Research Article

Effect of Industrial Dust Deposition on Photovoltaic Module Performance: Experimental Measurements in the Tropical Region

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Received 16 September 2019; Revised 21 November 2019; Accepted 4 December 2019; Published 20 December 2019

Guest Editor: Jorge Esteban Rodas Benítez

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Dust particle accumulation affects outdoor photovoltaic module transmittance of solar cell glazing and thus leads to significant degradation of conversion efficiency owing to lower irradiance reaching the surface. In this study, the sensitivity of the polycrystalline silicon photovoltaic module towards industrial dust deposition was experimentally investigated under the tropical climatic condition of Arusha, Tanzania. Dust involved in the study came from fertilizer, gypsum, aggregate crusher, and coal mine industries. The experimental measurements were outdoor conducted under 720 W/m^2 , 800 W/m^2 , and 900 W/m^2 solar irradiances. Results indicated that dust accumulation on the polycrystalline silicon photovoltaic module negatively affected output power as well as short-circuit current, however having no significant impact on open-circuit voltage. Maximum module efficiency loss was observed to be 64%, 42%, 30%, and 29% for coal, aggregate, gypsum, and organic fertilizer dust, respectively; hence, coal dust was the most effecting dust among the four. It was also demonstrated that PV module performance deteriorated with temperature rise owing to heat dissipation caused by dust accumulation.

1. Introduction

Global climate change, energy security, and potential exhaustion of fossil fuel reserves have attracted renewable energy technology development [1, 2]. Approximately 80% of energy consumption in the world is from fossil fuels which significantly contributed to climate change [3]. Application of renewable energy technology is valuable due to less impact on environmental degradation as well as the unlimited resource availability [4]. Away from being sustainable, solar energy symbolizes the most favorable renewable energy resources [5]. Solar energy harvesting through the use of photovoltaic (PV) systems for the production of electricity is well thought out as one of the potential markets in the field of renewable energy [6, 7]. Electricity production through the conversion of solar radiation into electricity materializes as a result of photovoltaic effect [8–10]. Energy conversion through the use of PV technologies does not cause serious environmental challenges as compared to conventional power generation sources, such as fossil fuels [11]. The pres-

ent conversion efficiency of PV systems is approximated at different efficiencies ranging between 7 and 40% [12, 13].

PV system operations encompass features such as module technology, battery type, and converter topology. Despite these features, the PV system is exposed to environmental agents such as aging, radiation, shading, temperature variations, wind, and dust accumulation [14–16]. Climate change contributes to sunlight availability variation causing rises in air temperature, which may always affect performance efficiency of the PV module. Solar tracking technology has emerged to assist PV systems in capturing maximum solar irradiance thus an increase of power output [17]. Dust is among the factors that affect the performance efficiency of PV module worldwide output [18–20]. The smallest particle size of less than $500 \mu\text{m}$ is termed as dust [21, 22]. The morphological structure, composition, and deposition of dust always depend on location characteristics [23]. Reduction in PV module performance highly depends on particle size and surface density of dust deposited over the modules [24]. Deposition of dust on a panel influences the solar cell

FIGURE 1: Dust samples used for the experimental study: (a) aggregate crusher dust; (b) coal dust; (c) fertilizer industry dust; (d) gypsum industry dust.

to heat up whereby affected cells will act as a resistance to the generated current; this tendency may lead to substantial degradation of conversion efficiency and even to formation of a hot spot that can ultimately damage the PV module [25, 26]. Due to minimal interparticle distance between fine particles, a small amount of solar radiation can pass through; therefore, it reduces more performance efficiency of a module compared with the larger particles [27, 28].

There are existing studies on the effect of dust on solar PV performance, but much of the information available is only valid for a specific location [29, 30]. Generally, there is a lack of relevant information on the effects of soil dust deposition for a specific location in Tanzania that can be effectively utilized in the design and sizing of PV modules. Deposition of dust on the PV panel blocks solar radiation from reaching cells. Density, composition, and particle size distribution of accumulated soil dust have been shown to have a significant impact on power generated by hindering solar radiation from reaching the cells through the glass cover of the panel [23]. Unawareness of the soil dust effect might bring to improper maintenance of solar PV systems and loss of some energy.

TABLE 1: PV module technical characteristics.

