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The Field Performance of a 558 kWp Ground Mounted Single-Axis PV System in Pretoria, South Africa

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Abstract

According to a recent Green Tech Media (GTM) publication [Moskowitz, 2017], 23% of all ground-mounted photovoltaic (PV) systems are installed on trackers. Trackers are especially beneficial for commercial and utility scale applications, particularly in sunniest parts of the world where the direct normal irradiance (DNI) component of sunlight is relatively high. However, very few studies have been reported on the field performance of single axis tracking systems installed and operated in the Southern Africa region. In this study, therefore, the real-world performance of a 558 kWp ground mounted single-axis PV system at the Council for Scientific and Industrial Research (CSIR) Pretoria campus over a period of 21 months was analyzed. The plant performance was evaluated in terms of the standard performance ratio based on the irradiance in the plane of array and in terms of the performance ratio based on the Global Horizontal Irradiance. It is anticipated that the result of the study will provide useful inputs in assisting system designers, researchers and operators of solar PV plants in South Africa in understanding the optimal operation of solar tracking systems.

1. Introduction

Owing to a wide range of drivers, from technology through social, environmental and business preferences and innovations, the energy systems in many countries around the world are undergoing fundamental and rapid changes (Mitchell, 2016). Over the last 30-40 years the need to decarbonize the electricity sector has led to a significant rise in renewable energy generation, especially from wind and solar, and this has resulted in significant impacts on how energy systems are operated and managed. With this transformation of the energy sector, there is an increase in installations of small-scale technologies. Consequently, the energy systems are becoming more decentralize, with households, businesses, local government and other entities taking back more control over their own energy production. The mainstream renewables, wind and solar photovoltaics (PV), are already independent from government subsidies in many and an increasing number of countries. Solar PV is expected to play a key role in creating sustainable energy future and demonstrated a promising future towards a Terawatt-scale, carbon-free electricity generation by 2050 (Jean et al., 2015).

Renewable energy presents a huge opportunity for South Africa to address the energy challenges. South Africa can drive its own energy transition while leveraging its geographic position, economic and innovation power to “energize” Africa’s sustainably. Technology cost reduction for renewables combined with world-class solar and wind resources in South Africa have made renewables cost competitive to any alternative new-build generation capacity option in the country today. South Africa is one of the first countries where this full new-build cost-competitiveness was achieved. It can therefore be a frontrunner in creating the knowledge-base around cost-efficient designing, building and operating renewables-based energy systems. The Department of Energy of the South African government’s Integrated Resource Plan (IRP) 2010 plans a doubling of power capacity by 2030 (compared to 2010) and a significant diversification of the power mix (Department of Energy, 2010; Department of Energy, 2013). As per that plan, the energy-share of renewables in the domestic electricity generation will increase from less than 1% in 2010 to 9% in 2030. However, the current utility scale projects are all hold pending power purchase agreement finalization from the Department of Energy. A combination of drastically reduced prices of PV systems and significantly increased electricity tariffs in the last five years make residential and commercial PV systems cost competitive to grid power in South Africa today. The life time cost of residential PV systems are between 0.8-0.9 R/kWh (5.7-6.4 €-ct/kWh), while residential electricity tariffs are 1.1-1.4 R/kWh (7.9-10 €-ct/kWh), and alternative new build options (coal or natural gas) cost 0.8-1.1 R/kWh (5.7-7.9 €-ct/kWh) (Bischof-Niemz and Roro, 2015). Therefore, embedded PV generators are now attractive for many electricity customers in South Africa as a supplement to their main electricity supply without subsidies.

The Council for Scientific and Industrial Research (CSIR) intends to create an Energy-Autonomous Campus by supplying energy from the three primary energy sources: solar, wind and biogas from biogenic waste. These projects will stand as a real-world research platform for designing and operating a primarily renewables-based energy system at the lowest possible cost in R/kWh. This platform will be used to demonstrate in a real-world setting of significant size (> 10 MW total installed capacity) how a future energy system that is based on fluctuating and dispatchable renewables can be designed and operated in the most cost-efficient manner.

