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Analysis of measured and simulated performance data of a 3.2 kWp grid-connected PV system in Port Elizabeth, South Africa

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ABSTRACT

This paper analyzes and compares the actual measured and simulated performance of a 3.2 kWp grid-connected photovoltaic system. The system is located at the Outdoor Research Facility (34.01°S, 25.67°E) at the Nelson Mandela Metropolitan University (NMMU), South Africa. The system consists of 14 poly crystalline silicon modules connected in two strings of 7 series-connected modules, each facing north at a fixed tilt of 34°. The data presented in this study were measured in the year 2013, where the system supplied a total of 5757 kW h to the local electric utility grid. The performance of the system was simulated using PVsyst software using measured and Meteonorm derived climate data sets (solar radiation, ambient temperature and wind speed). The comparison between measured and simulated energy yield are discussed. Although, both simulation results were similar, better comparison between measured and predicted monthly energy yield is observed with simulation performed using measured weather data at the site. The measured performance ratio in the present study is 84% which is slightly higher than values of 74%, 81.5%, 67.4%, 70% and 64.5% reported is Khatkar-Kalan (India), Dublin (Ireland), Crete (Greece), Karnataka (India) and Malaga (Spain), respectively.

1. Introduction

Electricity generation using photovoltaic (PV) systems is clean, reliable and has the potential to play a significant role in mitigating CO_2 emissions. Considering the potential for cost reduction of PV systems and increase in their efficiency, it is envisaged that PV will become one of the major future sources of electricity generation. Global PV electricity generating technology has shown an impressive annual growth with an annual total of 39 GW new installations registered in 2013 [1]. The global PV installed capacity at end of 2013 was estimated at more than 139 GW [1].

Knowledge on the energy yield performance of a PV system in a given location is important in designing a suitable system for a particular application. A number of commercial software packages are available for predicting PV system performance at a location of interest. These software packages use meteorological databases, PV module and inverter data to predict the energy yield of PV systems. In this study, PVsyst simulation software [2] is used to simulate the performance parameters for a grid-connected system. PVsyst is a system software package for the study, sizing and data analysis of complete PV systems. It deals with grid-connected, stand-alone, pumping and DC-grid PV systems, and includes extensive meteo and PV systems components databases, as well as general solar energy tools.

In this paper, both the measured and simulated performance of a grid-connected PV system were carefully analyzed. Data collected in the year 2013 are analyzed and actual measured performance parameters are compared with parameters simulated using PVsyst software under different resource data sets. Simulations were performed using measured climate data and also with data generated by Meteonorm [3]. Some of the performance parameters analyzed include: annual energy generated, final yield, reference yield, and performance ratio. A comparison between measured wind speed and Meteonorm derived wind speed values are also discussed. The results obtained provide an insight on the performance of solar PV system at Port Elizabeth, South Africa and the validity of using measured and derived meteorological data. Finally a comparison is made of results from this study with those obtained from other studies internationally.

2. Description of the PV system

The PV system is installed on a rack structure mounted on the ground with a clearance distance of one meter, at the Outdoor Research Facility (34.0°S, 25.7°E) at the Nelson Mandela Metropolitan University (NMMU) campus in Port Elizabeth, South Africa. The system consists of 14 multi-crystalline silicon modules connected in two strings of 7 series-connected modules. The

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modules were oriented facing north at a fixed tilt of 34° and azimuth angle of 0°. The PV modules with power rating of 230 W each were used and the modules specifications are provided in Table 1.

A single inverter is used to convert DC to AC and the output AC is fed directly to the Nelson Mandela Bay electricity grid. The inverter has a maximum DC input power of 3.2 kW and maximum AC power output of 3 kW.

Both the in-plane global solar radiation and the wind speed data were measured at the PV array installation shown in Fig. 1. The ambient temperature was measured using k-type thermocouple. The output AC power was recorded and averaged after every 5-min interval. For this system, the DC parameters of the PV system were not recorded and therefore the DC/AC conversion efficiency for the inverter used in this study is not analyzed.

3. System analysis

3.1. Performance parameters

The performance of the 3.2 kWp grid-connected system is analyzed using the performance parameters developed by International Energy Agency (IEA) [4]. These performance parameters include: final yield (Y_F), reference yield (Y_R), performance ratio (PR), capacity factor (CF) and energy loss (L).

