MODELLING OF SOLAR PHOTOVOLTAIC MODULE PERFORMANCE

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Abstract: Accurate performance models of solar PV systems are critical for accurate estimates of the Levelized Cost of Electricity (LCOE) generated by the systems. Modelling of solar PV systems is widely used for predicting the seasonal, annual, and lifetime electricity generation of a solar PV system which is a key input to estimate the LCOE. Inaccurate models lead to inaccurate estimates of the LCOE which impacts the business case for PV systems. This study compared modelled versus actual DC output across various flat-plate PV technologies installed at the CSIR outdoor test facility (OTF). The Solar Advisor Model (SAM) is used to simulate the predicted DC output based on a typical meteorological year (TMY) weather file downloaded from PVGIS and the expected output based on a weather file created from ground-based resource measurements. The predicted and expected data is compared with actual PV power output measured on a pair of individual modules for each of six (6) PV technologies. During project planning and business case development, often only the satellite data is available. The root mean squared error is calculated for each month and technology. The expected and predicted output of the modules exceeded the actual output by 5-10%, except for one technology. The calculated RMSE between the expected and actual ranges from 9% to 16%.

Keywords: PV technology; Modelling; SAM; Predicted; Expected; Actual; RMSE.

1. Introduction

The increased global installation of solar PV has created an interest in the operations, maintenance and the financial aspects of the technology, which has led to development of models which simulate and analyse solar PV prior installation. The modelling and simulation phase is crucial in predicting the potential energy output for a given location and system design based on different technologies and mounting configurations [1],[2].

Solar energy is one of the most readily accessible renewable energy resources in South Africa with a daily average range of 4.5 to 6.5 kWh/m^2 [3], [4]. **Fig. 1** shows the annual sum of the global horizontal irradiance (GHI) across South Africa with the best resource in the Northern Cape [3]. The solar resource available in South Africa is higher than in many other regions of the world.

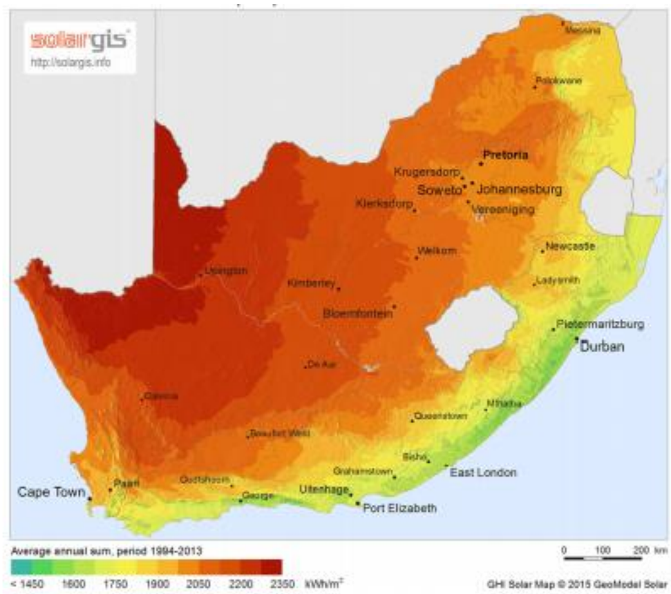

Fig. 1. Distribution of GHI in South Africa [3]

The high solar resource in South Africa means that the LCOE should be amongst the lowest in the world because the higher solar resources result in higher electricity generation for the same system configuration installed elsewhere in the world. This assumes that the prices for construction, operations, and maintenance are equal or less than other regions of the world. **Fig. 2** shows the growing number of solar PV installations in South Africa in recent years [5].