Performance monitoring of PV systems is useful for many reasons: to verify the performance guarantee, determine associated penalties for under-performance, assess the health of a system, verify the performance model for future installations, etc. (Kurtz et al., 2013). Although several studies have been reported on the performance of single-axis tracking system installed and operated elsewhere, very few studies have been reported for systems installed in South Africa and it is important for the growing South African PV industry to have relevant case studies available in the scientific literature for future reference. In the light of the above, a 558 kWp DC ground mounted single-axis PV system has been installed and operated since October 2015 within the Energy Autonomous Campus project to study the performance and operational behavior of this type of system. The generated electricity from the system is self-consumed as the base-load at the CSIR is higher than the peak output of the PV Plant.

In this work, evaluation of the performance of the system during its first 21 months of operation from October 2015 to June 2017 has been analyzed and presented. The predicted performance of the system during the design of the project using a widely used commercial tool, PVSYST, is compared with the actual performance of the system. The results of the study could be used to provide guidance for future PV investment at other institutions in South Africa and other countries that have similar climatic conditions and economic situations.

1.1. Overview of PV market in South Africa

A variety of mid- and long-term interventions has been implemented by the government of South Africa in order to quickly acquire new capacities while ensuring sustainable development. The South African Department of Energy implemented the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) in order to enable largescale and grid-connected renewable energy systems such as PV to increase the installed capacities by independent power producers (IPP Office 2012, 2013)). A total of 8.1 GW of renewables (mainly from wind and PV) for procurement from IPPs has already been allocated. Out of this, 6.3 GW have reached preferred bidder status, 4.0 GW have financially closed and signed the Power Purchase Agreements with Eskom and 1.5GW of solar PV were operational and fed energy into the grid by Dec 2016 (Figure 1). Due to the rapid decrease in the cost of solar PV systems recently many countries already achieved “grid parity”, the situation whereby it is cheaper to self-generate and consume electricity rather than buy from the electric company. Comparing the results of the REIPPPP of the Department of Energy of the South African government with the costs of alternative new-build options in South Africa (Bischof-Niemz and Roro, 2015), it can be observed that un-subsidized solar PV has reached “new-build” parity where the cost of electricity produced from PV systems over the life time per energy unit is equal to, or less than, the cost of all alternative new-build options. Figure 2 shows the results of the first four Bid Windows of the South Africa’s Department of Energy’s REIPPPP. In Bid Window 4 expedited, which closed in November

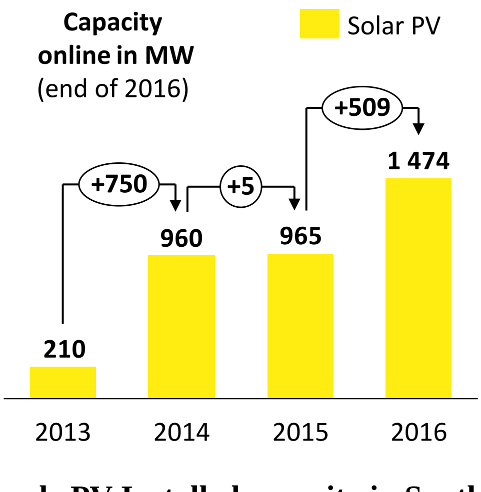

Figure 1: Total utility scale PV Installed capacity in South Africa. From 1 November 2013 to 31 Dec 2016, 1 474 MW of large-scale solar PV were commissioned in South Africa

