

## Development of an Indoor Line Scanning System for Photovoltaic Modules Performance characterization

## A B S T R A C T

Uganda's interest in using solar energy for various applications began 20 years ago. However, there have been numerous reports by the public over the poor performance of the photovoltaic (PV) modules during their operations. This study determined the performance of selected PV modules openly sold in the Ugandan markets. The low-cost indoor line scanning system developed using locally available materials was used to assess the performance of each of the solar cells in the PV module by determining their photogenerated currents. In addition, the electrical characteristics of the PV modules were determined using the outdoor characterization method, which assumed the actual operation of the PV modules under direct sunlight. From the indoor line scans, the percentage of performing solar cells in the three PV modules of single-crystalline silicon (c-Si), multi-crystalline silicon (mc-Si), and amorphous silicon (a-Si) technologies were determined as 79%, 61%, and 95% respectively. The outdoor characterization results revealed that the c-Si, mc-Si, and a-Si PV modules had measured maximum power outputs of 18.5 W, 19.0 W, and 18.9 W, respectively and these were lower than the rated power values of 20 W. The line scan results had a direct relationship with the measured power output of the PV module, which implied that solar cells mismatch, affected the performance of the PV modules by lowering their performance. This developed testing system is affordable for developing countries with limited testing systems and would in the long run contribute to significant increase in the deployment of PV technology in Uganda since only performing PV modules would be allowed into the open market.

**Key words:** Uganda's PV module market; Solar cell defects; Outdoor Characterization; Industry PV standard ratings; Uganda National Bureau of Standards

## 1. INTRODUCTION

The energy resources in every nation play vital roles in its social and economic transformation since they are applied in domestic, industrial, and technological sectors (Zhang et al., 2019). In Uganda, there is an enormous demand for energy, arising from the increasing industrialization and high population of approximately 44.2 million people coupled with the rapid population growth rate of 3.3% per annum (Fashina et al., 2018). The country's energy sector is not sufficient enough to handle the increasing energy demands (Aarakit, Ssennono, et al., 2021). At present, Uganda's total installed energy generation capacity is 2,048.1 MW, with hydropower accounting for 84%, bagasse co-generation at 7%, thermal electricity at 5%, and solar photovoltaics at 4% (Electricity Regulatory Authority, 2024). Solar energy although having the lowest capacity still remains as the best renewable energy source in the world (Lee & Chang, 2018).

According to Uganda Vision 2040, the estimated energy production will be 52.5 GW in 2040, with solar PV technologies projected to provide 5,000 MW (Micheal et al., 2018). The solar energy technology is the cheapest and most sustainable renewable energy source that provides clean energy and contributes greatly in the reduction in ecological problems globally, particularly CO<sub>2</sub> emissions (Al-Dousari et al., 2019; Gebreslassie, 2021; Islam et al., 2018; Kumar & Kumar, 2019). Globally, solar energy is projected to contribute 60% of the total capacity by 2025 (Rabelo et al., 2021). This projection is quite feasible as long as reliability, accessibility, and performance issues are routinely monitored and rectified. The amount of solar photovoltaic (PV) modules installed on residential rooftops and utility rooftops has increased dramatically in recent years. Long-term warranties, scalability, affordability, and the steady decline in the levelized cost of electricity (LCOE) for solar PVs across the globe are all major contributors to this trend (Celik et al., 2017; da Fonseca et al., 2020; Sun et al., 2017).

In the past 20 years, Uganda has witnessed increased demand for solar energy, especially in areas not connected to the national grid. The increase is attributed to the availability of PV modules at local markets, and their affordability (Aarakit, Ntayi, et al., 2021). Due to the country's geographical location along the equator, it has an abundance of sunlight with an hourly direct normal solar radiation intensity of 500 Wm<sup>-2</sup>, expected between 09:00 hours and 16:00 hours in most parts of the country (Okello et al., 2011). This makes solar energy more favorable for use in most parts of the country. Currently, Uganda imports PV modules from the US, Germany, India, China, and the UK. These modules are being extensively used domestically on small scales in both rural and urban areas for lighting purposes in schools, homes, town streets, hospitals, etc., and for powering devices like fridges, charging mobile phones, and other electronic devices (van Hove & Johnson, 2021).

