ASSESSING THE LONG-TERM PERFORMANCE DEGRADATION OF PV MODULES IN THE SUB-SAHARAN ENVIRONMENT

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Abstract

This experimental study evaluates the long-term performance and degradation of solar PV modules exposed to the tropical climate of the sub-Saharan. The methods employed for the assessment are Visual inspection, I-V curve characterization, and thermal evaluation by IR imaging. In determining the state of the bypass diodes, the process of partial shading was applied. After thirteen (13) years of exposure in actual outdoor operation, modules showed a reduction in short circuit current (I_{sc}), from 7% to 16.4%, with an average drop of 11.7% compared with the nameplate values. The decline in open-circuit voltage (V_{oc}) ranges from 11.4% to 17.1% with an average reduction of 14.8%. Reduction in Fill Factor (FF) ranges from 11.3% to 24.2%, and a power loss is of 34.5% to 41.4%. EVA browning was the most severe and widespread defect observed through the visual analysis of the modules.

Keywords: PV system, performance, reliability, tropical climate, characterization,

1. Introduction

The market share of solar PV in the power industry has experienced unmatched growth in the past years as a result of its potential as a feasible alternative for fossil fuels. Solar PV has seen increases in both the utility-scale and small scall applications as a result of the continuous drop in cost. As of 2019, the total global capacity stood at 646.8 GW, which about 21.3% change over the previous year's capacity. The yearly additions of Solar PV have also been unprecedented. The new installations in solar PV for 2019 alone amounted to 137.5 GW, which is 34.3% higher than 2018's additions (Powerweb, 2020). The growth experienced in this area is as a result of the favourable policies by various governments and international organizations, and the attractive investment environments that exist in different countries coupled with the rising cost of conventional energy sources and their negative environmental impacts. The increasing growth is, however, not without the challenges of reliability and degradation encountered on-site.

Consistent performance evaluation of solar modules under different climatic conditions will help curb site-specific reliability issues and further enhance its acceptance and growth. Warranty for the non-failure of solar modules given by most manufacturers is for 25 years which provides the assurance of 80% power output for the given time (Vázquez and Rey-Stolle, 2008). However, the reliability of solar modules is dependent on conditions present at the location of operation controlled by factors such as radiation levels, temperature, humidity wind speed and ultraviolet radiation (Rahman et al., 2015).

To further guarantee the reliable performance of PV modules, they are passed through rigorous testing requirements as prescribed by the IEC standards (IEC, 2016). This includes the accelerated ageing test to reveal any design and manufacturing lapses (Jordan and Kurtz, 2013). The factors that lead to failure of solar modules in operation include corrosion, light-induced degradation, break-in contacts, crack cells encapsulant discolouration, delamination, diode failure, hotspots and broken interconnects (Chamberlin, 2011).

Before PV modules are certified for commercial use, they are taken through rigorous test procedures according to regional and international standards such as the EN, IEC, ANSI standards. These test procedures are intended to reveal design and manufacturing defects which are capable of initiating the early failure and degradation of PV modules than anticipated whiles in operation. Recently, the accelerated ageing test has been incorporated in the qualifications which have led to the improvement of PV technology over the past few decades. However, not all

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failure and degradation modes PV modules that take place whiles in operation in different climates are revealed by the abovementioned tests. It is thus a deliberate approach to investigate the issues that arise under outdoor operating conditions (Sharma and Chandel, 2003). The long-lasting and durability PV modules in operation are dependent on the failure and degradation modes controlled by factors like solar irradiation, humidity, ambient temperature ultraviolet intensity (UV) and wind. Other factors that influence the degradation are the defects that occur during the production process, transportation and installation (Rahman et al., 2015)

Several studies have been conducted in different locations to assess the degradation rate of varying PV technologies as shown by (Chamberlin, 2011 Jordan and Kurtz, 2013). However, data available on module performance and reliability assessment for the Tropical sub-Saharan climate, which experiences relatively severe environmental conditions, is negligibly small (Rajput et al., 2016).

