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Characterization of solar photovoltaic modules in outdoor and indoor conditions

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SUMMARY

This paper summarizes the results of solar photovoltaic (PV) module electrical characterization under outdoor and indoor conditions in the Republic of South Africa. Under outdoor conditions, the bi-facial PV modules on fixed racks and dual-axis trackers yielded more energy than mono-facial modules on the same mounting configuration due to the active backside. The indoor current-voltage (IV) measurements conducted on an A+A+A+ sun simulator matched within ± 3% of the manufacturer's nameplate ratings on a sample of crystalline PV modules, with some exceptions. The measured electrical characteristics from the outdoor system was corrected to standard test conditions (STC) and compared with indoor measurements at STC. The corrected maximum power from the outdoor system measured roughly 5% below maximum power as measured on the indoor system.

KEYWORDS

Photovoltaic, characterization, indoor, outdoor, IV, bi-facial

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1 INTRODUCTION

Solar energy is viewed as a major intervention opportunity in the long term to address the challenges in a transition to a sustainable global energy system. The solar energy resource is unlike the fossil based fuels which are globally traded commodities with price risks. The projections for South Africa in the solar energy industry predict positive growth in the coming decades. Solar photovoltaic (PV) modules are rated by the nominal maximum power (Wp) [1] as measured under the standard test conditions (STC) as per the IEC Standard 60904 [2], [3]. The indoor PV measurement ensures a fast and precise power determination of the PV modules [4], however the STC condition does not cover the extent of real outdoor conditions under which the PV module will operate [1]. Therefore, it is important to monitor and model the energy yield of PV installations under outdoor exposure [1], [4]. The PV modules must be operated at maximum power point tracking system (MPPT) to characterize the current, voltage and power outputs. It is important to measure the solar irradiance at the same module plane for energy yield comparison studies [5]. The characterization of PV module technologies is being performed in outdoor and indoor conditions at CSIR Pretoria campus and the comparison results are published in this paper.

2 CSIR ENERGY CENTRE RESEARCH AND TEST FACILITY

CSIR Energy Centre commissioned an outdoor solar PV testing facility in the beginning of 2018 and the commissioning a PV module performance and reliability testing facility is underway at the campus located in Pretoria, South Africa. The facility supports the domestic solar PV industry with aspects of industrial development, research, quality assurance, knowledge generation and human capital development. The facility was conceived to support the PV manufacturing sector in South Africa as a pre-qualification test facility so that the design, build and test of new products could happen in parallel, shortening the time to market for South African components. The facility also supports the renewable energy industry, specifically on PV module quality, reliability, design, system modelling, operations, maintenance and monitoring. The facility furthermore contributes to knowledge transfer and human capital development through research, publication of results, and by training emerging researchers.

2.1 Outdoor solar PV testing facility

As the photovoltaic industry in South Africa is growing, there is a need for high-quality research on solar system design and optimisation in realistic outdoor environmental conditions. The outdoor testing facility makes it possible to study the performance of PV modules that have been manufactured locally and internationally under real-world South African climatic conditions. It enables laboratory-quality diagnostic measurements on individual PV modules and small scale PV systems (up to 5 kilowatt) of alternating current in a fielded environment. The facility is instrumental to improve model accuracy, optimize on-site battery storage, and analyze the performance of different PV technologies. The energy yield system can switch automatically between grid-tied operation and IV mode. The AC, DC, and power quality electrical characteristics can be monitored under normal grid-tied operation. Full IV curves can also be recorded at set intervals, given this unique switching feature of the system. A weather monitoring system forms an integral part of our outdoor testing facility.