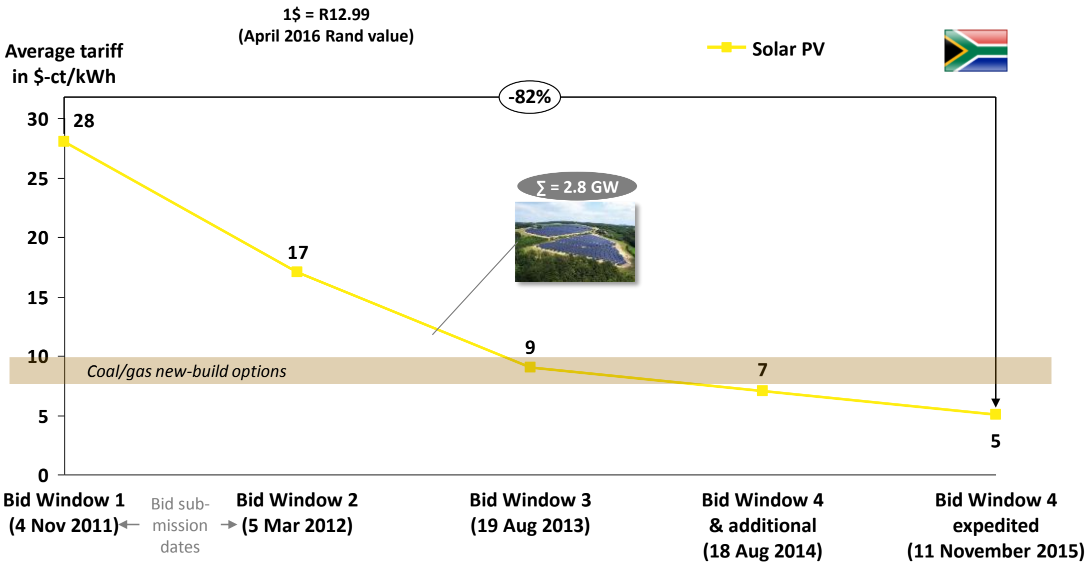

Figure 2: Results of the first four Bid Windows of the South Africa's Department of Energy's procurement programme for RE Independent Power Producers (IPPs)

2015, the average tariff bid for solar PV was $-ct 5/kWh which shows the competitiveness of solar PV in the South African power system. This implies that PV will play an increasing role in the South African power system. It is interesting to note that the costs of PV to the power system in the form of tariffs that have to be paid to the IPPs decreased sharply by more than 82% from Bid Window 1 ($-ct 28/kWh) to Bid Window 4 expedited, in four years ($-ct 5/kWh).

2. System description

The PV system used in this study is located in the CSIR main campus in Pretoria. Construction of the facility started in the beginning of June 2015 and was completed at the end of August 2015. The total peak power installed is 558 kWp DC. The system consists of a total of 1800 BYD 310W polycrystalline silicon PV- modules, 8 SMA 60 kW inverters, and a single-axis solar tracking system pre-programmed to follow the sun's position in the sky. The facility's total module surface areais 3 493 m^2. The PVSYST model provided by the contractor predicted an annual yield of 1183 MWh AC, the equivalent of the energy needed to power over 200 middle-income South African households. The single-axis tracking system was 100 % designed and manufactured in South Africa. The incident solar radiation (in $Wh/m^2/day$) on the PV panel surface was measured by two Kipp & Zonen SMP 10 Pyranometers, and the Global Horizontal Irradiation (GHI) was measured by similar SMP10 pyranometer installed in conjunction with the weather station of the facility. The measurement uncertainty of the irradiance sensor is below 2%. The axis of tracking is horizontal in N-S direction and the modules move from a +55° inclination in the morning towards the East, to a -55° inclination in the evening towards the West. At night the tracking system goes to a resting position which is set at - 20° to avoid accumulation of dust on the modules and keep the modules clean. Table 1 and Figure 3 depict the system specifications and Google Earth satellite image of the PV system, respectively.

Table 1: System specifications of the PV plant

Parameter	value
Installed capacity	558kWp
PV module	BYD310PC6-36
Inverter	SMA Sunny Tripower 60
Transformer	Wegezi 500kVA, 400V/11kV
Mounting assembly	PIA Solar Single axis tracker
Pyranometer	SMP10 (ISO 9060 Secondary standard)
Weather station	Lufft WS600-UMB
Energy meter	Schneider ION7550
Geographical location	-25.74° N, 28.28° E
Site area	0.997 Hectare
PV area	0.8 Hectare

Figure 3: Google Earth image of the single axis tracker and the adjacent 202 kWp DC dual-axis plants at the CSIR Pretoria campus.