The final yield is the total energy generated by the system for a defined period (day, month, and year). The annual final yield is given by the expression [5,6]:

$$Y_{F,a} = \frac{E_{\mathrm{AC},a}}{P_{\mathrm{PV,rated}}} \quad (1)$$

where $E_{\mathrm{AC},a}$ is total annual AC energy output (kW h) and $P_{\mathrm{PV,rated}}$ is nominal power of the installed PV array at standard test conditions (STC). The corresponding values for the monthly and daily final yield are obtained using the ratio of the monthly and daily AC energy output (kW h) to the nominal PV array power, respectively. The final yield is a representative figure that enables comparison of similar PV systems in a specific geographic region.

The reference yield (Y_R) is the ratio of the total in-plane solar radiation H_t (kW h/m^2) to and the array reference irradiance (G_o = 1 kW/m^2) [6,7]

$$Y_R = \frac{H_t\ (\mathrm{kW\ h/m^2})}{G_o(\mathrm{kW/m^2})} \quad (2)$$

The performance ratio (PR) represents the ratio of energy fed to the grid (final yield) to the energy that the system could have produced had it operated at its rated conditions (STC) of 1 kW/m^2 (reference yield). It represents the fraction of energy actually available after deducting energy losses [6]. Performance ratio is expressed as:

$$\mathrm{PR} = Y_F / Y_R \quad (3)$$

The annual capacity factor (CF) is defined as the ratio of the actual annual energy output to the amount of energy the PV system would generate if it operated at full rated power for 24 h a day for a year and is expressed as [6]:

Table 1
PV modules specifications.

PV module	Specifications
Type of material	Poly crystalline
Maximum power (Pmax)	230 Wp
Open circuit voltage (Voc)	36.9 V
Short circuit current (Isc)	8.25 A
Maximum power point voltage (Vmax)	29.8 V
Maximum power point current (Imax)	7.72 A
Power specifications at STC	1000 W/m^2 @25 °C, AM 1.5

Fig. 1. View of the 3.2 kWp grid-connected PV system installed at the Outdoor Research Facility at NMMU.

$$\mathrm{CF} = \frac{Y_{F,a}}{24 * 365} = \frac{\mathrm{PR} * Y_R}{8760} \quad (4)$$

Finally, the total energy loss (L) from this system is obtained from the difference between the reference yield and the final yield as:

$$L = Y_R - Y_F \quad (5)$$

The final yield and performance ratio are investigated both experimentally and theoretically and their results compared. The simulations are performed using measured and Meteonorm derived climate data sets.

3.2. PV array thermal losses

The thermal behavior of a PV system has strong influence on the electrical parameter. It is determined from the energy balance between the ambient temperature and the back of module temperature (T_{BOM}) rising due to the incident irradiance, by the expression [2]:

$$T_{\mathrm{BOM}} = \frac{\alpha G(1-\eta)}{U} + T_{\mathrm{amb}} \quad (6)$$

where G is the incident irradiance, α is the absorbance of the PV modules, η is the module efficiency and U is the thermal loss factor given by

$$U = U_c + U_v v \quad (7)$$

where v is the wind velocity and U_c is the thermal loss constant and U_v is the wind speed constant. The values for the U_c and U_v used in this study were 20 W/m^2 K and Uv = 6 W/m^2 K/m/s, respectively [2]. Eqs. (6) and (7) shows the effect of wind speed on the back- of module (BOM) temperature. A low wind speed value leads an increase in the BOM temperature, and vice versa. A rise in the BOM temperature result into a reduction in power production due to increase in PV energy loss.

4. Results and discussion

4.1. Estimation of soling distributions

The influence of soiling on the energy production of the PV array has been estimated using precipitation values derived from Meteonorm and local weather knowledge. The variation of soiling and precipitation levels is shown in Fig. 2. The monthly soiling loss values were estimated at less than 1% since the system was installed in a nature reserve with relatively less soiling sources.