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2.1.1 Energy Yield test system

The test facility hosts six (6) pairs of different PV technology modules mounted on a fixed tilt rack facing true north (0 degrees azimuth) at 25 degrees tilt on a horizontal, two-story rooftop. The PV modules currently under test include Bi-facial PERC 270 Wp, Bi-facial n-type c-Si 280 Wp, Mono-facial mono-crystalline 275 Wp, Mono-facial mono-crystalline 330 Wp, Mono-facial poly-crystalline 315 Wp, and Thinfilm175 Wp modules. Each module is connected to the MPPT system coupled with electronic load and is configured in accordance with the rating label of each module. The Maximum Peak Power (Pmp) measurements on the crystalline modules are taken every 1 minute and IV sweep at every 10 minutes interval. Thin film modules IV sweeps are carried at every 2 minutes interval. The photograph in Figure 1 shows the different PV technologies mounted side-by-side, and Figure 2 shows the MPPT system where the PV modules are connected to for MPP measurements and current-voltage (IV) sweeps.

Figure 1: Different PV technology modules under test at Pretoria campus

Figure 2: MPPT system

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2.1.2 Weather station

Weather Station 1 (WS1) was commissioned in September 2016. WS1 comprises of two (2) Pyrheliometers (CHP1) mounted on a dual axis Suntracker to measure Direct Normal Irradiance (DNI), two (2) Pyranometers (CMP21) measuring Global Horizontal Irradiance (GHI) and Diffuse Horizontal irradiance (DHI), an anemometer measuring wind speed and direction, and the temperature sensor measuring ambient temperature (Figure 3). Weather Station 2 (WS2) was commissioned in December 2017. WS2 includes an Ultrasonic Clima sensor measuring wind speed and direction, ambient temperature, rainfall intensity and humidity. A Spectroradiometer (MS711) records spectral distributions in the range 300 ~ 1100 nm, and Pyranometers (SMP10) measure GHI, Plane of Array (PoA) front side irradiance, and albedo from the back side. Figure 4 shows the front side PoA and albedo sensors. The data from both weather stations are being recorded at 60s and 30s interval respectively.

Figure 3: Weather station

Figure 4: Plane of Array irradiance measurements

2.2 CSIR INDOOR TEST FACILITY

The indoor quality and reliability lab is being commissioned for pre-qualification testing of PV modules and for conducting quality and reliability test protocols that are emerging in the global PV market. The indoor lab includes large environmental chambers and a mechanical load tester to accelerate degradation mechanisms that can otherwise take years to occur naturally in the field. The data from these accelerated stress tests will help ensure that reliable PV modules are developed and installed in South Africa. The environmental and mechanical stress testing in the facility forms the foundation for the pre-qualification of new concepts, certification of new products, and reliability testing of existing technology. Accelerated stress tests shorten the learning cycle for development of new products. PV modules are subjected to harsh conditions which mimic the actual life-time of the modules which otherwise would take up to 25 years. The facility constitutes sun simulator, climatic chambers, mechanical load tester, hi-pot tester and other test infrastructures.

The indoor sun simulator enables high precision, accurate performance measurements on PV modules over a range of temperature and irradiance levels in a controlled environment. Different types of sun simulators are available on the market to serve different market segments. The CSIR has commissioned a walk-in, pulsed simulator with a xenon arc lamp light source and an integrated thermal chamber. Sun simulators

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are classified as class A, B or C depending on how closely the quality of light matches the target specifications for spectral distribution, temporal stability and non-uniformity of irradiance, as specified in the IEC 60904-9 standard for the requirements of solar simulators (Table 1).

Classifications	Spectral match	Non-uniformity of irradiance	Short term instability of irradiance (STI)	Long term instability of irradiance (LTI)
A	0.75 – 1.25	2%	0.5%	2%
B	0.6 - 1.4	5%	2%	5%
C	0.4 – 2.0	10%	10%	10%

Table 1: IEC Classification table for Sun simulator

CSIR Energy Centre has commissioned a class A+A+A+ sun simulator (Figure 5) which exceeds the requirements of class A in all segments at shown in Table 1 above by a factor of 2. This simulator is capable to produce irradiance from 100 W/m^2 to 1100 W/m^2 and has an integrated thermal chamber which mimics the environment temperatures from 15^{0}C to 75^{0}C at a controlled rate. The simulator is calibrated using the WPVS monitor cell traceable to international calibration labs.