Electrical specification	Value
Maximum power	100 W
Current at maximum power (I_{mp})	5.36 A
Voltage at maximum power (V_{mp})	18.65 V
Short-circuit current (I_{sc})	5.71 A
Open-circuit voltage (V_{oc})	22.25 V
Nominal operating cell temperature (T_{noct})	$45 \pm 2^\circ\text{C}$
Module dimension	1020 mm*675 mm*25 mm

This study is aimed at experimentally investigating the performance degradation of PV module output power caused by a different type of industrial dust deposition. In achieving its objectives, the study estimated the impact of dust from manufacturing and mining industries. The study provides information, which may help users in better maintenance of the system and gain more power output.

FIGURE 2: Equipment and accessories: (a–c) data loggers with temperature and humidity sensors; (d) solar meter; (e) rheostat; (f, g) digital multimeters; (h, i) solar panels.

FIGURE 3: PV module experimental setup.

FIGURE 4: PV module circuit diagram for I - V curve measurements.

2. Materials and Methods

2.1. Materials Used in This Study. Dust samples were collected from manufacturing and mining industries located in different parts of Tanzania. The four dust samples (Figure 1) were selected from Organic Fertilizer Industry (Minjingu), Saint Gobain Lodhia Gypsum Industry, Mining Aggregate Crusher located in Arusha City, and Ngaka Coal Mining located in Ruvuma—southern part of Tanzania.

2.2. Dust Sample Preparation. Particle size analysis for the collected samples was conducted at NM-AIST Laboratories. The collected samples were sieved into different particle size ranges $90\ \mu\text{m}$ – $180\ \mu\text{m}$, $45\ \mu\text{m}$ – $90\ \mu\text{m}$, and $20\ \mu\text{m}$ – $45\ \mu\text{m}$ under sieve analysis technique. The system comprised of stowage of the sieves with dissimilar sieve holes, and the smallest sieve was placed at the bottommost of the stack. The technique separates particles from a bigger size to the smallest size according to the sieve arrangement. Each sample was weighted by digital weight before putting it on the upper sieve set; then, the sieve set was placed on the Retsch sieve shaker, vibration frequency was configured, and the Retsch sieve shaker was allowed to start and stop after 15 minutes. After the Retsch sieve shaking completed, each sieve was taken to the digital weight balance and weighted.

2.3. Experimental Setup. The experiment was conducted in an outdoor environment at the Innovative Technology and Energy Centre within the Nelson Mandela African Institution of Science and Technology premises, Tanzania (latitude -3.23°S , longitude 36.47°E). Two identical photovoltaic

FIGURE 5: Weather parameter data taken at the site.

TABLE 2: Temperature effect on a clean module performance.

$G = 720 \text{ W/m}^2$			$G = 800 \text{ W/m}^2$			$G = 900 \text{ W/m}^2$		
T_p (°C)	$P_{\max}$ (W)	η (%)	T_p (°C)	$P_{\max}$ (W)	η (%)	T_p (°C)	$P_{\max}$ (W)	η (%)
30.0	83.8	16.9	37.3	86.0	15.6	30.6	96.7	15.6
31.0	67.0	13.5	42.1	81.0	14.7	32.6	86.2	13.9
31.5	65.0	13.1	48.3	79.4	14.4	39.9	84.3	13.6
42.1	63.0	12.7	48.5	75.0	13.6	40.3	79.4	12.8
46.4	62.5	12.6	48.6	65.0	11.8	41.6	78.8	12.7

modules of the model SLP100-12 manufactured by Kishen Enterprises Ltd. (Jiangsu, China) with rated maximum power of 100 W and 45 cell (each of 105 mm width and 155 mm length) polycrystalline silicon were tilted at 15° angle facing north; electrical characteristics of the panels are shown in Table 1. The experiment is aimed at assessing the effects of dust deposition over the PV module; four different types of dust collected from different sites were tested to assess impact on the PV module performance. One module was covered with dust while another module was left clean for output power comparison purposes. The cleaning method of the dirty module may be with a fine brush [31], which was also adopted for this study in cleaning the polluted panel.

Accessories and equipment used for experimental measurements are presented in Figure 2 where H and I are solar PV modules. The USB SSN-11e data loggers represented by A and B were attached at the back of the module surface for monitoring module operating temperature. The USB SSN-22e data logger C was attached to the panel

FIGURE 6: Ambient air and PV module operating temperature.

FIGURE 7: Impact of solar irradiance on operating voltage, current, and power output for clean and dirty modules (45-90 μm aggregate dust).

frame while its sensor was left hanging for recording air temperature and relative humidity. The solar meter TES 132 USB indicated by letter D, with its sensor attached to the module surface (with the same inclination angle as the PV module), was employed for monitoring solar irradiation intensity reaching the module. Furthermore, rheostat E (load variable resistor) and digital multimeters G and F were used for current and voltage monitoring. Each module was connected to digital voltmeter and ammeter; current and voltage were measured by supplying power to a rheostat, as depicted in Figure 3 and circuit diagram in Figure 4; current-voltage (I - V) and power-voltage (P - V) correlations were examined.