3. Approach

In order to analyze the performance of the single-axis system, the tracking gain of the system with respect to the horizontal system was evaluated. The tracking gain is a dimensionless quantity defined by the ratio between global irradiation in module plane to global irradiation and given by:

$$Solar\ gain = \frac{GTI - H_m}{H_m} = \frac{GTI}{H_m} - 1 \quad (1)$$

where:

GTI is the global irradiation in module pane of the tracking system;

H_m is the global irradiation of a horizontal system.

All days were categorized into three types: low, medium, high GHI. Days with high GHI are generally characterized as those with a blue sky from morning to evening, no cloud cover and low aerosols in the air. Days with low GHI are typically overcast with cloud cover throughout the day. Days with medium GHI are in between, with scattered cloud cover or with a sunny periods / cloudy periods changing throughout the day.

The Performance Ratio (PR) is defined as described in the following. The PR is measured in accordance with IEC 61724 (IEC 61724, 1998-04) with the exception that Global Horizontal Irradiation serves as the reference as measured by a calibrated secondary-standard pyranometer, and not Global Inclined Irradiation in module plane.

The PR is:

$$PR = \frac{Y_f}{Y_r} \quad (2)$$

where

$$Y_f = \frac{E}{P_{STC}} \quad (3)$$

where:

Y_f is the specific yield or equivalent nameplate hours of the Facility measured in kWh/kWp;

E is the energy output of the Facility measured in kWh AC;

P_{STC} is Facility rated power measured as the total flash list power of all modules evaluated at standard test conditions (STC) being irradiation of 1 kW/m² , cell temperature of 25°C, and air mass of 1.5. Measured in kWp;

and

$$Y_r = \frac{H_m}{G_{STC}} \tag{4}$$

where:

Y_r is the equivalent hours of STC experienced by the Site;

H_m is the total Global Horizontal Irradiation measured with a secondary standard pyranometer in kWh/m²;

G_{STC} is the reference solar radiation at STC of 1 kW/m²;

The standard PR calculation used in industry takes the solar radiation in module plane as reference. With this method, PR will typically be around 80-85%. In the CSIR approach, values of around 100-110% are the norm. That is because the industry PR calculation considers the PV module efficiency, cable losses, soiling losses, shading losses, inverter losses and transformer losses, but it excludes other losses such as suboptimal orientation of the array and tracker operational issues, which are important to the CSIR for tender purposes (see Figure 4). This will force an EPC contractor to take responsibility for all design issues and optimize better plant performance.

