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PERFORMANCE ANALYSIS OF 8 KW GRID-TIED SOLAR PHOTOVOLTAIC POWER PLANT IN DURBAN, SOUTH AFRICA

Abayomi Aduragba Adebiyi
Department of Electrical Power Engineering, Durban University of Technology, Durban, South Africa

Ian Joseph Lazarus
Department of Physics, Durban University of Technology, Durban, South Africa

Akshay Kumar Saha
School of Engineering, Howard College, University of KwaZulu-Natal, Durban, South Africa

Evans Eshiemogie Ojo
Department of Electrical Power Engineering, Durban University of Technology, Durban, South Africa

ABSTRACT

Results obtained from monitoring an outdoor experimental 8 kW distribution grid-tied solar photovoltaic (SPV) system installed at Energy Technology Station known as KwaZulu-Natal Industrial Energy Efficient Training and Resource Centre (IEETRC) of Durban University of Technology, South Africa is presented in this study. The study was carried out to investigate and compare the system performance with similar installations in a few selected countries. Data were collected between January 2018 and December 2018 and computational analysis was completed with the aid of Simulink and MS-Excel. The evaluated monthly average daily and annual performance parameters of the SPV system – array yield, reference yield, final yield, system efficiency, inverter efficiency, capacity factor, and performance ratio – were discussed in term with the International Electrotechnical Commission (IEC) standard. A comparison of this study to other studies conducted in Dublin, Morocco, India, and Spain shows that this study final yield and performance ratio of 4.93 kWh/kWp/day and 87.1% is greater than what is reported in the extant literature.

Key words: Performance ratio, solar photovoltaic (SPV), annual energy generated, final yield, array yield, efficiency, capacity factor

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1. INTRODUCTION

The global goal to reduce climate change and environmental pollution caused by fossil fuel based energy sources have prompted the deployment of renewable energy resources like solar energy, wind power, hydro-power and biomass. The solar photovoltaic (SPV) and wind power generation have received more attention globally [1]. The SPV system could be installed in remote location (stand-alone) or integrated to the grid (grid-tied) [2]. Grid-tied SPV system uses the direct conversion of solar energy into electricity that is fed directly into the grid without battery storage. Like many other renewable energy alternatives, this option is generally carbon-free and as such does not emit greenhouse gasses during operation, as global warming and climate change are mostly caused by releasing carbon dioxide and other greenhouse gasses into the atmosphere. The solar irradiation level in South Africa is among the highest globally, with an average of 2500 hours of solar irradiation per annum ranging between 4.5 to 6.5 kWh/m^2 per day [3]. The country different regions are well exposed to solar irradiation as shown in figure 1. The annual average 24-hour global solar irradiation for South Africa is about 220 W/m^2 compare to 150 W/m^2 in the USA and relatively 100 W/m^2 for Europe and United Kingdom [4] [5].