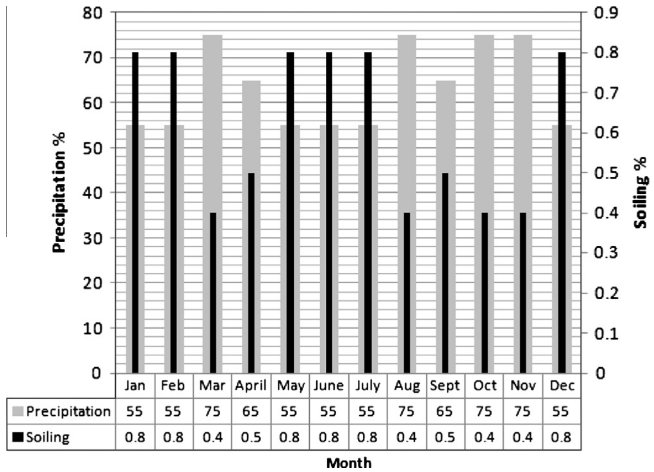

Fig. 2. Monthly relation between precipitation and estimated soiling level at Port Elizabeth.

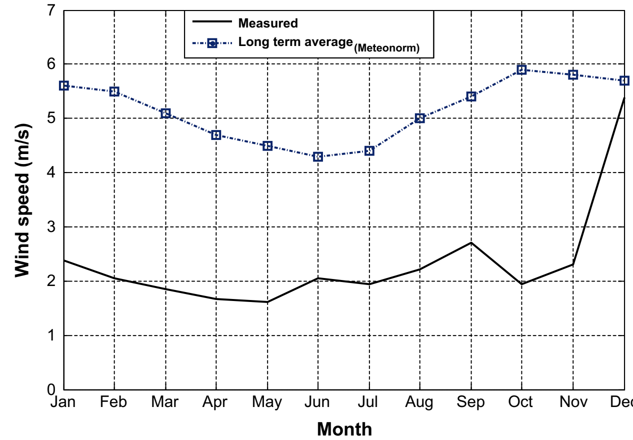

Fig. 4. Measured and long term monthly average of daily wind speed (m/s).

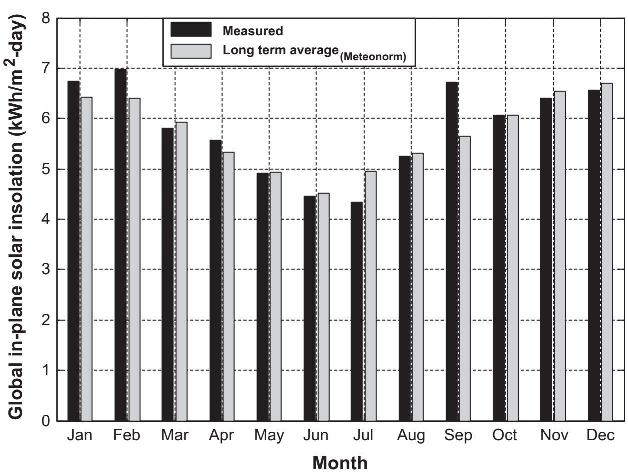

Fig. 3. Monthly average daily total in-plane solar insolation.

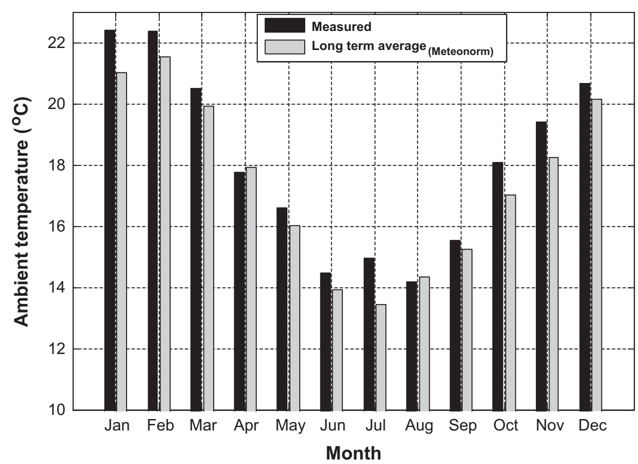

Fig. 5. Monthly comparison between measured and long-term average daily ambient temperature.

When these estimated monthly soiling loss values were used in the simulation together with measured climate data sets, a good approximation to the experimentally determined monthly and yearly energy yields as seen from Fig. 6.