The industrial implementation of photovoltaic (PV) modules in Uganda is a growing sector driven by the need for reliable and sustainable energy solutions. This expansion is primarily motivated by the need to increase energy access, and reduce on use of biomass fuels (Mugagga et al., 2019).

Uganda has made strides in the solar energy sector with notable plants like the MSS Xsabo Solar Power Limited generating 10 MW while both Soroti and Tororo Solar Power Stations produce 10 MW (Avellino et al., 2018; Mugagga et al., 2019). These facilities are key to Uganda's efforts in expanding its renewable energy sources. Furthermore, the government initiatives such as tax exemptions on solar products and partnerships with international donors for rural electrification projects, have significantly spurred growth in this sector (Fashina et al., 2018).

As much as Uganda is increasingly embracing solar technology, there is a growing outcry by the public on the poor performance of PV modules, which operate for a shorter period. The poor performance of the PV modules could be attributed to

cell mismatch during manufacturing (Alonso-Garcia et al., 2006; Kaushika & Rai, 2007), damage to the solar cells during transportation (Tyagi et al., 2013), poor storage of the solar modules at the factories or selling centers (Luo et al., 2021), dust concentration on the solar modules (Santhakumari & Sagar, 2019; Shenouda et al., 2022; Singh et al., 2022), humidity (Hasan et al., 2022; Kazem & Chaichan, 2015; Touati et al., 2013), temperature, wind speed (Tahir et al., 2022), and poor system pre-installation (Akinyele et al., 2015). Many factors affect the performance of PV modules, and this study specifically focused on investigating the performance levels of PV modules openly sold in Ugandan markets to ascertain if they have standardized performance.

There have been some related studies on assessment of the performance of the PV modules in the world. This research was arrived at after careful review of the related studies in some African countries, where solar cell mismatch before installation was identified as one of the major challenges affecting the PV technology performance. Table 1 gives some of the similar researches conducted in other African countries.

**Table 1.** Comparison of the our research with PV experience in other African countries.

Country	Research topic	Research findings and References
Ethiopia	Solar photovoltaic modules' performance, reliability and degradation analysis	The study highlights the effectiveness of various assessment techniques, including electroluminescence and thermography, and recommends integrating advanced machine learning models for predictive maintenance and improved performance assessment. The research underscores the importance of early defect detection and data-driven approaches to enhance PV module reliability and longevity in Ethiopia (Alimi et al., 2022)
Morocco	Thermal Infrared and Visual Inspection of Photovoltaic Installations by UAV Photogrammetry—Application Case: Morocco	Using thermal and visual imagery taken by unmanned aerial vehicles (UAVs), this study inspected photovoltaic installations, detecting visual defects such as cracks, soiling, and hotspots, and developed a semi-automatic procedure for hotspots' extraction, demonstrating the potential of UAV imagery for effective PV system inspections. (Zefri et al., 2018)
Nigeria	Effect of Technological Mismatch on Photovoltaic Array: Analysis of Relative Power Loss	The study developed an equivalent circuit model to analyze maximum Fill Factor (FF) and Relative Power Losses (RPL) for different module

Algeria Investigation and Analysis of Defects and Degradations in Desert Fielded Photovoltaic Modules

The study of five-year-old PV modules in Dubai's desert environment identified significant defects such as structural breakages, glass abrasions, and encapsulant discoloration, highlighting the need for new standard tests tailored to desert conditions due to these defects not being detected under existing protocols.

Ghana Investigation into the impacts of design, installation, operation and maintenance issues on performance and degradation of installed solar PV systems

(S. Kumar et al., 2021)

**Design and Installation Issues:** The study found that many installers ignored proper PV system design procedures, resulting in systems that were undersized and unable to meet the energy demands agreed upon with the owners. Overall, 69% of the systems were improperly sized, which led to lower than expected power output and system failures.

Kenya Photovoltaic module quality in the Kenyan solar home systems market

(Aboagye et al., 2022)

There was a significant variability in the quality of PV modules available in the market. While many brands offer high quality, reliable products, there are also numerous standard modules that failed to meet expected performance standards.