2. Materials and Methods

The system under study is located in Koforidua in the Eastern Region of Ghana and situated on the coordinates 6.062545 *N*, -0.266001 W at an elevation of 173 m above sea level. According to the Köppen-Geiger climate classification, its climate is as 'Aw' which is savanna with dry winter (Merkel, 2019). The annual average temperature and rainfall figures for the location are 25.9 °C and about 1407 mm, respectively, as shown in Fig. 1. The average yearly horizontal radiation of the site is 1,733.75 kW h m^{-2} Yr^{-1} with average daily irradiation of 4.75 kW h m^{-2} d^{-1}. The average monthly humidity values for the site range from 76.5 - 88.3%. Minimum and maximum wind speed are 2.40 and 4.19 ms^{-1}, respectively. The dry season and the wet seasons are the two major seasons experienced in Koforidua. The dry season usually starts from December and ends in March while the wet season starts from April to November.

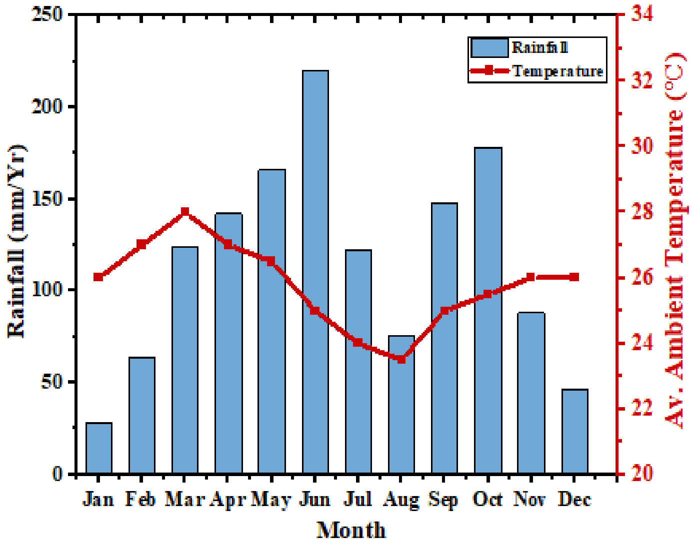


Fig 1: Rainfall pattern and the ambient temperature of the site (Merkel, 2019)

The system for study, an off-grid PV system was installed in 2007, at the student entrepreneurial centre for the training of students and also as a backup for the power requirements of the centre. The system is a ground-mount system with the modules fixed on a structure made of aluminium angle bars and bolted onto metal bars, as shown in figure 2.

Fig. 2: Picture of the installed system

The installation consists of four monocrystalline modules with specifications presented in Table 1. The modules have been certified according to the standards of CE Europe, TÜV and ESTI. The manufacturer's warranty provided is 25 years for 80 % power output.

Tab. 1: Specification of the PV module at STC given by the manufacturer

Parameters	Value
Maximum power (P_{max})	50Wp
Short circuit current (I_{sc})	3.16A
Open circuit voltage (Voc)	21.6V
Voltage at Pmax (V_{mp})	17.60V
Current at Pmax (I_{mp})	2.9A
NOCT	43±2°
Power tolerance	±10%

The methods employed for the analysis include Visual inspection, I-V curve characterization and thermal evaluation by IR imaging were used for the assessment of the modules (Atsu et al., 2020). The process of partial shading of modules was applied to assess the state of the bypass diodes. The uniform translation procedure developed by the Joint Research Centre of the EC is adopted for the translation procedure.

The modules were electrically isolated from each other during the experimentation. The parameters of the modules obtained by employing the EKO MP–170 I-V curve plotter under the experimental conditions. The curve plotter has an accuracy of (± 1% for 10 –1000 V) for Voltage (V_{dc}) and (± 1% for 0.1 – 10 *A*) for current (I_{dc}). Solar irradiation was measured at the plane of the array using the Kimo solarimeter LSL 200 (resolution *1* Wm^{-2}, accuracy *5%).* The Voltcraft infrared thermometer *(IR260 – 8S)* having a measuring range of *-30 to 260 ℃ (± 2 ℃)*, resolution and emissivity of *0.1 ℃* and *0.95* respectively was used to measure the temperature of the modules. Infrared (IR) images were obtained using the (NEC Avio H2640) camera with the following specifications: Accuracy of ± *2% or* ± *2* °C, Spectral range, *8-13 μm*, temperature range, *−40 to 500 °C,* and emissivity of *0.1–1.00.* Quantitative analysis of the captured IR images was performed with the aid of the Report Generator Lite software. The experiment was conducted on a bright sunny day in order to obtain the corresponding results at STC devoid of significant variations which would have occurred at low levels of solar irradiation (Priya et al., 2015).