4.2. Weather data

The weather data used as inputs into PVsyst software to simulate the performance parameters of a 3.2 kWp system are presented and compared in this section

Fig. 3 shows comparison between measured (2013) and long term (1985–2005) average values derived from Meteonorm for the monthly average daily total in-plane solar radiation on the PV system. The measured and Meteonorm derived monthly average daily solar radiation showed small deviations except for the months of January, February and September where the measured values exceeded the Meteonorm data. An unusually high solar irradiance was measured in September at the beginning of spring, whereas the measured solar irradiance for the winter month of July was noticeably smaller than the Meteonorm derived data. The annual total of the measured and Meteonorm derived values for in-plane solar radiation were 2119 kW h/m^2 and 2047 kW h/m^2, respectively.

The monthly variations in the measured and Meteonorm derived long term average values for wind speed are shown in Fig. 4. The position of the anemometer on a PV rack behind a building resulted in a measured monthly average daily wind speed that is consistently and significantly lower compared to the Meteonorm data. The Meteonorm derived wind speed data may not correspond to the exact wind speed value measured in a particular month but

Table 2
Simulated energy values for a 3.2 kWp grid-connected system for whole year.

Simulation parameters	SIM_{meas}	SIM_{meteo}	Unit
Global incident in collector plane	2116.3	2047	kW h/m^2
IAM loss factor, near Shadings and soiling loss	3.1	3.3	%
Effective collector area	23	23	m^2
Effective irradiance on collector plane	47.15	45.517	MW h
PV efficiency at STC	13.72		%
Array nominal energy at STC	6603	6374	kW h
PV loss due to: (Irradiance level, Light induced degradation, Module array mismatch and Ohmic wiring)	3.3	3.4	%
PV loss due to temperature	6.7	3.3	%
Module quality (gain)	1.5	1.5	%
Array virtual energy at MPP	6050	6044	kW h
Inverter loss	4.8	4.4	%
Energy injected into grid	5754	5771	kW h
Measured injected into grid in 2013	5757		kW h

Table 3
Comparison of the performance of different ground mounted, grid-connected PV systems.

Location of PV technology	Installed capacity	Monitoring duration	Annual average final yield (kW h/kWp/day)	Performance ratio	Refs.
Khatkar-Kalan, India	190 kWp	2011	2.23	74	[7]
Dublin, Ireland	1.72 kWp	Nov. 2008–Oct. 2009	2.4	81.5	[5]
Eastern Cape, South Africa	3.22 kWp	2013	4.9	84	Present study
Crete, Greece	171.36 kWp	2007	3.66	67.4	[8]
Karnataka State, India	3.056 MWp	2011	3.75	70	[9]
Malaga, Spain	2 kWp	1997	3.67	64.5	[10]
Trieste, Italy	2.99 kWp	14th Oct. 2011 to 15th Oct. 2012	3.83	89.1	[11]
	11.7 kWp		3.49	82.7	

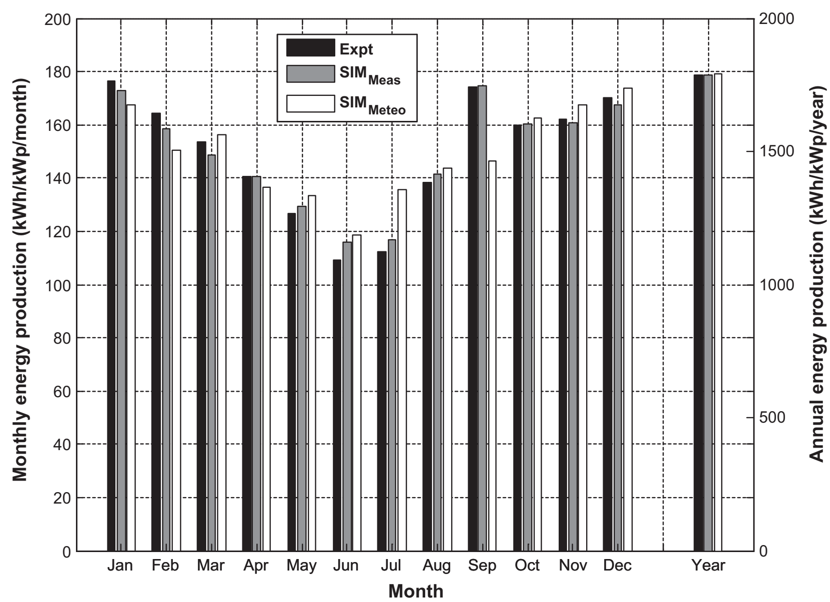

Fig. 6. Comparison between measured and simulated monthly/yearly energy yield.