Figure 5: A+A+A+ Sun simulator with integrated thermal chamber at CSIR campus Pretoria

3 RESULTS

3.1 Outdoor characterization

For this paper, the performance of mono crystalline silicon (mc-Si) and poly crystalline silicon (pc-Si), bi-facial and thinfilm modules was monitored during the calendar year 2018 and the recorded data was analyzed to determine the real time performance of these technologies in South African conditions. Weather stations at the campus measured an annual GHI and PoA irradiance of 1929 kWh/m^2 (WS2 GHI) and 2125 kWh/m^2 (WS2 EY2 PoA), respectively, during the calendar year 2018. The Performance Ratio (PR) is a metric commonly used to determine the solar PV performance during its operations [6]. PR_{DC} is the ratio of actual DC energy generated

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over the rated DC power of the solar PV module divided by the ratio of the measured POA irradiance at the front surface over the irradiance at STC (Eq. 1).

$$PRDC = \left(\frac{Actual\ DC\ Energy}{Rated\ DC\ Power}\right) / \left(\frac{POA\ irradiance}{Irradiance\ at\ STC}\right) \quad (1)$$

Two (2) samples of each technology are under the test; hence an average of both the modules output is used to depict the performance of each technology. MPP measurements were not carried out during January, February, May and October due to software upgrades and indoor characterizations. In November, the bi-facial modules were removed from the test racks for indoor characterizations; hence no data is presented for these months. Figure 6 presents the results of the performance analysis.

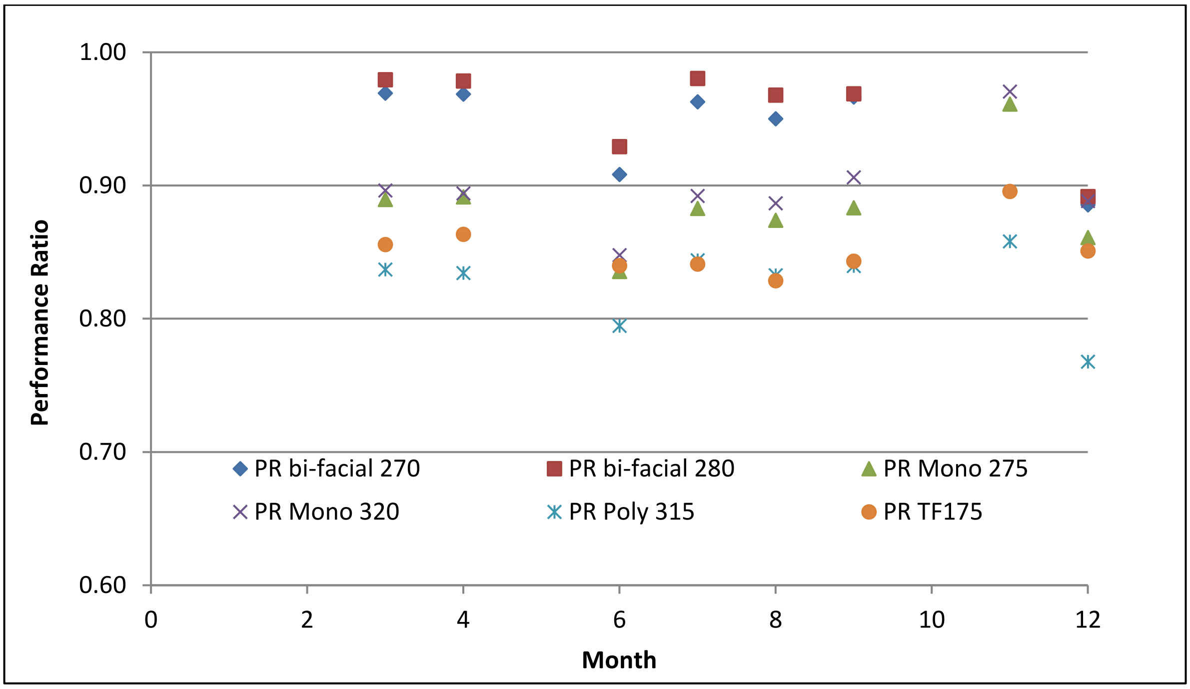

Figure 6: Performance of the PV module technologies

Bi-facial modules showed the highest performance ratios with an average PR of 0.96 and 0.94 for bi-facial 280 Wp and bi-facial 270 Wp, respectively. The mono-Si 275 Wp and 330 Wp recorded an average PR of 0.91 and 0.92, respectively. The poly-Si 315 Wp recorded 0.85 and the thinfilm175 Wp recorded an average PR of 0.87.