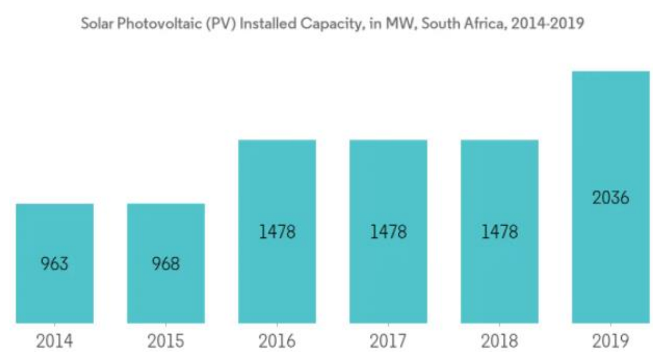

Fig. 2. Number of Solar PV installations in South Africa [5]

The levelized cost of electricity (LCOE) from PV systems in South Africa has also dropped in recent years. According to the Integrated Resource Plan (IRP) 2010, the cost was predicted to be R0.62/ kWh for the year 2021 [6]. **Fig. 3** shows the actual tariffs for utility scale projects developed under the Renewable Energy Independent Power Producers (REIPP) program in recent years. The predicted tariffs for electricity from REIPP projects is also shown out to 2040 [6].

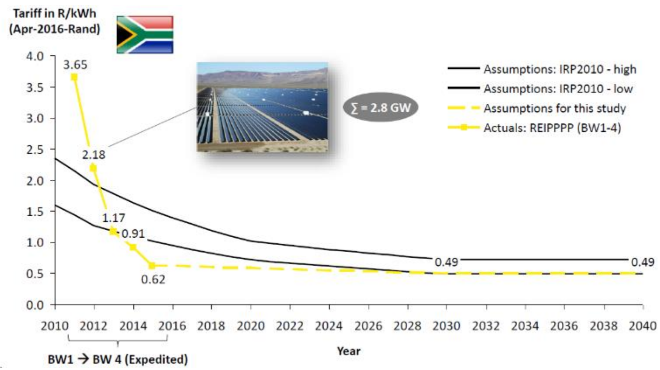

Fig. 3. Actual and predicted future cost of electricity [6]

Solar PV power plants deploy different PV technologies and system mounting configurations. PV technologies include PV modules made from mono crystalline silicon cells (mc-Si), multi or poly crystalline silicon cells (pc-Si), amorphous silicon (a-Si) and thin film (TF) technologies like copper indium di-selenide (CIS), copper indium gallium selenide (CIGS) and cadmium telluride (CdTe) [7]. Mono c-Si technology is proven to the more efficient and is the most used around the world [7]. The performance and lifetime of today's PV technology is typically warrantied for 25 years of operation [5]. Mono c-Si and poly c-Si and thin film (TF) technologies are dominant in the market today. PV system mounting configurations include fixed tilt array, single-axis tracked, and dual-axis tracked. This paper will focus on comparing modelled PV output versus actual PV module performance and assess the model accuracy across various flat-plate PV technologies.

2. CSIR Outdoor test facility

CSIR Energy Centre commissioned an outdoor testing facility (OTF) for PV modules in 2018. The facility supports the renewable energy industry, specifically on PV module quality, design, system modelling, operations, maintenance, and monitoring [8]. As the photovoltaic industry in South Africa is growing, there is a need for high-quality research on solar system design and optimization based in real-world environmental conditions [8]. The OTF makes it possible to study and understand the performance of PV modules under real-world South African climatic conditions.

2.1. Different PV technologies under test

The OTF monitors six (6) pairs of different PV module technologies mounted on a fixed tilt rack facing true north (0 degrees azimuth) at 25 degrees tilt. The OTF is located on a two-story building with a flat rooftop, so shading from nearby trees and building is minimized. **Fig. 4** shows five (5) of the different PV module technologies mounted side-by-side. One identical rack sits nearby with the second module for each of these five (5) technologies. A third rack hold two pairs of bifacial modules and includes a pyranometer on the backside to measure the albedo.

Fig. 4. Different PV module technologies under test at the CSIR Pretoria campus

The PV modules currently under test include Bi-facial PERC 270 Wp, Bi-facial n-type c-Si 280Wp, mono-crystalline 275Wp, mono-crystalline (HIT) 330Wp, poly-crystalline 315Wp and Thinfilm175 Wp modules, as shown in **Table 1**.