The measurements were performed at clear sky condition during the day; performance degradation assessment for the PV module was done at three different solar irradiances 720 W/m^2 , 800 W/m^2 , and 900 W/m^2 . Weight of 10 g for each dust sample was weighted by the digital weight balance. Dust was uniformly distributed over the module with a baby

powder bottle covered with sieve mesh in front of it (Figure 3).

2.4. Data Processing and Measurements. The experiment was done under three different selected solar irradiances for all four dust samples under particle size range. Instantaneous current and voltage were recorded at real-time condition. The efficiency of the module depends on several factors including design and maintenance of the panel, temperature, and solar irradiance (G), and it may be calculated through the following equations:

$$P_{\max} = I_{\text{mp}} \times V_{\text{mp}}, \quad (1)$$

$$\eta = \frac{P_{\max}}{G \times A}, \quad (2)$$

where A is the surface area of the panel. From the individual module efficiency, performance efficiency loss η_{loss} of the PV

FIGURE 8: I - V and P - V curves are represented in thin and bolded lines, respectively, while black and red colours represent clean and dirty modules, respectively (with 20-45 μm coal dust).

module can be calculated through Equation (3), by using the relationship [32]:

$$\eta_{\text{loss}} = \frac{\eta_{\text{clean}} - \eta_{\text{dirty}}}{\eta_{\text{clean}}} \times 100. \quad (3)$$

3. Results and Discussion

This section presents data acquired from experimental measurement and analysis. The first part is about a variation of weather condition during experimental measurements in the study area. PV module performance, power, and current output drop due to dust deposition; PV module efficiency is shown in the second section. In the last part, analysis of results is given regarding the impact of temperature and different types and particle sizes of dust on the PV module performance.

3.1. Variation of Weather Condition at the Site. As described in Figure 5, during data collection in the study area, there was fluctuation of weather condition, i.e., solar radiation, relative humidity, and ambient temperature. It was observed that solar radiation was high from 12:00 AM to 03:00 PM; also, ambient temperature was increasing from morning towards 03:00 PM. Moreover, relative humidity was high during the morning time and was decreasing towards noontime; this indicated that as sunlight intensity increased, relative humidity decreased. Short-term varia-

tions of weather parameters are normally caused by turbulences within the atmosphere.

3.2. PV Power and Efficiency Loss due to Temperature for a Clean Panel. In this study, power and efficiency losses due to temperature on the PV module were investigated; the assessment was done for the clean module. Change in power P_{max} and efficiency yield due to temperature effect at different solar irradiances (720 W/m^2 , 800 W/m^2 , and 900 W/m^2) were assessed (Table 2). Experimental results proved that temperature rise reduced P_{max} and module efficiency as well. Minimum and maximum module temperatures were observed to be 30.0°C and 48.6°C, respectively, whereby P_{max} rose to 97% of rated power and dropped to the minimum level of 63% accordingly. At $G = 900 \text{ W}/\text{m}^2$ and $T = 30.6^\circ\text{C}$, the $P_{\text{max}} = 96.7 \text{ W}$ was very close to the rated value, and efficiency was also high, $\eta = 15.6\%$. In average, the power decreased by 1.3-1.8 W and efficiency lowered by $\sim 0.3\%$, per each degree in temperature rise.

3.3. Impact of Dust on PV Module Temperature. Dust accumulation on the PV module has also impact on the cell operating temperatures. The observation was made during the experimental test when aggregate dust with particle size 20-45 μm was deposited over the module, whereby temperature difference between the clean and dirty modules was observed to be varying between 1°C and 9°C (Figure 6). The abrupt rise of cell operating temperature for both modules (at 11:10 AM) occurred which may be caused by the sudden

TABLE 3: $P_{\max}$, I_{sc} , and V_{oc} for clean and dirty modules under fine particles.