3.2 Indoor characterization

3.2.1 Indoor Delta to name plate comparison

Sixty (60) modules of mc-Si and pc-Si technology from different manufacturers were characterized on the newly commissioned sun simulator. The IV characterization is carried out at Standard Test Conditions (STC) which corresponds to 1000 W/m^2, 25°C cell temperature, and Air mass 1.5. The repeatability in maximum power measurements of the control modules measured on the sun simulator over multiple days is +/- 0.3% with a k=2 coverage factor. The measured electrical parameter of each module is compared against the manufacturer rating label values and the delta

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to name plate in percentile is presented in Figure 7. A positive delta indicates the CSIR sun simulator measured higher than the nameplate rating and the negative indicated CSIR measured below the nameplate rating.

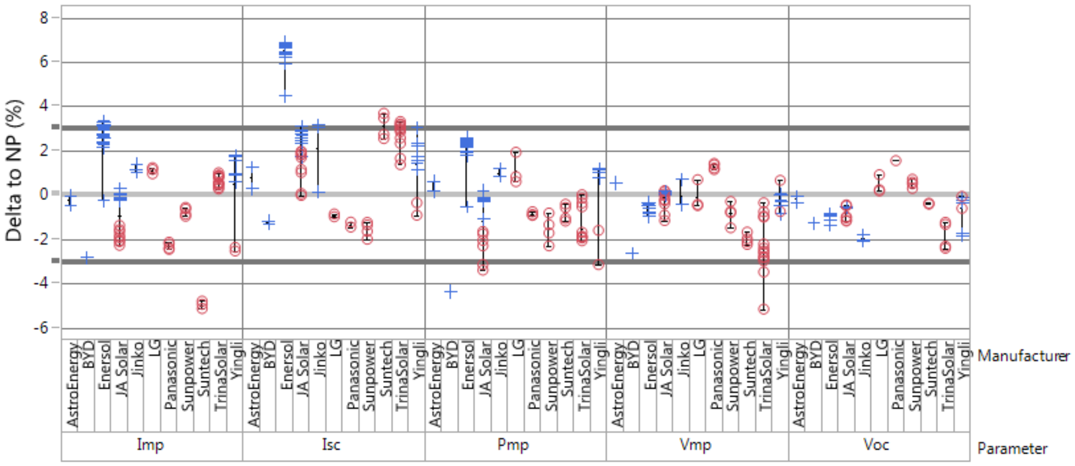

Figure 7: CSIR measurements vs PV Manufactures nameplate rating

Based on Figure 7, most of the CSIR measurements were within +/- 3% of the manufacturer's nameplate ratings. In general, PV module manufacturers market their products either with a positive tolerance (+ 3 /- 0) or both positive and negative tolerance range (+/- 3). A few modules measured outside +/- 3 % range, so a further investigation is necessary to understand the measurement variations between the systems and the environment conditions. All the measured modules were readily available in the commercial market and were procured by CSIR. It is recommended to perform STC measurements at a third party laboratory during larger roll-out of PV plants. An under-performing PV plant will rather cost high compared to cost of quality expenses incurred during the implementation phase.

3.2.2 Stabilization and Sun soaking

Light Induced Degradation (LID) is a phenomenon that arises in crystalline modules during the very first hours of exposure to the sun and can result in a loss in the performance. This may affect the real performance in comparison with the manufacturers rating label values if the LID was not accounted for during the manufacturer's rating process. During the light exposure, the entrapped oxygen from the wafer manufacturing process diffuse through the silicon lattice creating complexes with boron dopant acceptors. These complexes create their own energy levels in the silicon lattice and can capture electrons and holes which are lost for the PV effect [7]. The complexes also act as a harmful defect and reduce minority carrier diffusion length accordingly. LID is therefore related to both boron and oxygen concentration. Crystalline p-type boron doped silicon solar cells generally exhibit a degradation of conversion efficiency during the first hours of exposure to the sun light [8].