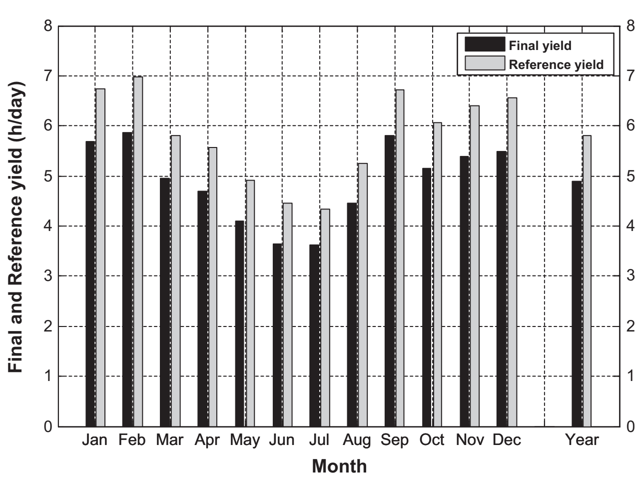

Fig. 7. Plots of final and reference energy yield measured over the year 2013.

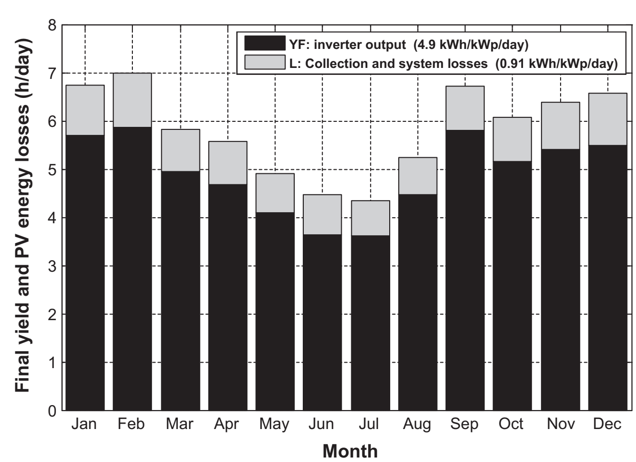

Fig. 8. Monthly averaged daily final yield and energy loss.

it gives a representative figure since it is based on long-term averages [3]. The relatively low values of the measured wind speed were mainly due to the shielding from the principal South/Southwest wind directions of the anemometer behind a building as seen from Fig. 1. From Eqs. (6) and (7), the low wind speed measured data results in increased solar cell temperatures thereby reducing the energy production from the PV system. The effect of the low measured wind speed is also depicted in the measured ambient temperature as seen in Fig. 5, being slightly higher than the Meteonorm derived values.

4.3. Performance parameters

Table 3 provides detailed simulation results performed using measured and Meteonorm derived climate data sets. It shows the