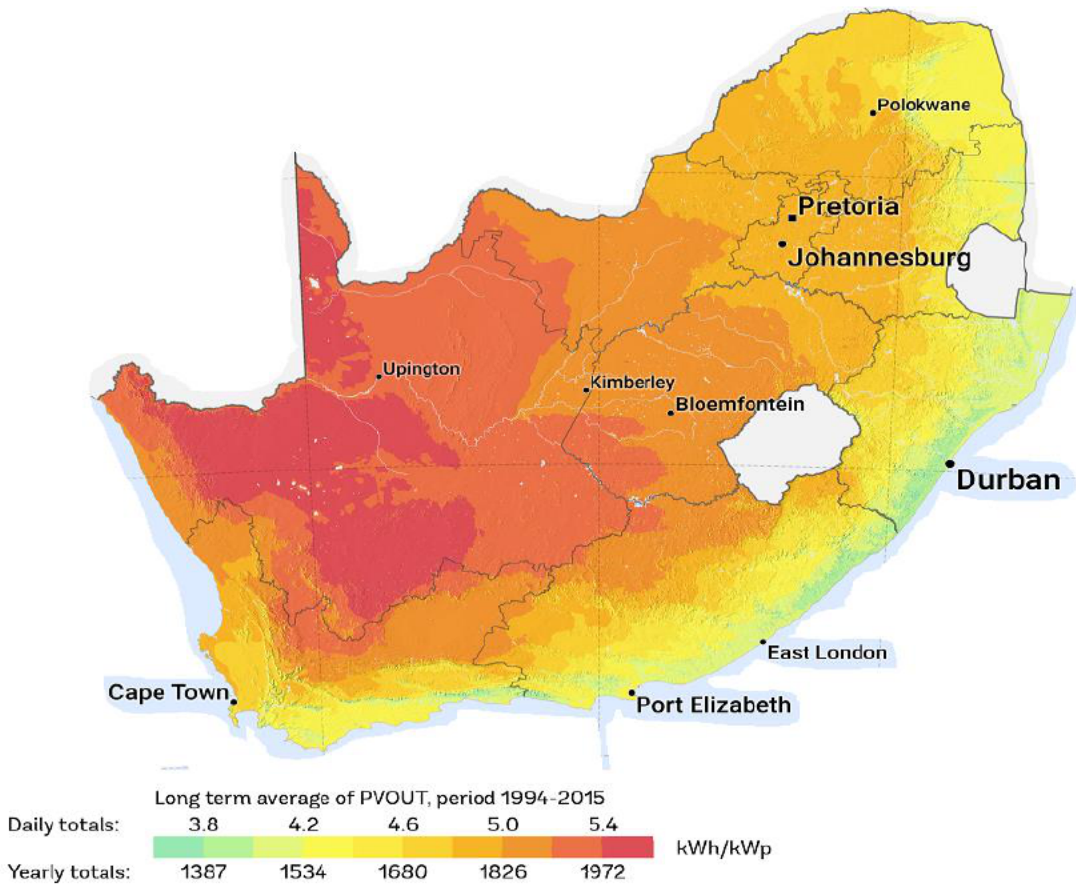

Figure 1 South Africa Global Horizontal Irradiation

Due to rapidly rising electricity costs and growing awareness of global warming issues, in 2010, the South Africa government developed the Renewable Energy Source (RES) legal framework - Integrated Resource Plan (IRP), which deals with the concept of RES development. The IRP 2010 conceptualize programs to achieve 20 percent of renewable energy supply by 2030 [6]. Durban is the largest city on South Africa's East Coast province of KwaZulu-Natal (KZN), despite its high population density and energy consumption, no comprehensive study has been carried out to classify Durban's solar resource and grid-tied SPV system performance [7]. The basic requirement of any SPV power plant is to have an accurate estimate of its outdoor operating conditions performance. The information provided by a SPV module manufacturer is based on standard test condition (STC) of 1000 W/m^2, 25°C and 1.5 Air Mass panel temperature. Due to the variation of environmental parameters, the results of STC may not agree with the actual operating conditions. Therefore, accurate performance data are required to install a SPV system at a specific location. Crystalline silicon and thin film SPV panels are the basic types of commercially available SPV panels [8].

Solar energy is playing a major role in the global energy mix due to improved technology and reduction in SPV system components costs leading to an increase in the global cumulative installed capacity from 1.4 GW in 2000 to approximately 408.7 GW in 2017 [5]. Table 1 shows the cumulative installed SPV capacity in selected countries in 2017, China has the highest capacity at 131 Gigawatt installed capacity. SPV systems performance analysis is the best way to determine the potential for producing solar power in an area. The objective of this study is to provide research results from a studied grid-tied SPV system at Industrial Energy Efficient Training and Resource Centre (IEETRC) of the Durban University of Technology, South Africa on the production of energy. It is believed that the results presented in this study will provide useful information on the actual performance of grid-tied SPV systems in this country to policymakers and interested individuals.

Table 1. SPV system installed capacity in 2017

Country	SPV installed capacity (GW)
Australia	7.2
Belgium	3.8
Canada	2.9
China	131
Germany	1.75
India	24.9
Japan	49.1
South Africa	0.15
South Korea	5.7
Spain	5.6
USA	51.8