(Duke et al., 2002)

South Africa Identification and characterization of performance limiting defects and cell mismatch in photovoltaic modules

The degraded modules exhibited current mismatch, as evidenced by the I-V curves and supported by the Electroluminescence (EL) images. The study demonstrated that combining EL imaging with I-V curve analysis effectively characterizes the degradation in PV modules, highlighting the importance of identifying and addressing cell

Ghana Correlation of Infrared Thermal Imaging Results with Visual Inspection and Current-Voltage Data of PV Modules Installed in Kumasi, a Hot, Humid Region of Sub-Saharan Africa.

mismatch to maintain PV module performance and longevity (Crozier et al., 2015)

The results showed that the higher the temperature difference in the hot spot tests, the higher the rate of power degradation. 11 out of the 14 PV modules assessed failed the hot spot tests. The power performance factor for all 14 modules fell below the average 80% standard set by most manufacturers for modules operating within the 25-year warranty. (Takyi, 2017)

Egypt Fault identification of photovoltaic array based on machine learning classifiers

This study developed an optimal machine learning (ML) algorithm for detecting and diagnosing common photovoltaic (PV) array faults, including permanent faults (Arc Fault, Line-to-Line, Maximum Power Point Tracking unit failure, and Open-Circuit faults) and temporary faults (Shading). The researchers compared Decision Tree (DT), K-Nearest Neighbors (KNN), and Support Vector Machine (SVM) classifiers, using different splitting criteria, distance metrics, weighting functions, and kernel functions. Both simulation and experimental case studies demonstrated that the SVM classifier, optimized with Bayesian methods, provided the best performance in accurately identifying and diagnosing PV array faults under diverse conditions. (Badr et al., 2021)

This study used three PV modules of a 20 Wp power rating from the same manufacturer with different technologies of c-Si, mc-Si, and a-Si types as shown in Figure 1. Table 2 shows the specifications of the PV modules used in this study. The c-Si, mc-Si, and a-Si PV modules had 48, 56, and 20 solar cells respectively. A smaller number of PV modules with a low power rating were used to reduce the cost of purchasing PV modules from the open market since wattage is directly proportional to the price of the PV module.



Figure 1. The PV modules of different technologies used in this study.

Table 2. Specifications of the PV modules

Parameters	c-Si	mc-Si	a-Si
Rated maximum power $P_{max}$ (Wp)	20.0	20.0	20.0
Current at $P_{max}$ (A)	1.15	1.11	1.11
Voltage at $P_{max}$ (V)	17.6	18.0	18.0
Short circuit current (A)	1.27	1.24	1.2
Open circuit voltage (V)	21.4	21.6	29.0
Efficiency (%)	16.2	8.80	5.10
PV module area (m <sup>2</sup> )	0.125	0.227	0.394
Number of solar cells	48	56	20

## 2.2. The Indoor Line Scanning System

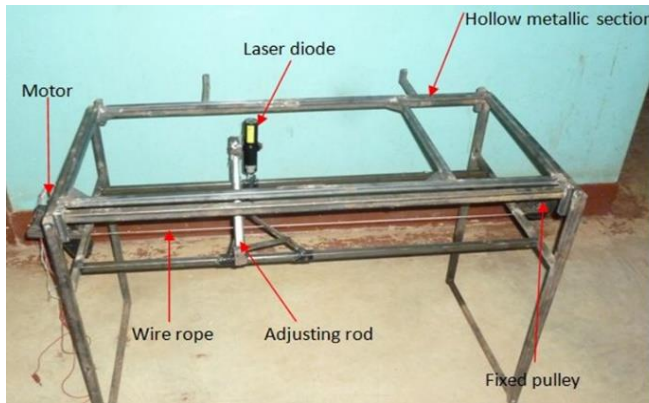
### 2.2.1. Design of the System

The materials used to fabricate the system included a car wiper motor, pulleys, a laser diode, a laser diode holding system, wire rope, and metallic hollow sections as shown in Figure 2. The fabrication was conducted such that the developed system accommodates the surface area of each selected PV module. The key instruments used to achieve the research objectives of this study are listed in Table 3.

In this study, the indoor line scanning technique was used to carefully scan each solar cell to determine their photogenerated currents when illuminated. In addition, an outdoor characterization method was used to evaluate the performance of the same PV modules when installed on the rooftop of a building. The goal was to compare the measured electrical properties of the PV module to the specifications listed on the PV module's nameplate.