G (W/m ²)	Clean module					Dirty module			P_{max} (dirty)/ P_{max} (clean) (%)	I_{sc} (dirty)/ I_{sc} (clean) (%)
	P_{max} (W)	V_{oc} (V)	I_{sc} (A)	T_p (°C)	P_{max} (W)	V_{oc} (V)	I_{sc} (A)	T_p (°C)		
Fertilizer industry dust										
720	65.2	21.1	2.6	31.5	48.3	20.8	1.9	33.1	74.1	74.5
800	41.1	20.6	4.1	32.6	29.1	20.3	3.2	37.0	70.8	76.5
900	84.2	20.5	5.7	43.0	65.8	20.3	4.6	49.0	78.1	80.4
Aggregate dust										
720	25.4	20.2	1.7	29.6	16.6	19.7	1.2	32.2	65.4	72.1
800	41.1	20.6	2.6	31.8	23.8	20.0	1.7	36.4	57.9	63.1
900	85.9	20.3	5.7	49.9	49.9	19.6	3.7	47.8	58.1	64.0
Coal dust										
720	62.8	20.4	4.3	42.1	29.3	20	2	49.9	46.6	46.8
800	75.2	20.5	5.0	48.6	26.9	20.1	2.2	48.7	35.8	43.6
900	77.3	20.4	5.7	35.6	27.6	19.9	2.5	39.5	35.7	43.9
Gypsum industry dust										
720	84.2	20.7	4.5	30.8	62.3	20.5	3.7	32.3	74.0	81.1
800	65.0	20.2	5.0	48.3	45.8	19.8	4.1	51.3	70.5	82.1
900	96.7	20.5	6.3	49.3	72.9	20.2	4.8	50.3	75.4	75.8

rise of solar irradiance. Moreover, increase or decrease in cell operating temperature also depends on the solar irradiance intensity reaching the panel surface. Our observation about impact of dust on the PV panel temperature is agreed with the study done by [33], which reported that dirty module temperature was observed to be higher compared with the clean one. Due to dust accumulation, the incoming solar irradiation over the panel tends to be hindered. Deposited dust also leads to heat dissipation to the dirty module [34]. This is the reason why the temperature of the dirty module is higher compared to the clean one.

3.4. Impact of Dust on Solar PV Performance. A mass of 10 g from aggregate dust with a particle size of 45-90 μm was distributed uniformly over the module before the measurement. The data were acquired on operating electrical parameters, voltage, current, and power output, from both clean and dirty modules simultaneously. There was difference in voltage ~ 0.5 V between clean and dirty modules, where dirty module voltage was observed to be higher (Figure 7). It was examined that the current and power outputs were linearly increasing with solar irradiance intensity as shown in Figures 7(b) and 7(c). However, the current drop due to dust deposition was ranging between 1.0 A and 1.5 A, and output power drop was 20 W-40 W.

Furthermore, the experimental measurement for I - V and P - V curves for the all tested samples at different irradiances was conducted, but in this paper, I - V and P - V curves for the fine particles (20-45 μm) from coal dust were selected to represent (Figure 8) because fine particles from coal dust have been observed to affect most the module performance compared with the other samples. For 720 W/m^2 , 800 W/m^2 , and 900 W/m^2 irradiances, the output current (I_{sc}) reduction due to dust deposition was 53%, 56%, and 32%, respectively.

FIGURE 9: Maximum efficiency loss basing on dust with particle size 20-45 μm .

3.5. Analysis of Results

3.5.1. $P_{\max}$, I_{sc} , and V_{oc} Loss due to Dust Deposition. The impact of dust deposition with fine particles (20-45 μm) on power $P_{\max}$ and current I_{sc} is shown in Table 3 for all four dust types. It has been examined that dust accumulation does not have a substantial impact on open-circuit voltage of the PV module; this observation is correlated with the study conducted by [31]. Open-circuit voltage of the dirty module is lower than that of the clean module to some extent for all solar irradiances. Dust deposition has a significant impact on short-circuit current generated by the modules. The clean module reliably generates higher output current; the ratio $I_{sc}(\text{dirty})/I_{sc}(\text{clean})$ ranges from 43% to 82% for all tested dust

FIGURE 10: Performance efficiency loss for the four tested dust samples.

types under all solar irradiances as depicted at the last column in Table 3. The disparity in output current reduction may be caused by the fluctuations in solar irradiance received by the module at real-time condition. More strong effect of dust is seen on maximum power. The ratio of $P_{\max}(\text{dirty})/P_{\max}(\text{clean})$ varies from 36% to 78% for different types of dust. $P_{\max}$ produced by the coal dusted panel is reduced most drastically, more than twice (by 53%-64%), compared to the clean one. Less impact on power is resulted from fertilizer and gypsum dusts where the drop in $P_{\max}$ occurred by 22-30%. Therefore, dust accumulation on the photovoltaic module negatively affected output power as well as short-circuit current, however, had no significant impact to open-circuit voltage.