Table 1. PV technologies on the CSIR Outdoor test facility commissioned in 2018

PV Technology	Rated Power peak (W)
SolarWorld bifacial n-Type c-Si	280
Yingli bifacial PERC	270
Yingli mono c-Si	275
Panasonic HIT	330
BYD multi c-Si	315
Solar Frontier CIS	175

Each module is individually connected to an electronic load housed inside a cabinet on the roof (**Fig. 5**). The cabinet is configured with the electronic loads, a data logger, an ethernet switch, and an air-conditioner. The electronic loads are capable of maximum power point tracking (MPPT), measuring DC current-voltage (I-V) curves, and connecting to the local AC distribution network to provide AC electricity to the building between measurements. The maximum peak power (Pmp) measurements on the crystalline modules are recorded every one

(1) minute and I-V sweeps every ten (10) minutes. Thin film modules I-V sweeps are carried at every two (2) minutes.

Fig. 5. MPPT system connected to every PV module under test

3. Methodology

The System Advisor Model (SAM) software is used to simulate the "predicted" and "expected" power output of the different PV technologies. The predicted output is based on a SAM model and a weather file downloaded from the PVGIS website. The PVGIS weather data is largely derived from satellite data. The expected output is based on the same SAM model with a weather file recorded from ground-based measurements from the weather station co-located with the PV modules at the OTF. The predicted and expected output is compared with actual PV power output measured at the OTF.

Solar PV output depends on the environmental conditions such as solar irradiance, ambient temperature, spectral distribution, and other climatic parameters. Therefore, the expected output from a simulation using ground-based measurements and the predicted output from a simulation based on PVGIS satellite data should be different. The accuracy of the expected and predicted is summarised by calculating the root mean squared error (RMSE) between the measured and simulated values of the solar PV output power [9], [10]. The RMSE for actual and simulated is calculated using equation 1:

$$\text{RMSE}=\sqrt{\frac{\sum_{i=1}^{N}(P_{Actual}-P_{simulated})^2}{N}} \qquad (1)$$

Where "P_{actual}" is the actual measured energy output, "$P_{simulated}$" is the simulated energy output and "N" is the total number of records for the measurement period. For this analysis, the measurement period is hourly.

3.1. Data pre-processing

The data pre-processing necessary for the analysis is extensive. The work is scripted in python for traceability and consistency. First, the measured datasets are averaged to hourly intervals. Then the hourly datasets are merged on the datetime field so that the measured, expected, and predicted performance data is aligned for each hour for each module. The expected and predicted performance data is exported from the modelling software for each module type. The expected performance data is based on the measured weather data and the predicted performance data is based on the TMY satellite data. Next the weather files are merged with the electrical data to create a final dataset at the hourly interval. The measured data is scaled up to the match the system size modelled in SAM using 4-6 PV modules approximating a one kW system for each technology. For example, the measured power for the BYD module is multiplied by four (4) to match the system size in SAM. The hourly records are then filtered to exclude records if the electrical data or the weather data is missing. Extreme outliers are removed. The final dataset consisting of hourly values for measured performance, modelled performance, and weather is then used to generate the monthly and yearly analysis.

4. Results and analysis

4.1. Performance ratio by PV technology

Fig. 6 shows the annual DC performance ratios of six (6) pairs of PV modules. The performance ratios are calculated using the front side plane of array irradiance only. Albedo measurements are not included when calculating performance ratios of bifacial modules, which explains the higher PR measured on the bifacials. The highest DC PR is measured on the Yingli and SolarWorld bifacial modules, followed by the Panasonic 330, the Solar Frontier 175, the Yingli 275, and lastly the BYD 315. The two types of bifacials (Bifacial_280Wp and Bifacial_270Wp) show an average PR of 95% and 94%, respectively. The Panasonic HIT_330 Wp cells show an average PR of 88%. The Solar Frontier 175 Wp shows an average PR of 85%. The Yingli mono c-Si_275 Wp shows an average of 86%. Finally, the BYD multi c-Si_315 Wp technology measured the lower PR of 80%. All but one module measured a flat or decreasing PR year-over-year.