The translation procedure developed by the Joint Research Centre of the European Commission was used for the translation of experimental data to standard test condition (STC) values. It is a convenient and straightforward method that can be used without applying specific parameters determined under specified conditions of temperature and irradiation. This procedure has a translation accuracy of 4% that is achieved under one experimental measurement (IEA-PVP, 2014).

The following default values were applied: temperature coefficient of I_{sc} (α)= 0.0045, temperature coefficient of V_{oc} (b) =0.06 and irradiance correction factor (a)= 0.06. These default values are valid for crystalline silicon modules. These values are valid for crystalline silicon modules. Equations 1 to 4 provide the procedure for translation of the parameters of the PV modules in operation without determining any specified constants at predetermined ambient and irradiation conditions which are not achievable with modules in real operation (Quansah et al., 2017).

$$I_{sc,2} = I_{sc,1}[1 + \alpha(T_2 - T_1)]\frac{G_2}{G_1} \qquad \text{(eq. 1)}$$

$$V_{oc,2} = V_{oc,1}\left[1 + a In\frac{G_2}{G_1} + b(T_2 - T_1)\right] \qquad \text{(eq. 2)}$$

$$I_2 = I_1\left(\frac{I_{sc,2}}{I_{sc,1}}\right) \qquad \text{(eq. 3)}$$

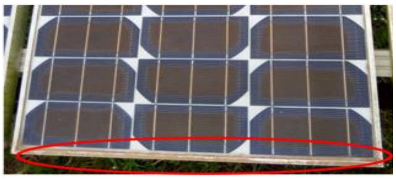
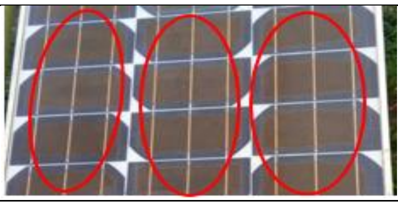
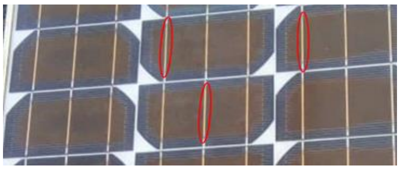
$$V_2 = V_1 + \left(V_{oc,2} - V_{oc,1}\right) + R_s\,(I_1 - I_2) \qquad \text{(eq. 4)}$$

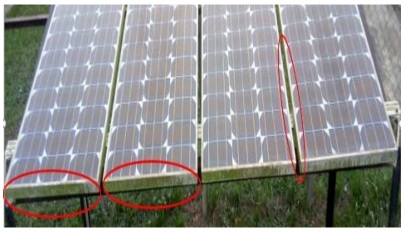
3. Results and Discussion

3.1. Visual Inspection

Visual inspection is the quickest and less intricate process for detecting defects and failures in solar modules (Oliveira et al., 2017). The most suitable period for performing the visual inspection on solar modules is under the illumination of about 1000 lux and applies to defects detectable with the unaided eye (Priya et al., 2015). The experimental measurement and the visual inspection of the PV modules were conducted at irradiation levels close to 1000 W/m2. Table 2 presents the results of the visual inspection.

Tab. 2: Results of the visual inspection

PV module component	Observation/remark	Image
Front of PV module	Shows no sign of delamination, or browning. Glass still feels smooth. Except for accumulated dirt in the lower end and the edges.	
PV cells	All cells uncracked and not broken. Each cell shows some level of discoloration of encapsulant (>70%). EVA discoloration was observed in all the modules.	
Cell metallization	Shows no sign of burns or having been oxidized except for browning or colouration of cell interconnects ribbons.	
Junction box	Intact and all well closed but corrosion observed at portions when opened. This was seen in the junction boxes for all four modules at similar spots. This may be due to moisture ingress. It can also be as a result of the material used which may have a high affinity for water vapour	

	Evidence of bad wiring was observed. (Module wire touching conducting components within the box). This may lead to internal arcing in the box. This was seen for only module 4. This could be a result of students' activities on the system.	
Module frame	Well intact with no scratches or broken parts and not askew. Some discoloration as a result of the accumulation of dirt and water mostly at the bottom half of the module.	