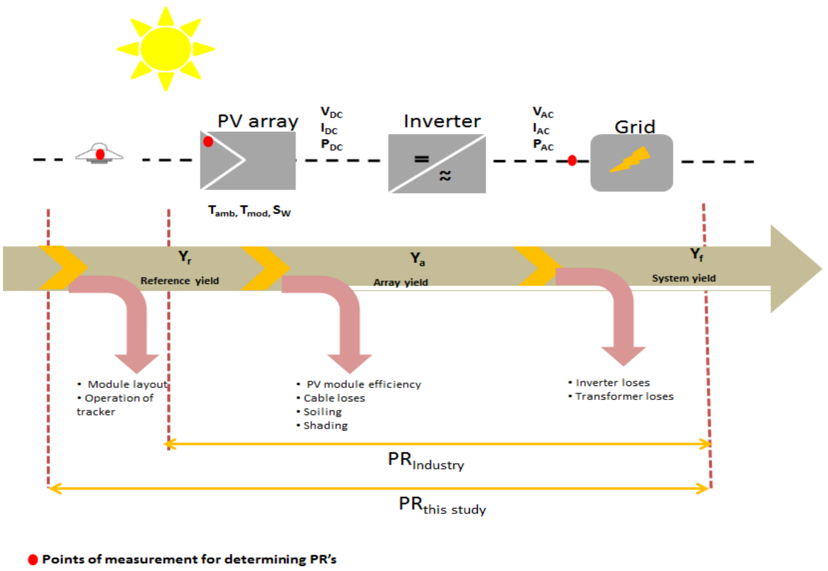

Figure 4: Energy flow diagram for justification of using GHI for PR calculations

4. Results and discussion

Figure 5 shows the comparison of daily insolation of horizontal and tracking (in-plane) configurations in Pretoria, South Africa for days with high, medium and low GHI. As can be seen in the figure, the tracking system receives significantly more insolation on clear sky days, particularly in the morning and afternoon. Clear sky days have a higher DNI component, so the benefits of tracking are greater under those conditions. Tracker gain is less significant during cloudy, overcast conditions when a larger component of the available irradiance is diffuse light. Diffuse light is assumed to be the same on the horizontal plane and the inclined surface because diffuse light comes in from all directions anyway [Demain, 2013]. The GHI irradiance exceeds the POA irradiance only for a few brief periods during cloudy sky days. It is observed that the solar irradiance shows an irregular profile during medium and low GHI day.

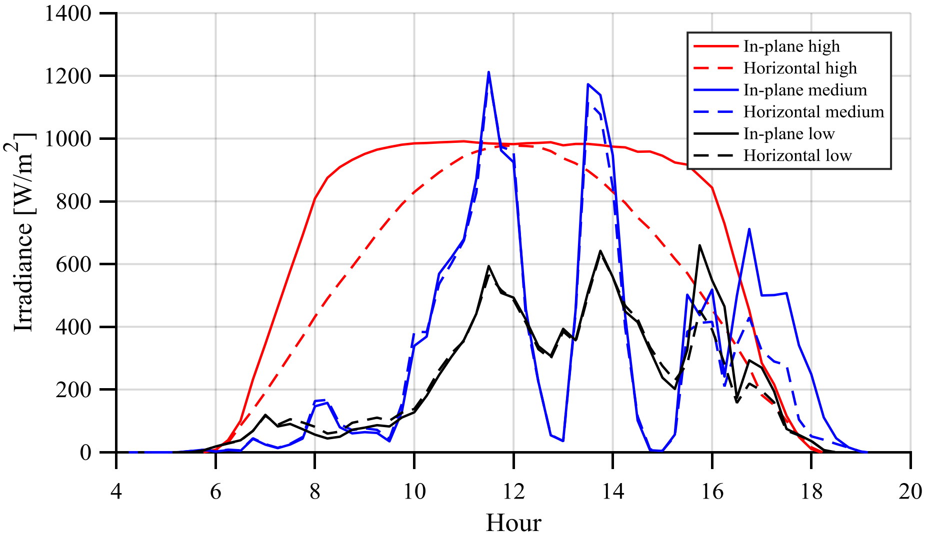

Figure 5: Typical daily insolation of horizontal and tracking configurations in Pretoria, South Africa for days with high, medium and low GHI

The economics of a PV system is dependent on the expected energy output and determines the feasibility of a project for developers and investors. As a common practice by the industry, at the beginning of a project the performance of a system is evaluated using modelling software tools. Meteorological conditions of the site, details of the system and specifications of the main components are used as input parameters to the model. The energy yield is then calculated using the modelling algorithms. PVSYST is one of the most commonly used software in the PV industry. In the following sections, PVYST predicted values were compared with monitored data for the PV plant with respect to the irradiance, electrical generation and performance ratio. The PVYST model used PVGIS input data, and a soiling loss of 1.5% has been assumed. The energy generation is mainly influenced by the solar irradiation, the system layout of the PV power plant and the quality of the system components. Figure 6 shows the monthly estimated and actually measured values of the in-plane insolation. The measured insolation varied between the values of 127 kWh/m^2 in June and 228 kWh/m^2 in December 2016. The lowest values of solar insolation were during the winter season in Pretoria, and the highest values were in summer. It is observed that during the month of February 2017, the measured in-plane insolation was affected by a high number of cloudy days, thus reducing the monthly insolation relative to the predicted insolation based on historical satellite data. Figure 7 shows the electricity generation of the PV system both estimated and actually measured over the monitored period. As expected, the electrical energy produced and insolation shows a good correlation. Monthly electrical generation is higher in summer months because of the increased number of daylight hours. Similarly, the electrical generation during the winter is lowest due to shorter days.