2. SYSTEM DESCRIPTION AND METHODOLOGY

Radiometric data for an outdoor experimental 8kW distribution grid-tied SPV system was recorded at the Energy Technology Station known as KwaZulu-Natal Industrial Energy Efficient Training and Resource Centre (IEETRC) of the Durban University of Technology, South Africa (-29.8579 N; 31.0276 E). The equipment housed at the IEETRC includes SOLYS2 sun tracker, pyranometer, SPV panels, DC/AC inverter, and temperature monitoring sensors. The pyranometer has a hihgh accuracy rate and a resolution of 1W/m^2. The SOLYS2 operate from AC or 24 VDC power. The DC power operating temperature varies between -20°C to 50°C and could it could reach -40°C on AC power using the standard internal heater. The pyranometer measures solar irradiation from all directions. SPV panels convert the solar irradiation into DC energy that is fed into an inverter unit which converts the DC energy to AC to feed the grid. In order to optimize the collection of input solar irradiation, all the SPV panels were mounted on the rooftop at a fixed 30° tilt angle. At the SPV array installation shown in Figure 2, both the global horizontal solar irradiation and the wind speed data were logged and a computational analysis was completed with the aid of MS-Excel package. The evaluated monthly average daily and annual performance parameters of the SPV system – final yield, reference yield, array yield, system efficiency, inverter efficiency, capacity factor, and performance ratio – were discussed in term with the IEC standard. Comparative analysis of this system with other studies conducted in Dublin, Morocco, India, and Spain was conducted.

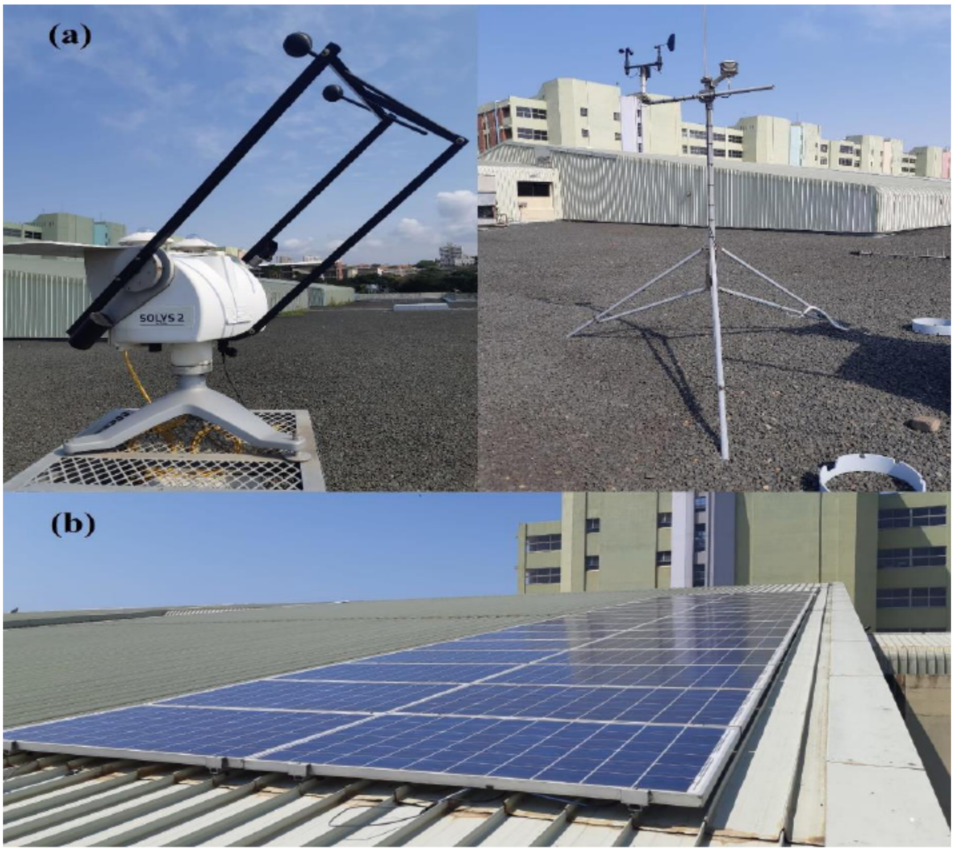

Figure 2 (a) Meteorological station installed at DUT *(IEETRC)* (b) Installed SPV array.

The SPV system consists of 30 poly-crystalline silicon panels linked in two string of 15 series-connected panels. The power rating of each panel is 220 Watt, the panels' specification is provided in Table 2.

Table 2. Heckert Solar NeMo P (54) 220 specification

P_{Max}	220Wp
Short-circuit current	8.62A
Open-cuitcuit voltage	33.77V
Maximum Power Point Voltage	27.54V
Maximum Power Point Current	8.08.A
Maximum System Voltage VDC	1000V
Reverse current feed IR	15,0A
Efficiency	15.0%

A three phase Sunny Tripower 8000TL inverter was installed to convert the SPV array DC output to AC which was fed directly to the grid. It rated efficiency is 98.3% and peak AC power of 8000W. The inverter technical data is presented in Table 3.