The IEC 61215 standard for degradation requires only total irradiation of *15 kWh/m*^{2} of UV energy. Hence, under real operation conditions, PV modules have the potential of degradation of *5%* or more, and EVA browning just under UV irradiation of *150 kWh/m*^{2} or more (Oliveira et al., 2017). With the annual radiation levels of the site being *1,733.75 kWh/m*^{2}, there is a high possibility of browning of the modules. Table 2 shows the prevalent rate of browning of EVA, covering about 70% of each cell surface. EVA browning is directly proportional to the Ultraviolet (UV) light, leading to transmittance loss and decline in the performance output. Other defects detected are the browning of the interconnect metallization and the corrosion of metal portions in the junction box.

3.2. Degradation rates

Conversion of measured module parameters to the corresponding values at standard test conditions (STC) was carried out using the JRC method. Module 2 recorded the highest Isc of 2.94 A compared to the nameplate value. Module 1 recorded the lowest Isc of 2.6 A. The average Isc for the array was 2.78 A, with the average decline in Isc, determined as 11.7%. Module 1 had the highest reduction of 16.4% in Isc and the lowest drop of 7% was observed for module 2, as illustrated in Figure 3. The annual average decline in Isc is 0.98%.

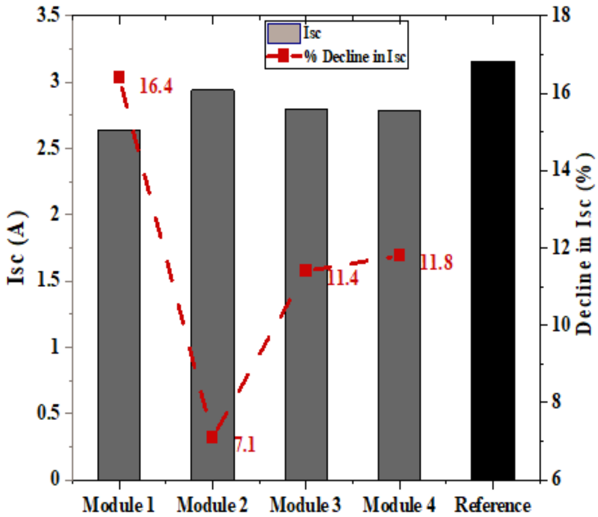


Fig. 3: Short circuit current at STC

The mean Voc for the array was found to be 18.4 V which is 14.8% less than the manufacturer‘s value of 21.6 V, as shown in figure 3. Module recorded the highest Voc of 19.4 V, and the least Voc of 17.91 V was determined for module 3, with a percentage decline of 17.1%. The average degradation in Voc is 14.8% which indicates an annual decrease in Voc of 1.23%.

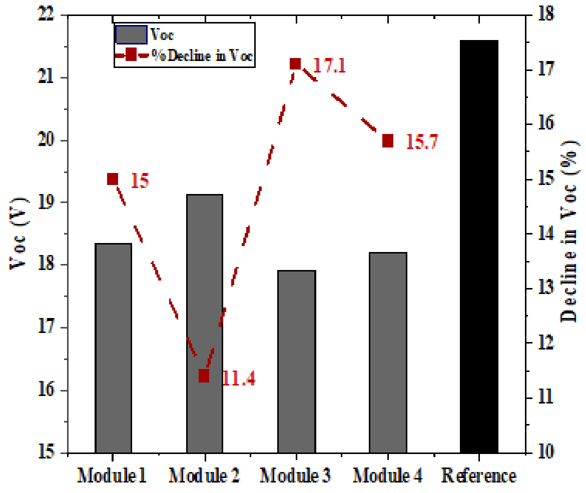


Fig. 4: Open-circuit voltage at STC

The average fill factor at STC determined for the array is 60.05. The highest decline in fill factor of 24.2% was determined for module 3, while the least drop of 11.3% is recorded by module 1, as illustrated by figure 5. The average decline in FF is 18.0%. This presents an annual mean reduction in FF to be 1.5%.