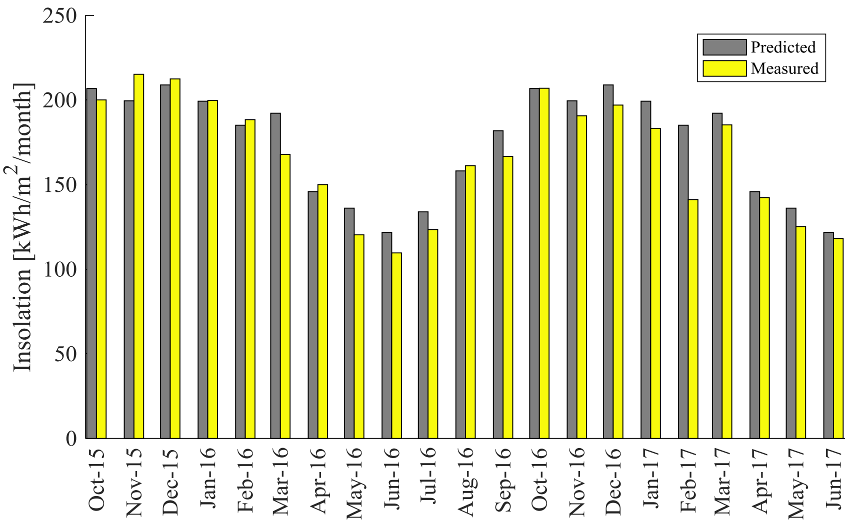

Figure 6: Comparison of monthly predicted and measured values of in-plane insolation

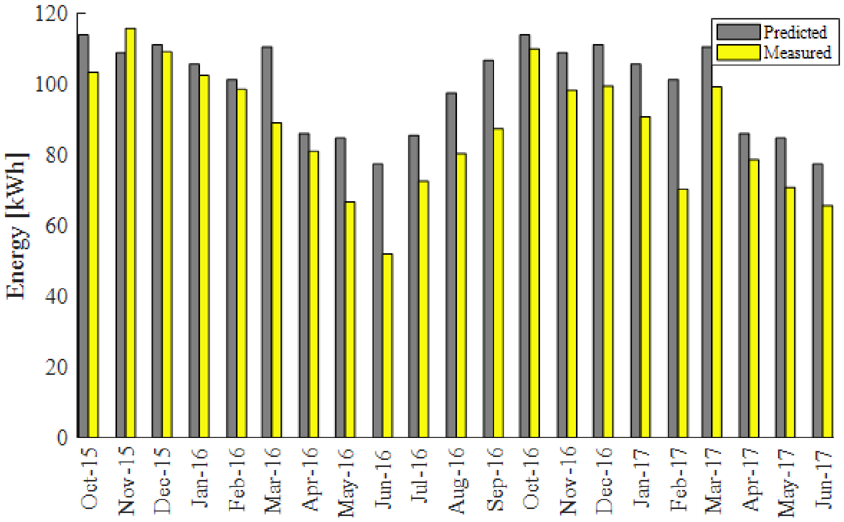

Figure 7: Comparison of monthly predicted and measured values of the electricity production

Comparison between the measured and estimated performance ratios is shown in Figure 8. The relatively low PRs in June and August of 2016 were largely due to scheduled downtime related to improvements in the tracker system and transformer. The monthly variation in predicted PR based on GHI varies approximately 20% over the course of a year, while the variation in predicted PR based on POA varies approximately 8%. The monthly variation in PR would be reduced further with a temperature corrected PR [Dierauf,2013]. The difference between predicted and actual PR based on POA is within 2.5% absolute for the year, whereas the difference between predicted and actual PR based on GHI is off by 10% absolute for the year. The larger bias in the PR based on GHI could be due to several factors: the difference in cosine loss for the GHI sensor relative to the module plane of array, particularly in winter months; the local performance of direct/diffuse separation methods [Gueymard, 2009]; or errors associated with transposition models [Westbrook, 2013]. June and August of 2016 performance was lower than predicted due to planned system downtime for equipment upgrades.