## 2. METHODS AND MATERIALS

### 2.1. PV Modules Used in the Study



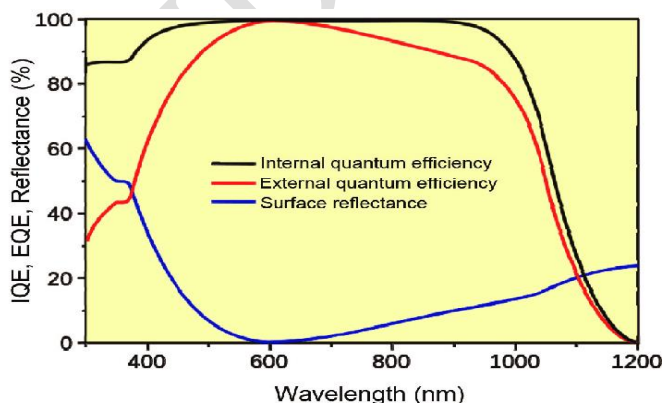
**Figure 2.** The fabricated frame of the indoor line scanning system.

**Table 3.** Instruments and their purpose in the research study

Name of the instrument	Purpose
Laser diode	Provided the only source of light for scanning the PV modules
Motor	Provide mechanical energy to run the laser diode across the solar cells
Pre-Amplifier	Increase the photogenerated currents to measurable values
Spirit level	Ensuring the PV modules are placed normally to the roof surface
Computer	For running the LabView and MATLAB soft wares
Variable resistor	Varying the resistance during outdoor characterization measurements
Multimeter	Measure the module and ambient temperatures
Tape measure	Measuring the dimensions of the PV modules

### 2.2.2. Choice of the laser diode for the study

The wavelength of 635 nm was selected for the diode because at this wavelength, the surface reflectance is 0% and the internal and external quantum efficiencies of the photovoltaic modules are 100% (Devi et al., 2021). The laser diode beam had a spot diameter of 1.5 mm thus the beam area was  $1.768 \times 10^{-6} m^2$  with beam intensity of  $2.828 \times 10^6 Wm^{-2}$  (Kaspari et al., 2008). Figure 3 illustrates how these factors change at different spectrum wavelengths.



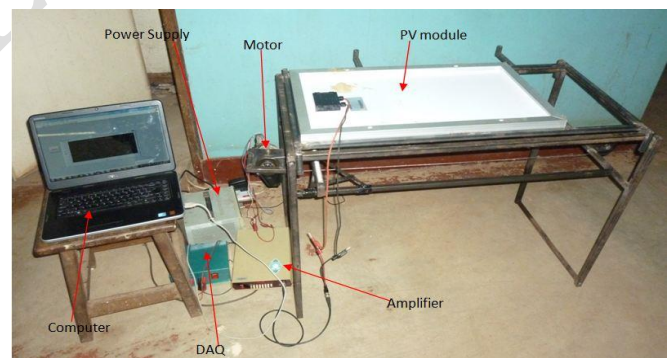
**Figure 3.** Variation of surface reflectance, internal and external quantum efficiency with wavelength of a photovoltaic module.

### 2.2.3. The line scanning of the PV Modules

Figure 4 shows the experimental setup placed in a dark room to avoid illuminations from other sources of light. This ensured that only light from the laser diode (wavelength 635 nm) was incident on the selected PV module. The chosen PV module was put in a rack so that the metallic contacts were parallel to the scanning direction. The system was set into motion by turning on the motor, which spun the pulley and made the laser diode move at the speed of the motor. The speed of the motor during the scanning process was set by adjusting the voltage and all the PV modules were scanned at the same speed of motion of the laser diode. A pulley was fixed onto the motor and the wire rope was made to pass over the pulley and connect to the other pulley via a system holding the laser diode. In the system, the movement of the motor is transmitted to the pulley, which in turn moves the laser diode system connected to the wire rope.

The pre-amplifier connected to the PV module amplified the small-generated currents in pico-amperes to measurable values and delivered them to the Data Acquisition (DAQ) system and to the computer, where readings and line scans were displayed.

The computer connected to the PV module had an installed LabView program that started running as soon as the beam from the laser diode touched the PV module and line scans of the outputs of the photo-generated currents of each solar cell were displayed on the computer. After completing the scanning of the first string, the reverse scanning of the next string was conducted after adjusting the laser diode. This process was repeated until all the solar cells in all the strings of the PV module were scanned. The photogenerated currents for all the solar cells were then merged and plotted to obtain the line scans of the whole PV module. This procedure was repeated for all three types of the selected PV modules.