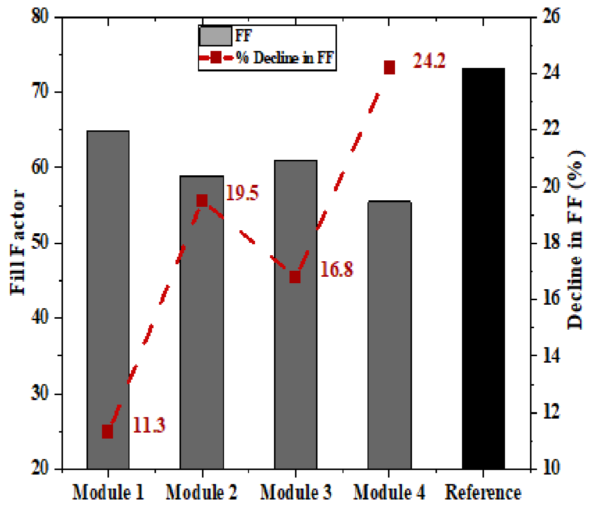


Fig. 5: Fill factor at STC

The average power output determined for the modules was 30.86 *W*. The highest and lowest power of 32.72 *Wp* and 29.3 *Wp* were determined for modules 2 and 3, respectively. A significant decline in the power output of 41.4% was recorded by module 3. The lowest drop was found to be 34.6% for module 2, as presented by figure 6. The average reduction in the nominal power for the array was 38.3% which indicates an average annual decline of 3.19% for the 12 years in operation.

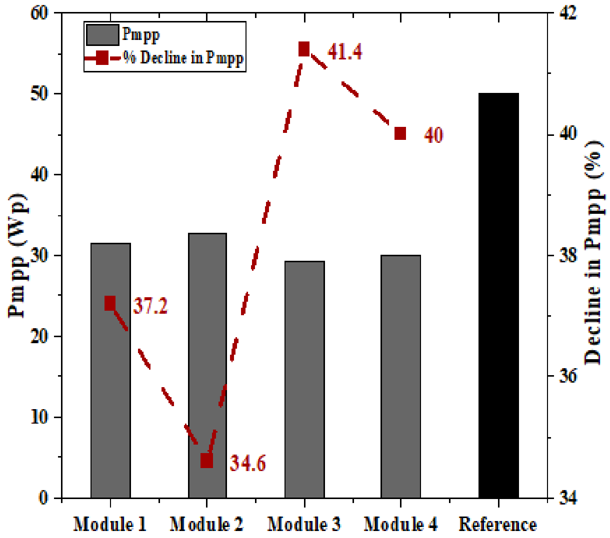


Fig. 6: Nominal power at STC

According to (Köntges, M. et al., 2017), the sequence of the impact of the failure modes is the potential induced degradation, failure of bypass diodes and discoloration of the EVA. This is because there are not appropriate tests yet approved for these failure mechanisms. It is therefore not unexpected the evidence of high degradation levels of the modules with proofs of acute EVA discoloration and bypass diode failures. As it is corroborated by (Munoz et al., 2011), the degree of discoloration of EVA determines the change in the transmittance of the light reaching the solar cells. Thus, the decrease in the power generated.

3.3. Temperature measurement

The method of thermography was applied to determine the trend of the operating temperatures of the modules for the period of the experiment. The report lite software was used to perform the quantitative analysis of the captured IR images. The total surface area of the modules was used during the process. Results show that module 3 had the highest temperature of 59.5 °C whiles the lowest temperature of 45.9 °C was recorded for module 4. The highest mean temperature of 56.3 °C was obtained by module 1, with module 4 recording the least mean temperature of 52.4 °C. Modules 2 and 3 had average temperatures of 55.3 °C and 55.03 °C, respectively, whereas module 4 had the most significant temperature dissimilarity of 10.7 °C, as well as the lowest mean temperature. Module 3, 2 and 1 respectively recorded temperature dissimilarity of 10.0, 6.5 and 4.2 °C. The determined standard deviation values are 1.5905, 2.8557, 3.8676, and 4.7545 for modules 1, 2, 3 and 4, respectively. The average temperatures were 56.28, 55.25, 55.03 and 52.38 for modules 1, 2, 3 and 4, respectively, as illustrated in figure 7. The temperature variations experienced by the four modules are as a result of the varying absorption rates of solar radiation caused by the non-uniform discoloration of EVA in each module. The uneven discoloration of the modules also causes dissimilar electrical defects which lead to mismatch losses and consequently causing the modules to generate different temperatures on their surfaces.