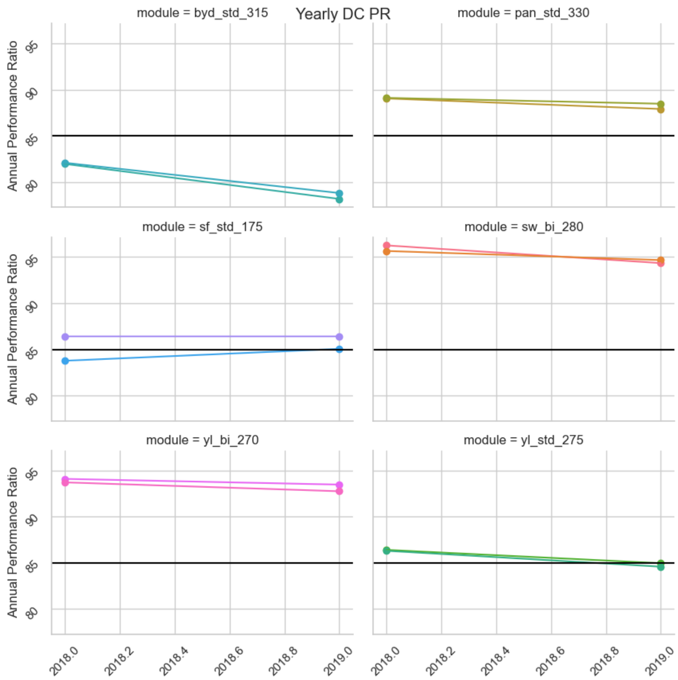

Fig. 6. Annual DC PR of twelve (12) PV modules from six (6) technologies from 2018-2 through 2020-03

Fig. 7 shows the comparison between actual measurements and the simulated DC output (predicted and expected) on a monthly basis for two modules of each technology type. Each subplot shows two trend lines which represent the pair of modules, so there are two trend lines for predicted versus actual and two trendlines for expected versus actual. The predicted monthly output does not track well with the actual monthly output because the weather file from the satellite data does not match the actual weather file. The trendlines for the difference between expected output based on the SAM model and the measured weather file are much flatter by comparison. The trendlines for the monofacial modules tend to show negative deltas indicating the actual measurements are lower than expected and predicted. The trendlines for the bifacial modules tend to show deltas centered near 0 indicating the actual measurements are similar to the expected and predicted. The SAM model for the bifacial modules included the bifacial parameter in the system configuration. The actual DC measurements are lower than the expected for five (5) PV technologies except the Yingli bifacial 270Wp which shows a positive difference (+0.83%), meaning the actual performance exceeded the expected performance. The difference between the actual and expected ranges from +0.8% to -12%.

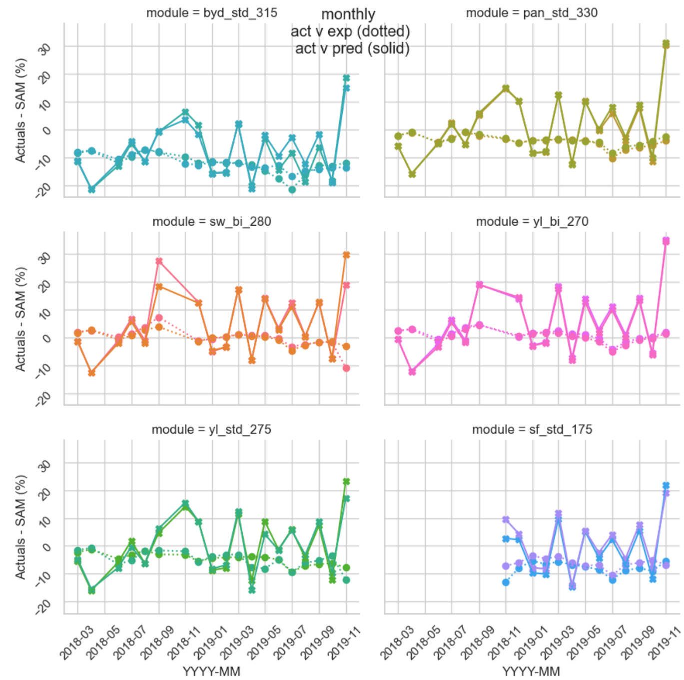

Fig. 7. Month-to-month predicted and expected DC output for two modules from each PV technology in comparison with the actual output from 2018-02 through 2019-10