Light soaking is carried out to quantify the LID by exposing the modules to natural sunlight at CSIR for a minimum of five (5) sun hours. Initial and post exposure power measurements at STC were measured and the delta is presented in Figure 8.

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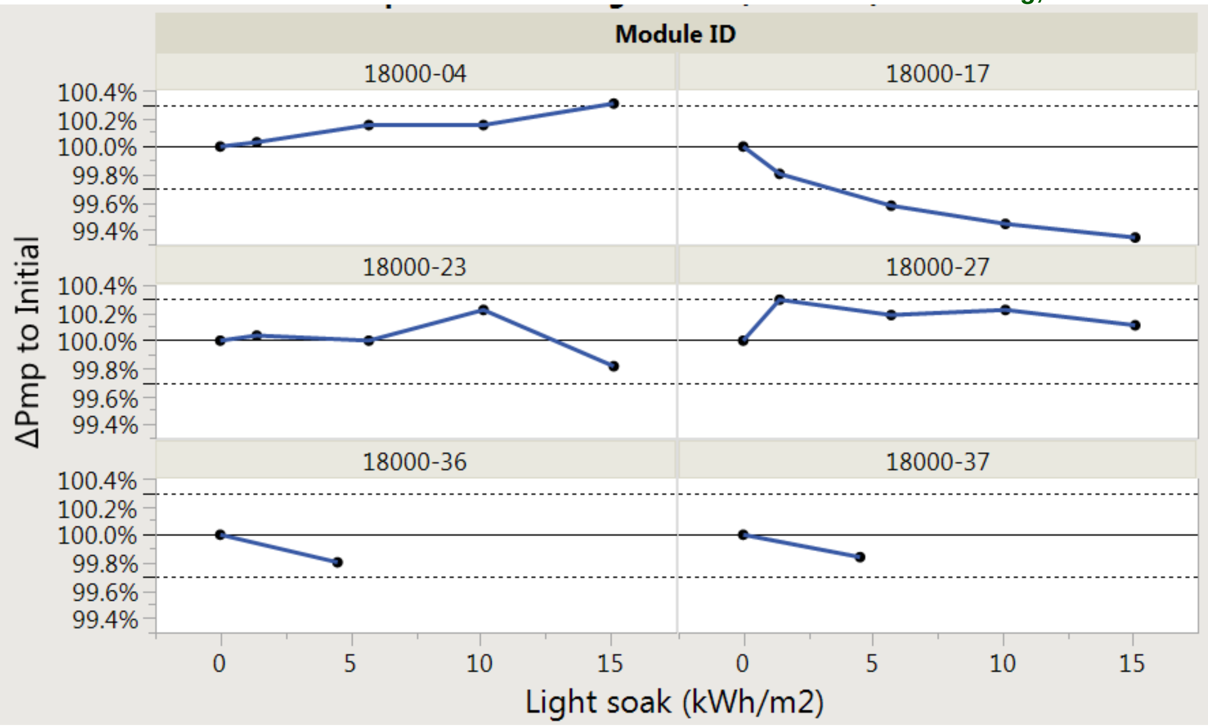

Figure 8: Delta between the Initial and Post sun exposure

Six (6) modules out of the 60 modules were subjected to light induced degradation test. One (1) module (18000-17) shows measureable light induced degradation on the order of 0.6%, but the other five modules showed no significant trends outside the bounds of the sun simulators repeatability of measurements, +/- 0.3% (k=2).