**Figure 4.** Experimental setup for the indoor line scanning system.

### 2.2.4. Determining the Proportion of Performing Solar Cells

To determine the proportion of performing solar cells, all the solar cells whose photogenerated currents were nearly equal to zero were considered non-performing solar cells (almost dead solar cells), and the rest were considered performing solar cells. The percentage of the performing solar cells was computed using the equation

$$P_s = \frac{100A}{T} \% \quad (1)$$

where  $A$  is the number of performing solar cells,  $T$  is the total number of solar cells in the PV module, and  $P_s$  is the percentage of performing solar cells.

### 2.2.5. Outdoor Characterization of the PV Modules



where  $I_2$  is the normalized current (A),  $I_1$  is the measured current (A),  $G$  is solar irradiance ( $\text{Wm}^{-2}$ ),  $T$  is module temperature ( $^{\circ}\text{C}$ ), and  $\alpha$  is the temperature coefficient for current. Subscripts 1 and 2 refer to the measured values, and values at reference conditions respectively. Similarly, the module voltage was normalized using equation 6 given by ([Chamberlin et al., 1995](#))

$$V_n = V_m\{1 + b(T - 25^{\circ}\text{C})\} \quad (6)$$

where  $V_n$  is the normalized voltage in volts,  $V_m$  is the measured voltage in volts,  $b$  is the temperature coefficient per degree Celsius, and  $T$  is the module temperature in degrees Celsius.

The efficiency for each PV module was calculated using the measured electrical parameters according to the equation

$$\eta_{max} = \frac{P_{max}}{P_{in}} \times 100 = \frac{V_{max} \times I_{max}}{E \times A} \times 100 \quad (7)$$

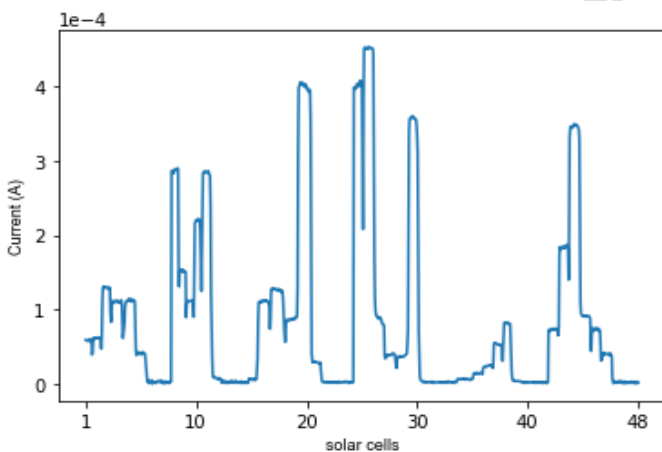
where  $E$  is the irradiance or total incident power per square meter and  $A$  is the total area of the solar cells.

The calculated efficiency values were then compared with the manufacturer's rated values on the PV modules. The results of the measurements and calculations are discussed in the following section.