Table 3 Sunny Tripower 8000TL Data [9]

Input (DC)	
Maximum generator power	13500 Wp
Maximum input voltage	1000 V
MPP voltage range	330 V to 800 V
Minimum input voltage	150 V / 188 V
Maximum input current	15 A
Maximum short-circuit current input	2 / A:2
Output (AC)	
Rated power (at 230 V, 50 Hz)	8000 W
Maximum AC apparent power	8000 VA
Nominal AC voltage	230 / 400 V
AC grid frequency	50 Hz ±5 Hz
Rated power frequency	50 Hz / 230 V
Maximum output current	11.6 A
Power Factor at rated current	0.8 leading to 0.8 lagging
Efficiency	98%

3. MONITORED INPUT RESULTS

The monthly average daily horizontal solar radiation and the ambient temperature are presented in figure 2. This indicates the expected seasonal trend for the coastal region of Durban, with the daily solar irradiation diffuse monthly average falling over the winter season and then rising towards the summer season. The monthly average daily irradiance varies from the least value of 110 kWh/m^2 in June to 190 kWh/m^2 in January. In January, February and March, maximum monthly average daily temperatures of 26°C, 25°C and 24℃ were recorded respectively while the lowest monthly average daily temperatures being 15°C and 16°C were recorded in June and July respectively.

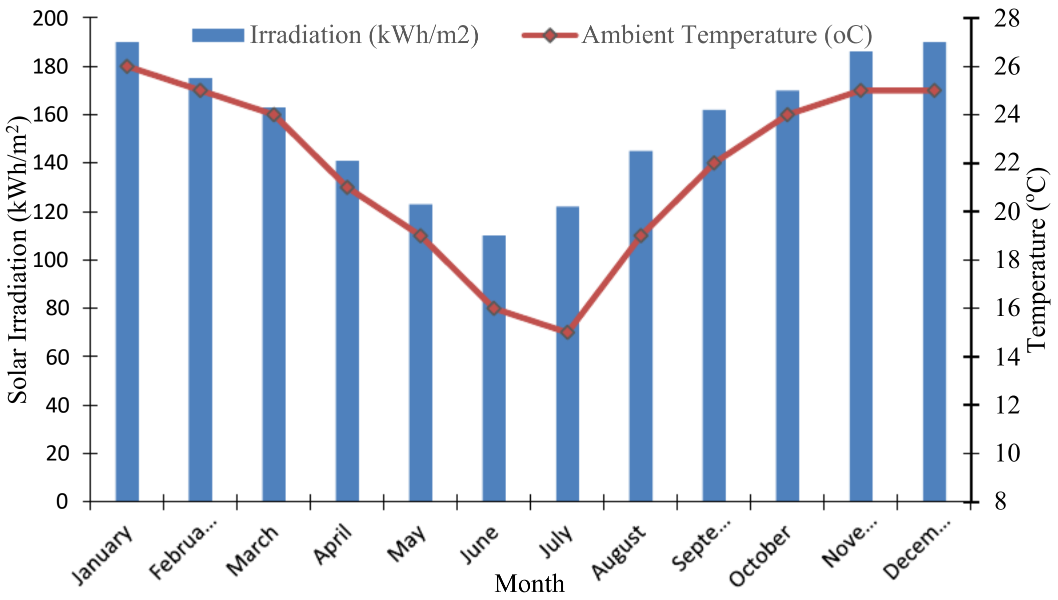

Figure 3 Monthly average global horizontal solar irradiation and temperature.

As shown in figure 3, the measured monthly average daily ambient temperature (T_a) and module temperature (T_m) vary throughout the monitored period due to the generation of thermal losses obviously occurring on power generation. The temperature of the SPV module was always found higher than the ambient temperature. It was observed that the ambient temperature varies from 15.3°C to 29.4°C over the measured period. Figures 4 and 5 represent the recorded data file for a cloudy and sunny day.