3.3 Outdoor versus Indoor measured results

Indoor and outdoor electrical measurements were compared on six (6) crystalline silicon PV modules. The indoor measurements are based on the average of three (3) IV curves characterized on 07 November 2018 and three (3) IV curves characterized again on 09 November 2018. The outdoor data is based on measurements taken between 21 November 2018 and 29 November 2018, and filtered to include only the intervals of PoA irradiance between 950 W/m2 and 1000 W/m2. The measured values were translated to STC conditions with a simple temperature correction for Vmp and a simple irradiance correction for Imp as per IEC Standard 60891[9]. The results of comparison between outdoor and indoor characterization for current at maximum power (Imp), Voltage at maximum power (Vmp) and maximum peak power (Pmp) is presented in Figure 9.

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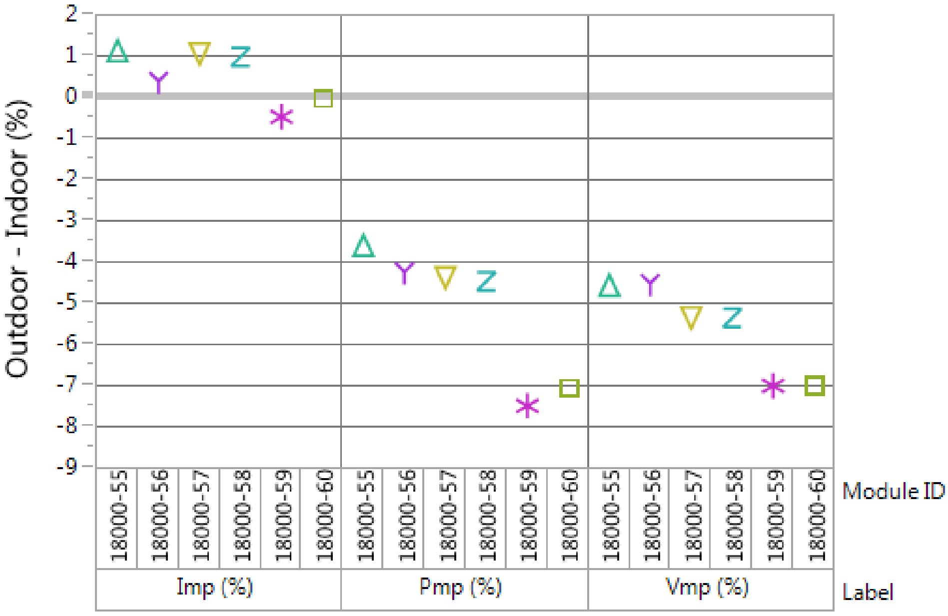

Figure 9: Results of comparison between outdoor and indoor characterizatiom

Power and voltage measurements were roughly 5% lower on the outdoor system compared to the indoor system. More specifically, the outdoor measurements were 0.5% higher for Imp, 5.5% lower for Vmp, and 5% lower for Pmp compared to indoor measurements. The mismatch in Vmp could be due to incorrect temperature measurements, temperature coefficients, resistive losses in the cabling, calibration of the data acquisition system, etc. Investigations are under way to understand the differences between the two systems and the results will be published with the comparison with Thinfilm technology which is also sensitive to spectral mismatch.

4 CONCLUSION

The performance of various PV module technologies is being analysed at the newly established indoor and outdoor solar PV test laboratory at CSIR Pretoria campus. The IV characteristics of PV modules is outdoors on a MPPT tracker coupled with electronic loads connected to outdoor energy yield racking system and indoors on a AAA+ sun simulator with integrated thermal chamber. The DC Performance ratio of various PV technologies subjected under outdoor conditions for a period of one (1) year under outdoor conditions resulted PRs of 0.96 (bi-facial 280 Wp), 0.94 (bi-facial 270 Wp), 0.91 (mono c-Si 275 Wp), 0.92 (mono c-Si 330 Wp), 0.85 (poly c-Si 315 Wp), and 0.87 (thinfilm175 Wp). During the indoor characterization, most of the PV modules measured within ± 3% of the manufacturer rated label specifications. One (1) out of six (6) modules tested for LID showed a measurable degradation in maximum power on the order of 0.6%. Outdoor measurements of six (6) crystalline silicon modules were lower compared to indoor measurements by 5% for both voltage and power. Further investigations are being carried out to understand the difference between the two systems.

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