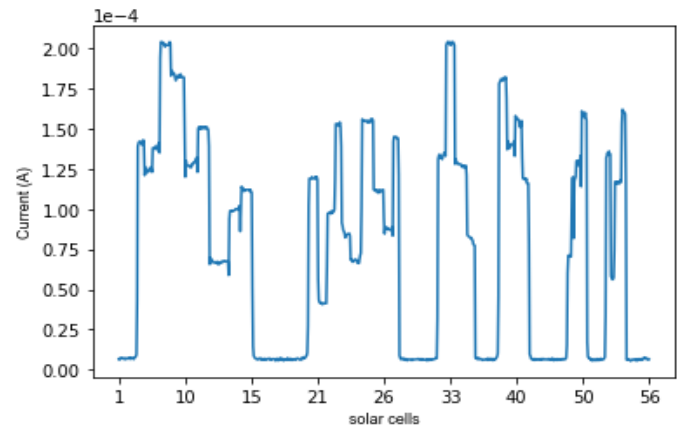
### 3. RESULTS AND DISCUSSION

#### 3.1. Indoor Line Scans

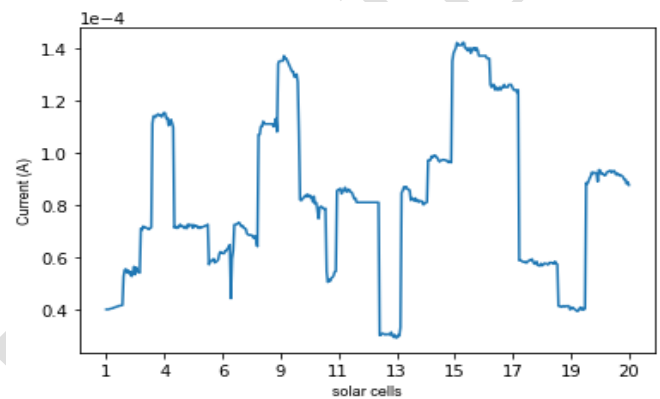
The scanning of the PV modules was conducted by following each string, which in PV technology is defined as a series of solar cells or PV modules that are electrically connected in series to form a larger array ([Huld et al., 2010](#)). A line scan of the entire PV module was created by combining the results of the individual scans of each string. The results of the line scans are in Figures 7-9.



**Figure 7.** Line scans for the c-Si module.



**Figure 8.** Line scans for the mc-Si module.



**Figure 9.** Line scans for the a-Si module.

The line scans of each PV module show that the solar cells have different performance levels, leading to a solar cell mismatch that affects the overall PV module performance. Some of the solar cells produced very low currents after being struck by photons and were nearly regarded as dead solar cells. The current mismatches between the worst performing and best performing solar cells in c-Si, mc-Si and a-Si were 99.9%, 97.4% and 79.2% respectively. The current mismatch of the solar cells in a PV module is a phenomenon that occurs when the solar cells have different electrical characteristics ([Wurster & Schubert, 2014](#)). This can lead to reduced power output and efficiency of the module, as well as potential damage to the cells due to overheating or reverse biasing ([Crozier et al., 2012](#)).

In this research study, the environmental causes of solar cell current mismatch like shading, and dust accumulation were controlled during the experimental work. Therefore, the most likely causes of current mismatch between the solar cells was during the solar module manufacturing processes like a lack of solar cell sorting, and slight differences in the solar cells material properties, such as doping concentration, thickness, or defect density, which can affect their electrical parameters ([Bakas et al., 2012](#)). Another factor is spectral mismatch where the solar cells may have different spectral responses to the incident light, depending on their band gap, absorption coefficient, or anti-reflective coating resulting in different current generation under different illumination conditions ([Chantana et al., 2019](#)).

Furthermore, even within the individual solar cell, there was non-uniformity in the current generated and this could have arisen from the non-uniform distribution of defects within the solar cell or from cracks developed during the soldering process (Kohler et al., 2014). The line scans were used to obtain the minimum and maximum photogenerated currents and to compute the percentage of performing solar cells in each PV module as indicated in Table 4.

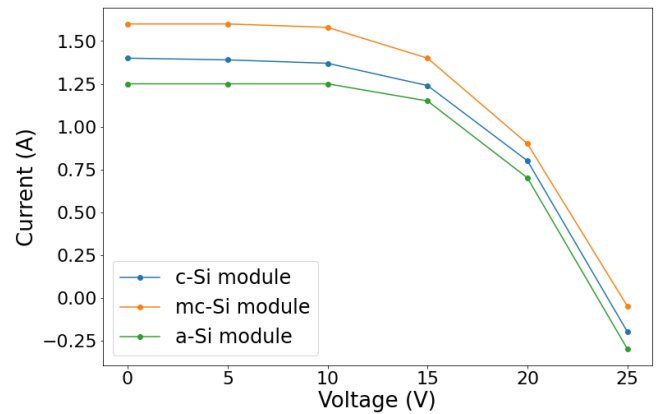
**Table 4.** Comparative performance of three PV modules.

PV type	Maximum $I_{ph}$ (mA)	Minimum $I_{ph}$ ( $\mu A$ )	Total number of solar cells in the module	Number of performing solar cells	Percentage of performing solar cells
c-Si	0.452	0.6	48	38	79
mc-Si	0.204	5.4	56	34	61
a-Si	0.142	29.5	20	19	95

From Table 3, the a-Si PV module had the highest percentage of performing solar cells among the three PV modules because only one of its solar cells had photogenerated currents near zero implying better overall performance. The mc-Si PV module had the lowest percentage of performing solar cells despite having the largest number of solar cells in the PV module, since most of them were nearly dead solar cells thus this module had some challenges in maintaining optimal performance across its solar cells. The a-Si module also performed better because each of the solar cells had a larger cross-sectional area as compared to c-Si and mc-Si PV modules. In addition, a-Si had the lowest percentage of current mismatch at 79.2% as compared to c-Si and mc-Si with 99.9% and 97.4% respectively. In summary, the differences in the percentage of performing solar cells highlight variations in the performance and reliability of the three types of PV modules. The amorphous silicon module stands out with the highest percentage, indicating better overall performance.