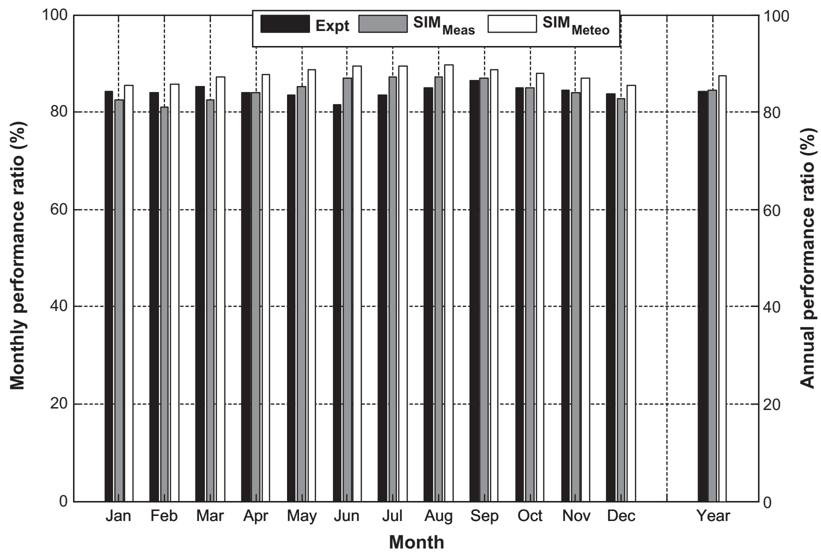

Fig. 9. Comparison between actual measured and simulated PR for a 3.2 kWp grid connected system.

input and output energy for the system, plus the associated energy losses.

The measured annual total energy generated by the PV system in 2013 is 5757 kW h/year as measured by the inverter while the predicted values as seen from Table 2 are 5754, 5771 kW h/year for simulation performed using measured and Meteonorm derived weather variables, respectively. Although both simulation results are similar, better comparison between measured monthly energy outputs is observed with simulation performed using on-site measured climate data set.

Fig. 6 shows plots comparing measured monthly/annual energy yield with simulated energy yield. The measured final yield is 1788 kW h/kWp/year while predicted values were 1787 and 1792 kW h/kWp/year for SIM_{meas} and SIM_{meteo}, respectively.

Fig. 7 displays the measured reference yield and final yield for each month and for the year 2013. The daily final yield from monthly averaged data varied between 3.6 and 5.9 kW h/kWp in June and February and while the daily reference yield varied between 4.3 and 7.0 h in July and February, respectively. The daily final and reference yield from yearly averaged data were 4.9 h and 5.8 h, respectively. As noted earlier, an unusually high solar irradiance occurred in the month of September with an increase of 7% of energy production in 2013 compared to energy produced by the same system in September 2012.

As the seen from Fig. 8, the measured averaged daily energy loss for the year 2013 is 0.91 kW h/kWp/day. The comparison between the measured and predicted performance ratios are given in Fig. 9.

The simulated performance ratio obtained using measured climate data sets is relatively lower than that obtained using Meteonorm derived parameters. This is due to high energy losses arising from increase module temperature due to low wind speed as shown in Table 2. The annual simulated performance ratios are 84.4% and 87.5% for SIM_{meas} and SIM_{meteo}, respectively. The actual measured monthly performance ratio ranges from 81% to 86% with an annual mean value of 84.3%.

5. Comparison of PV system performances with other installations elsewhere

The normalized energy yield (kW h/kWp/day) enable comparisons between different PV installations since it disregard the effect of installation size. Table 3 shows some performance parameters for different grid connected PV systems reported elsewhere. Comparison of results from this study with those obtained from other studies internationally revealed that the PV system's annual specific energy yield of 4.9 kW h/kWp/day is higher than other reported annual yield studies. The measured annual average capacity factor got from this study was 20.41% which is higher than 15.26% value reported in Crete [8].

Since this study was done in a relatively lower insolation region of South Africa, it could be concluded that South Africa is generally a good region for deployment of PV systems and better PV performance is expected in the Northern Cape region with high solar insolation [12].

6. Conclusions

A 3.2 kWp grid connected PV system installed at the Nelson Mandela Metropolitan University, Port Elizabeth, South Africa was monitored in 2013 and its monthly and annual performance parameters were evaluated and compared with simulated parameters. Both simulation results gave good approximation to measured energy output but better comparison between measured monthly energy outputs is obtained with simulation results performed using measured solar parameters. This implies that Meteonorm derived parameters can be used to estimate the performance of PV systems within Eastern Cape region with a reasonable accuracy but the simulation accuracy can be improved by using on-site solar resource measurements.

The measured annual performance ratio of 84.3% indicates the vast solar potential in the Eastern Cape region of Africa that is suitable for solar power generation. A comparison of the annual final yield and performance ratio of this system with other systems installed at different locations worldwide shows the final yield of 4.9 kW h/kWp/day higher than those reported in Ireland, Greece, India, Spain and Italy. The measured performance ratio 84.3% is higher than those reported elsewhere except for a 2.99 kWp grid-connected PV system in Italy which gave a performance ratio of 89.1%.

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