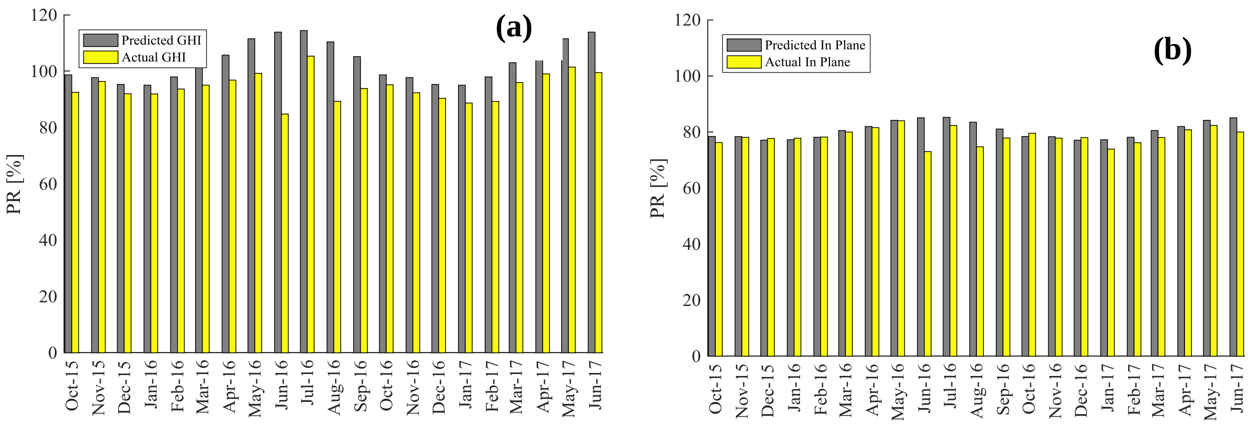

Figure 8: Comparison of monthly estimated and actually measured PR values based on: (a) GHI, and (b) POA

Figure 9 shows the graph of the power generated vs the hourly plane of array irradiance for the single axis tracking system. The r-squared of 98 % means that 98% of the variation in power output can be explained by the plane of array irradiance. In this case, we can assume a causal relationship and not simply a correlation. This highlights the singular importance of irradiance measurements in predicted and actual PV performance.

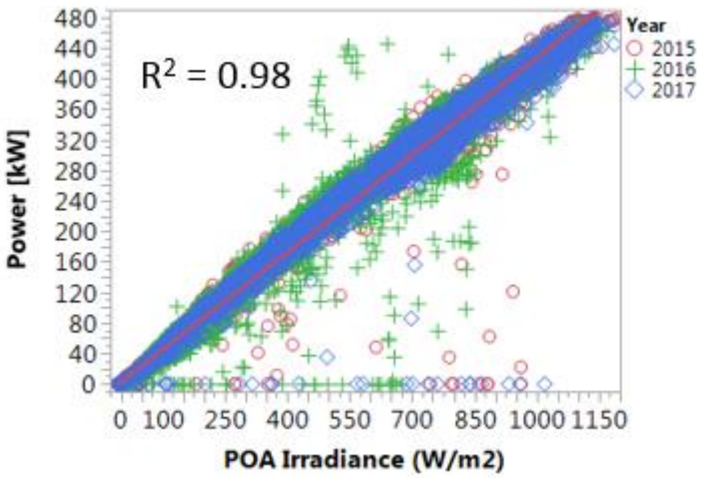

Figure 9: Hourly power generated versus the plane of array irradiance for the PV system used in this study

5. Conclusions and outlook

Field performance of a 558 kWp ground mounted single-axis PV system at the Council for Scientific and Industrial Research (CSIR) Pretoria campus over a period of 21 months was analyzed and reported. The performance monitoring of the PV system indicates that predicted performance based on the international standard PR using POA irradiance over-estimated production by 2.5% for the period. The predicted performance based on the modified PR using GHI irradiance for CSIR tender purposes over-estimated energy production by 10% for the year. Future work will include further investigation of discrepancies between predicted and measured performance ratio, including soiling effects and transposition models on the performance of this system.

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