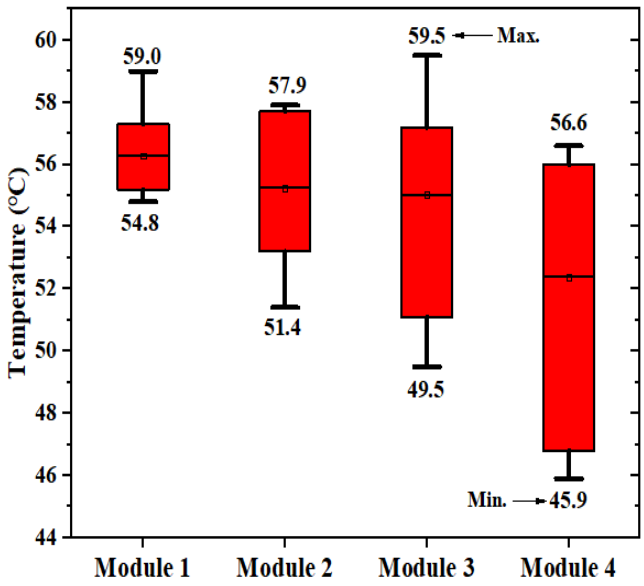


Fig. 7: Temperature distribution of modules

3.4. Bypass diode test

The state of the bypass diodes was assessed by applying the partial shading method. Each module was partially shaded using an opaque object; one at a time and the characteristic I-V and P-V curves traced. In the scenario of a malfunctioning bypass diode, there is a decline in the flow of current in the shaded string of cells as they are not protected. However, in the case of modules having functioning diodes, the decline in current is transformed into inflection points. The results show that the curve outputs deviate from the standard I-V curves with a significant drop in current to the extent of being negligible, as shown in figure 8. The I-V curves and P-V curves under partial shading conditions for all four modules are similar to figure 8 in magnitude and shape. The voltage of all studied modules, however, remained unaffected. This indicates an open circuit performance for the modules; a state in which an insignificant amount of current or no current flows through the circuit. This condition may be the result of defective bypass diodes or soldering disconnection between the bypass diode and the metal contact inside the junction box.

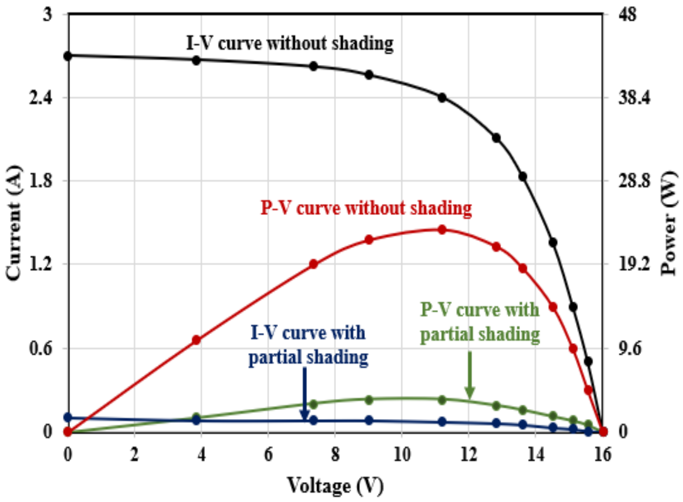


Fig. 8: Characteristic I-V, P-V curves (unshaded and partially shaded) for module 4

4. Conclusion

On-site performance evaluation of PV modules aims to reveal the degradation and failure modes influenced by climate-specific factors. The results of such studies help to enhance the reliability of PV modules by increasing the service life of PV systems.