### 3.2. Outdoor Characterization

The graphs for current against voltage (I-V curves) presented in Figure 10 were obtained by plotting the average of five measurements taken at different intervals of the day. The I-V characteristics for each technology were then used in the determination of parameters like the  $V_{OC}$ ,  $I_{sc}$ ,  $V_{max}$ ,  $I_{max}$  and  $P_{max}$  of the solar cells (Khunchan & Wiengmoon, 2018) as shown in Table 4.



**Figure 10.** I-V curves for the three different PV modules.

The measured electrical performance parameters of the PV modules were compared with the manufacturers' rated specifications. Table 5 shows the comparison of the average measured and rated electrical solar parameters at a solar irradiance of  $1000 \text{ W m}^{-2}$  for the three PV modules.

**Table 5.** Comparison of the electrical parameters of three PV modules.

Technology	Parameter	$I_{sc}$	$V_{OC}$	$V_{max}$	$I_{max}$	$P_{max}$	$\eta(\%)$
c-Si	Rated	1.27	21.4	17.4	1.15	20.0	16.2
	Measured	1.24	23.7	17.8	1.04	18.5	14.8
mc-Si	Rated	1.24	21.6	18.0	1.11	20.0	8.8
	Measured	1.55	24.4	17.3	1.10	19.0	8.4
a-Si	Rated	1.20	29.0	18.0	1.11	20.0	5.1
	Measured	1.27	23.8	17.8	1.06	18.9	4.8

From Table 4, the measured maximum power and efficiencies for all three PV modules were below the rated values on the nameplates of the PV modules. This can be attributed to the poor performances of some of the individual solar cells in each of the PV modules as seen in the indoor line scan results. In addition, the c-Si, mc-Si, and a-Si modules had decrease in their marked power output of 1.5 W, 1.0 W and 1.1 W respectively. The decreases in the power output could be linked to the under performance of the individual solar cells in each of the PV modules. This implies that the identified poor performing solar cells had an impact on the performance of the PV module when it was fully installed for long-term operations. In addition, all the measured and rated efficiencies of the selected PV modules were below the industry-reported efficiencies for c-Si, mc-Si, and a-Si of 24.4%, 20.4%, and 12.3% respectively (Green et al., 2021).

### 4. CONCLUSIONS

This research evaluated the performance of selected PV modules available in Ugandan markets using an indoor line scanning technique and an outdoor characterization method. The developed indoor line scanning quality control system generated line scans for each PV module, revealing that individual solar cells within a module performed differently. The percentage of performing solar cells in c-Si, mc-Si, and a-Si was 79%, 61%, and 95% respectively. In addition, from the outdoor characterization experimental results, the measured efficiencies for c-Si, mc-Si, and a-Si solar modules of 15.0%, 8.4%, and 4.8% that were lower than the rated values on the PV modules'

nameplates. These findings indicate that the PV modules in the Ugandan market are underperforming in terms of efficiency and power output, aligning with public concerns about their poor performance. Therefore, before allowing imported PV modules to enter the Ugandan market, the government of Uganda through its competent authority (Uganda National Bureau of Standards) should consider implementing this proposed method or any other similar technology to evaluate the imported PV modules' performance. The study suggests government of Uganda to establish the PV testing system so that only well performing PV modules are allowed into the open market and this will help to build public confidence in the use of PV technology in Uganda.

## 5. ACKNOWLEDGEMENT

The authors are very grateful to the department of Physics of Makerere University for the provision of the measurement equipment that made this research successful. Special thanks to the Physics Department technicians who helped in the fabrication of the indoor line scanning system.

## NOMENCLATURE

PV	Photovoltaic
a-Si	Amorphous Silicon
c-Si	Single crystalline silicon
DAQ	Data Acquisition
LCOE	levelized cost of electricity
m-Si	Multi-Crystalline silicon
MW	Mega Watts
STC	Standard Test Conditions
$\theta$	Zenith angle
$V_n$	normalized voltage
$V_m$	Measured voltage

## Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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