3.5.2. Effect of Dust Type and Particle Size. Dust collected from different sources has shown to have a dissimilar impact

on performance efficiency reduction of the PV module. It was observed that performance losses depend on the dust type (Figure 9). The coal dust was observed to have a higher impact on efficiency loss among the four types of dust. This fact is quite apprehensible owing to the highest absorptivity of the coal sample. Close to one absorptivity and hence lowest transmissivity of the coal dust are brought about by less sun energy reaching the panel as well as by additional heating of it as compared to other types of dust.

Moreover, the study done by [35] reported that module efficiency losses were progressively increased with the decrease in particle size. In the current study, the fine particles were also observed to bring higher performance efficiency losses in the PV performance as depicted in Figure 10. Therefore, the results agreed with the earlier authors [28] who reported that fine particles inhibit solar irradiance from passing through them due to the minimal

interparticle gap in between them. Therefore, with the observation stated also by [35], it is the reason for the fine particles to have a significant impact in efficiency loss compared with larger particles. The maximum performance efficiency loss was examined to be 64% for coal dust at a particle size of $20\text{ }\mu\text{m}$ - $45\text{ }\mu\text{m}$ (fine particle), while 48% was the minimum efficiency loss occurring at $90\text{ }\mu\text{m}$ - $180\text{ }\mu\text{m}$ (large particle) at irradiance of 800 W/m^2 . In addition, for the same solar irradiance and the same particle sizes, dust from the fertilizer industry revealed to have 29% maximum and 9% minimum efficiency loss. However, for aggregate dust tested at 900 W/m^2 , 42% was the maximum efficiency loss occurring at $20\text{ }\mu\text{m}$ - $45\text{ }\mu\text{m}$ (fine particle size) while 10% was observed to be the minimum performance loss for $90\text{ }\mu\text{m}$ - $180\text{ }\mu\text{m}$ (larger particle size). These are experimental justifications observed in this study; fine particles have more significant impact on performance efficiency loss on the PV module as compared to coarse particles.

4. Conclusion

Performance efficiency loss of the polycrystalline silicon module due to industrial dust deposition was investigated. Dust samples were collected from fertilizer, gypsum, aggregate crusher, and coal mine industries. The outdoor experimental measurement of the polycrystalline module performance was done; impact of dust deposition was determined by attaining operating parameters as well as the I - V and P - V characteristic curves of similar modules exposed to the same operating environment (i.e., solar irradiance and air temperature) while one module was covered with dust and the other was reserved clean for output comparison. It was examined that the efficiency loss depended on the type of dust accumulated over the panel surface. Maximum efficiency loss of the polycrystalline photovoltaic module was observed to be 64%, 42%, 30%, and 29% for coal, aggregate, gypsum, and organic fertilizer dust, respectively; hence, coal dust was the most effecting dust sample among the four owing to its highest absorptivity and hence lowest transmissivity. Also, the study proved that the finer dust particles reduced more performance efficiency compared with the larger particles. It was also found that the PV module performance deteriorated with temperature rise owing to heat dissipation caused by dust accumulation. The ratio of short-circuit currents for the dirty module to the clean module was in the range of 43-82% for all dust types tested under different sunlight intensities. Drop in current output due to dust deposition leads to power output drop which causes an immense loss of electrical power and, consequently, economic loss to photovoltaic power in consideration of the large-scale solar power plant.

Abbreviations

PV: Photovoltaic
 G: Solar irradiance
 I - V : Current-voltage curve
 P - V : Power-voltage curve
 I_{mp} : Current at maximum power

V_{mp} : Voltage at maximum power
 I_{sc} : Short-circuit current
 V_{oc} : Open-circuit voltage
 T_{noct} : Nominal operating cell temperature
 P_{max} : Maximum power
 η : Efficiency
 η_{clean} : Clean module efficiency
 η_{dirty} : Dirty module efficiency
 Rh: Relative humidity
 T_{a} : Ambient temperature.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors would like to declare that they have no conflicts of interest that might have influenced the performance or presentation of the work described in this paper.

Acknowledgments

The authors of this paper would like to give their great thanks to Water Infrastructure and Sustainable Energy Future for financing all processes regarding the preparation of this article. Great thanks should go to my fellow students from the Nelson Mandela African Institution of Science and Technology for their encouragement in the preparation of this work. Also, many thanks should go to Dr. Rhee Herb from Innovative Technology and Energy for providing electrical measurement accessories. Moreover, I would like to thank Eng. Kaare Manyama from Greenlink Energy for his support on the provision of some equipment and accessories for the experimental setup. The findings reported in this article were financed by Water Infrastructure and Sustainable Energy Future (Project ID: PI51847).

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