In this current study, the degradation rates and failure modes of a 12-year-old ground mount off-grid solar PV modules installed in the harsh weather conditions of the sub-Saharan was investigated. It was revealed that the decline in the nominal power ranges from 34.6% to 41.4% with an average decrease of 3.19% per year. In comparison with the nameplate module characteristics of a nominal power 50 Wp, Isc 3.16 A, Voc 21.6, the decline in the experimental values were 7.1 to 16.4% for Isc, 11.4 to 17.1% for Voc and 11.3 to 24.2% for the FF. All four modules had their bypass diodes malfunctioned and exhibited widespread EVA discoloration, covering about 70% of the total surface area of each module. The thermography analysis revealed temperature dissimilarities ranging from 4.2 to 10.7 ºC. This study provides more insights into the diverse impacts of different environments on the long term performance of PV modules.

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6. References

Powerweb (2020). http://www.fi-powerweb.com/Renewable-Energy.html (accessed: 01/08/2020)

Atsu D., Seres I., Farkas I. 2020. Thermal behaviour analysis of different solar PV modules via thermographic imaging, Journal of Renewable and Sustainable Energy, Vol. 12, No. 1:013503, 1-8.

Chamberlin, C.E., Rocheleau, M.A., Marshall, M.W., Lehman, P.A. Comparison of PV module performance before and after 11 and 20 years of field exposure. Proceedings of the 37th IEEE photovoltaic specialists conference; 2011.

IEC 61215-1-1:2016, Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-1: Special requirements for testing of crystalline silicon photovoltaic (PV) modules.

Jordan, D.C., Kurtz, S.R., 2013. Photovoltaic degradation rates-an analytical review. Prog. in Phot: Res. and Appl. 21, pp. 12–29.

Rahman, M.M., Hasanuzzaman, M., Rahim, N.A., 2015. Effects of Various Parameters on PV Module Power and Efficiency. Ener. Conv. and Mgt. 103, 348 – 358.

Vázquez, M., Rey-Stolle, I., 2008. Photovoltaic module reliability model based on field degradation studies. Prog. in Phot: Res. and Appl. 16, 419–433.

Merkel, A. 2019. Weather of Koforidua. https://en.climate-data.org/africa/ghana/eastern-region/koforidua-52344/ [accessed: 20/12/19].

Sharma, V., Chandel, S. S., 2013. Performance and degradation analysis for long term reliability of solar photovoltaic systems: A review. Renewable and Sustainable Energy Reviews, 27, 753–767.

Rajput, P., Tiwari, G. N., Sastry, O. S., Bora, B., Sharma, V., 2016. Degradation of monocrystalline photovoltaic modules after 22 years of outdoor exposure in the composite climate of India, Sol. Energy. 135, 786–795. https://doi.org/10.1016/j.solener.2016.06.047.

Priya, S. S., Sastry, O. S., Bora, B., Kumar, A., 2015. Comparison of curve correction procedure of current and voltage as per IEC 60891 for thin-film technology. 2015 IEEE 42nd Photovolt. Spec. Conf. PVSC, 2015. https://doi.org/10.1109/PVSC.2015.7355843.

IEA-PVPS. Review of Failures of Photovoltaic Modules; OECD/IEA: Paris, France, 2014.

Quansah, D., Adaramola, M., Takyi, G., Edwin, I., 2017. Reliability and Degradation of Solar PV Modules—Case Study of 19-Year-Old Polycrystalline Modules in Ghana. Technologies, 5(2), 22.

Oliveira, M. C. C. de., Diniz, A. S. A. C., Viana, M. M., Lins, V. D. F. C., 2017. The causes and effects of degradation of encapsulant ethylene vinyl acetate copolymer (EVA) in crystalline silicon photovoltaic modules: A review. Renewable and Sustainable Energy Reviews, 81, 2299-2317.

Köntges, M. et al.: Assessment of Photovoltaic Failures in the field. IEA PVPS Task 13, Subtask 3, 2017.

Munoz, M. A., Alonso-García, M. C., Vela, N., Chenlo, F., 2011. Early degradation of silicon PV modules and guaranty conditions. Solar Energy, 85(9), 2264–2274.