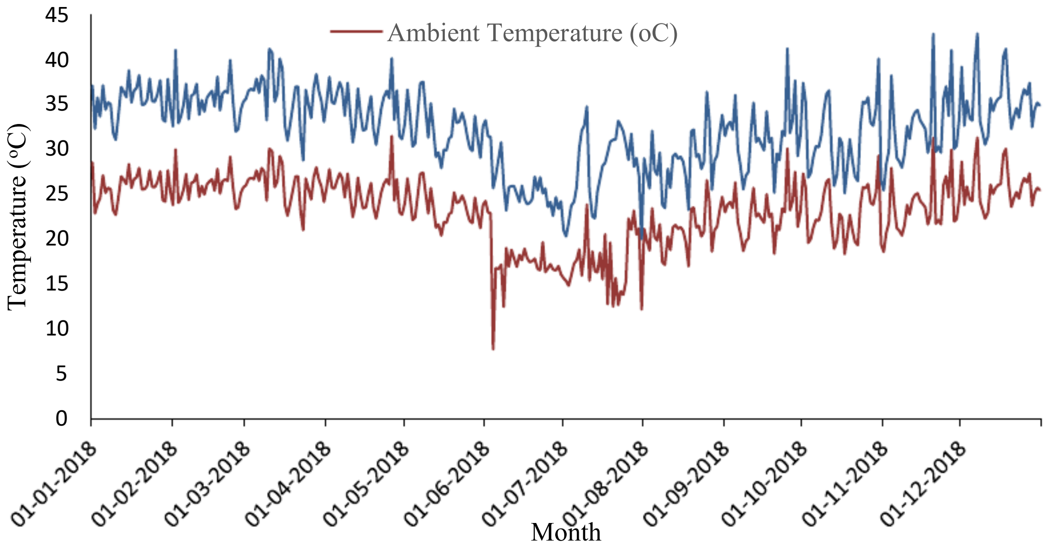

Figure 4 Monthly average daily ambient temperature (Ta) and module temperature (Tm).

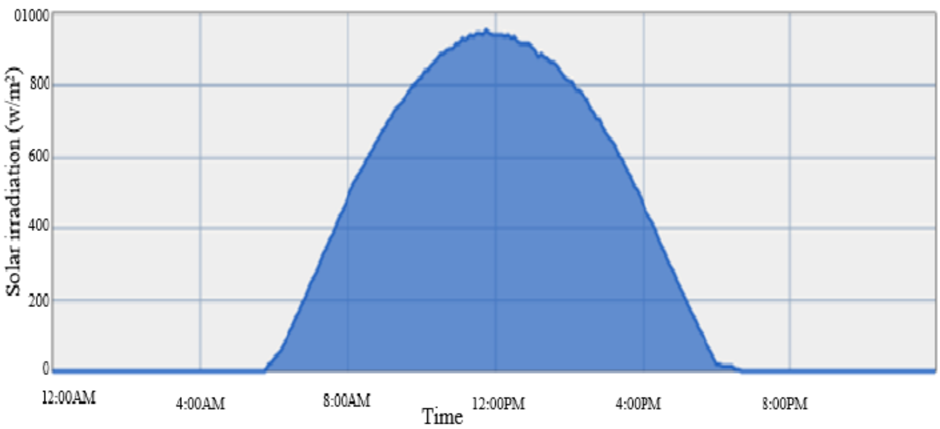

Figure 5 Irradiance plots for a sunny day in summer

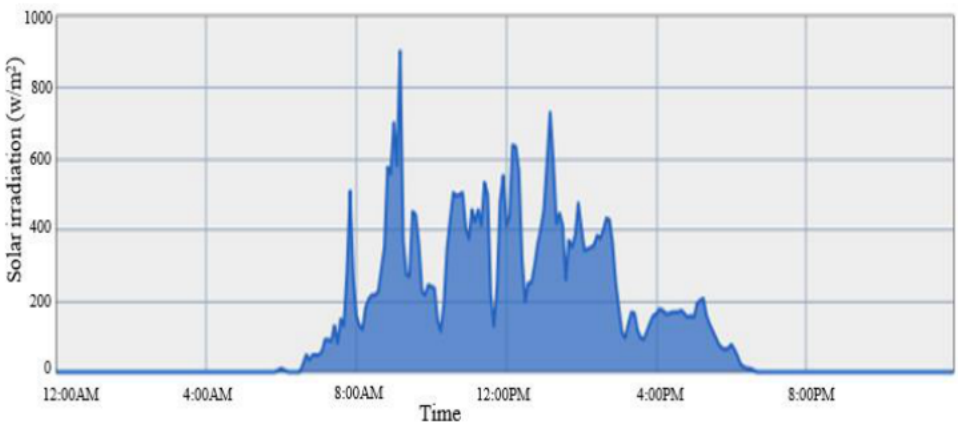

Figure 6 Irradiance plots for a cloudy day in winter.

