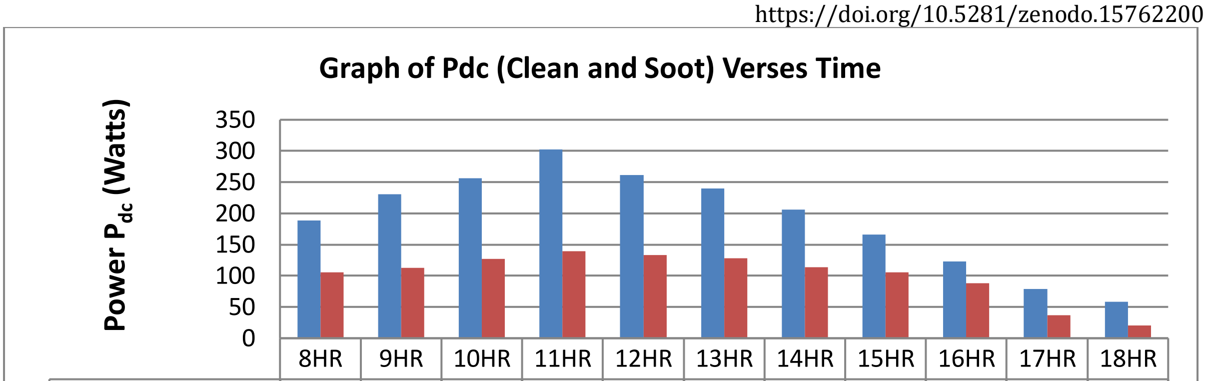
Figure 5: Graph of V_{oc} Verses Time for Clean and Sooty panel Day 1

Figure 5, shows the graph of V_{oc} verses Time for clean and sooty panel for the average measured values of open-circuit voltage V_{oc}. The maximum values of V_{oc} for the clean and sooty panels are 35.8V and 33.0V both at 11:00am respectively. Similarly, the reduction in the value of Voc for the sooty panel was due to the presence of black soot on the solar panel. The trendline shows direct proportionality between short circuit current, I_{SC} and open circuit voltage, V_{OC}.

Hence, the percentage (%) loss in output voltage at 11am for both control and sooty panel was calculated as:

Percentage Loss in output voltage =
(Max V_{oc} for control –Max V_{oc} for soot)/ Max V_{oc} for control x 100%
Percentage Loss in output voltage = (35.8 – 33.0)/35.8 x 100%
= 7.82%

The 7.82% loss in output voltage is due to the presence of black soot on the solar PV panel which reduces amount of solar irradiation incident on the panel's surface.



	8HR	9HR	10HR	11HR	12HR	13HR	14HR	15HR	16HR	17HR	18HR
Pdc Clean (Watts)	188.57	231.17	256.62	302.51	261.89	239.42	205.88	166.48	122.61	79.36	58.28
Pdc Sooty (Watts)	105.79	112.84	127.19	139.26	133.31	128.52	113.88	105.4	88.13	36.48	20.47

Figure 6: Average Power P_{dc} (watts) for control and sooty panels against Time of day (Hour)

Figure 6 shows the plot of average power (watts) for both clean and sooty panel against time of day. From figure 6, it can be seen that the maximum output power produced by clean panel is 302.51watts at 11am whereas that of the sooty panel was 139.26watts at same time.

Hence, the percentage (%) power loss can be calculated as:

$$\% \text{ Power Loss} = (302.51-139.26)/302.51 \times 100\%$$
$$= 53.97\%$$

The 53.97% loss in the output power can be traced to the effect of the black soot that accumulated on the solar panel.

Also, the maximum power produced by the clean panel as at 12noon was 261.89W and the corresponding maximum power for the sooty panel was 133.31W at the same time..

Thus,

$$\% \text{ Power Loss} = (261.89-133.31)/261.89 \times 100\%$$
$$= 49.01\%$$

From the analysis, it is clear that solar panel work optimally when they are completely clean. Table 3 summarizes the total average power output for the control panel and the sooty panel for the seven (7) days this measurement/reading was taken.

One key observation to note was that an increase or decrease in volume of the soot particles accumulated on the surface of the solar module determines the level of glass transmittance and thus the amount of solar irradiation reaching the solar cells which in turn affects the output current and output voltage generated by the solar module. The higher the quantity of soot particles across the panel's surface, the greater the reduction in solar irradiation reaching the solar cells which in turn affects the output power. These losses in output power are commonly referred to as optical losses because they chiefly influence the power generated from the solar module by reducing the short-circuit current. Optical losses consist of light energy which could have generated an electron-hole pair, but does not, because the light is reflected from the front surface by particles present on the surface of the solar module such as black soot. Thus, the photons can't get through the soot particles to the solar cells and most of the current is lost due to the reflection of the photons by the particles.

4.0 Conclusion

The output performance and efficiency of solar modules were studied. The materials used were; two monocrystalline solar panels, and two multimeters. The Output performance of modules with the presence of black soot on one module and the absence of soot on the other was analyzed and evaluated at a time interval of 15 minutes under varying weather conditions. From the I-V characteristics of both the control and sooty modules, the trendline shows direct proportionality between short circuit current, Isc and open circuit voltage, Voc. For instance, the maximum voltage measured from the control module for day 1 is 35.7V and the maximum voltage measured from the sooty module on same day is 34.3V. On day 7, the maximum voltage measured from the control module is 40.0V and the corresponding voltage for the sooty module is 38.6V. Thus, the percentage (%) output voltage loss for day 1 is 3.92% while the percentage (%) output voltage loss for day 7 is 3.50%. Also, it was observed that the accumulated soot particles largely affect the power output of the solar module, thus reducing its overall performance. For instance, the maximum power generated by control module for day 1 was 282.05W at 10:00am while the corresponding value for the sooty module was 115.94W at the same time during day 1 of the experiment. On day 7, the maximum power generated by control module was 353.94W at 1.45 pm while the corresponding value for the sooty module was 227.73W at the same time. Thus, the reduction in output power for the solar module with black soot typically ranges from 19.49% to 58.89%. Cumulatively, the total output power loss daily ranges from 32.04% to 63.90%.

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