Fig. 8 shows the monthly RMSE between the expected output and the measured output for each hour of the month. The average monthly RMSE between the simulated DC output (expected) and the actual DC output for the PV technologies ranged from 9% to 16.4%. The average monthly RMSE between the predicted output and the measured output ranged from 100% to 1200% due to the mismatch in the weather files.

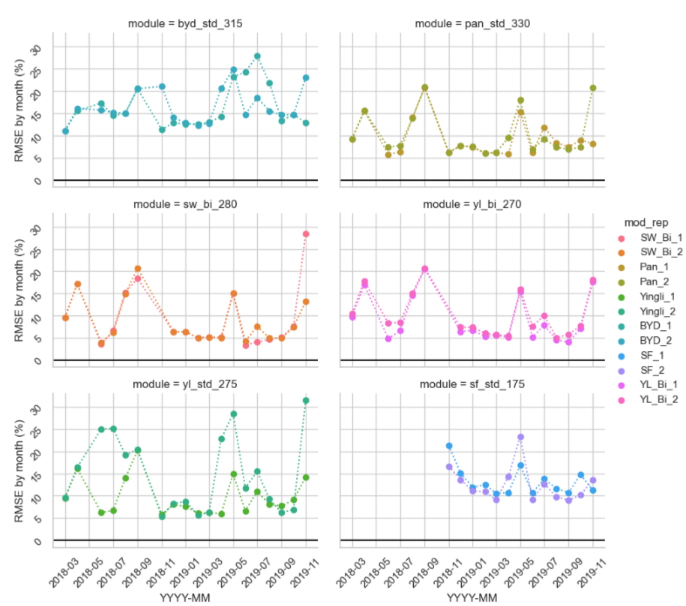

Fig. 8. Monthly RMSE of each pair of PV technologies comparisons between actuals and expected hourly values

Table 2 shows the RMSE for each module type averaged across the monthly values for each module type. The sample size (N) represents the number of monthly values included in the average. For example, N = 36 means that two modules are measured across 18 months and average together.

Table 2 Average of monthly values for actual – expected (%), actual – predicted (%), the RMSE for actual – expected (%), and the DC performance ratio by module.

Row	Module	N	Act-Exp (%)	Act-Pred (%)	RMSE Act-Exp (%)	PR (%)
1	SolarWorld bifacial	36	-0.1	4.7	9.0	95
2	Yingli bifacial	36	0.8	5.5	9.7	93.4
3	Panasonic HIT	38	4.0	1.4	9.8	88.6
4	Solar Frontier	26	-7.1	0.3	12.9	85.5
5	Yingli mono c-Si	38	-4.7	0.1	12.3	85.5
6	BYD multi c-Si	38	-12.0	-7.8	16.4	80.0

5. Conclusion

The annual DC performance ratio of each PV technology is calculated for 2018 and 2019. The performance ratios range from a high of 95% for a bifacial module to a low of 80% for a multi c-Si module. The difference between monthly actual and monthly predicted output averaged over the two years ranged from +5.5% to -7.8% across the different technologies. The difference between monthly actual and monthly expected output averaged across the two years ranged from +0.8% to -12% across the difference technologies. The actual DC measurements are lower than the expected for the technologies measured except for the Yingli bifacial which shows a 1% higher actual output compared to expected. The calculated monthly RMSEs for expected versus actuals averaged across the two years ranged between 9% and 16.4%. The large differences in actual verses expected output indicates an opportunity for improvement with either the simulation, the measurement system, or both.

Future work

We will incorporate the expected and predicted output from PVSyst to quantify any difference between the two simulation programs in the future work. We will also look at the correlation between PV module performance and spectral content.

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