4. SYSTEM ANALYSIS

In this paper, performance parameters established by the International Energy Agency (IEA) Photovoltaic Power Systems Programme Task 2 and defined in International Electrotechnical Commission (IEC) 61724-1:2017 were considered [10]. Field data of the 8 kW rooftop grid-tied SPV power plant was analyzed for the plant annual energy generated, final yield, reference yield, array yield, system loss, system efficiency, inverter efficiency, capacity factor unit, and performance ratio in the year 2018 and the actual measured and calculated performance parameters were compared with results obtained from extant literature.

4.1. Annual Energy Generated

The annual output energy generated by the SPV system is defined by the amount of DC and AC power generated over a given time period. The total energy produced hourly, daily and monthly can be evaluated by the equations (1) to (4) [11].

4.1.1. Energy generated by the SPV array (E_{dc})

The SPV array total daily and monthly DC energy output generated is given by:

$$E_{dc,d} = \sum_{t=1}^{t=T_{rp}} V_{dc} * I_{dc} * T_r \quad (1)$$

$$E_{dc,m} = \sum_{d=1}^{N} E_{dc,d} \quad (2)$$

Where E_{dc} = Array DC energy output,

T_r = the recording time interval,

T_{rp} = the recording period and

N = number of days plant operate in a month

4.1.2. Energy output fed to the grid (E_{ac})

The total daily and monthly AC energy output $E_{AC,m}$ (kW/h) measured across the inverter output terminal are defined as follow [12]:

$$E_{ac,d} = \sum_{t=1}^{t=T_{rp}} V_{ac} * I_{ac} * T_r \quad (3)$$

$$E_{ac,m} = \sum_{d=1}^{N} E_{ac,d} \quad (4)$$

Where E_{ac} = AC energy output to grid,

N = number of days plant operate in a month.

4.2. Array Yield (Y_A)

The array yield is the time it takes for the SPV system to operate at the E_{dc} generating nominal power [13]. It is, therefore, the ratio of the daily or monthly average DC energy generated by the SPV system to the nominal SPV system power. The daily and monthly array yield is obtained using Equations (5) and (6), as shown below.

$$Y_{A,d} = \frac{E_{DC,d}}{P_{PV,rated}} \quad (5)$$

$$Y_{A,m} = \frac{1}{N}\sum_{d=1}^{N} Y_{A,d} \quad (6)$$

Where $Y_{A,d}$ = Daily array yield,

$Y_{A,m}$ = Monthly array yield,

N = number of days plant operate in a month.

4.3. Final Yield (Y_F)

The final yield is the ratio of system's daily, monthly or annual total AC energy output (kWh) to the installed SPV array's rated power at 1 kW/m^2 solar irradiation and 25°C module temperature. It is a performance index that allows similar SPV systems comparison in a specific geographic area. It depends on the mounting type, the inclination of a roof, and also the plant location [14]. The final annual yield is given as:

$$Y_{F,d} = \frac{E_{AC,d}}{P_{PV,rated}} \quad (7)$$

$$Y_{F,m} = \frac{1}{N}\sum_{d=1}^{N} E_{AC,d} \quad (8)$$

Where $Y_{F,d}$ = Daily final yield,

$Y_{A,m}$ = Monthly average daily final yield,

N = number of days plant operate in a month.

4.4. Reference Yield (Y_R)

The reference yield is the ratio of total daily horizontal solar irradiance H_t (kW/m^2) to the reference solar irradiation ($G_{i\text{-}ref}$). This yield represents the number of peak sun-hour per day (h/d) expressed in equation (9).

$$Y_R = \frac{H_t(kWh/m^2)}{G_{i-ref}\left(\frac{kW}{m^2} - day\right)} \quad (9)$$

Where $G_{i\text{-}ref}$ = 1 kW/m^2

4.5. Efficiency

The grid-tied SPV system components efficiencies are SPV panel efficiency (η_{SPV}), inverter efficiency (η_{inv}) and the general system efficiency (η_{sys}) [15]. Basically, these efficiencies can be calculated instantaneously, per hour, per day, monthly and annually. The SPV panel efficiency is based on the DC energy output while the system efficiency is a function of the AC power output. The instantaneous SPV panel efficiency is calculated as:

$$\eta_{PV} = \frac{E_{DC}}{(H_t * A_a)} \tag{9}$$

where E_{DC} = SPV array output energy,

H_t = Global solar irradiation,

A_a = Area of SPV array.

The monthly average SPV array efficiency is determined by Equation (10):

$$\eta_{PV} = \frac{E_{DC,d}}{(H_t * A_a)} * 100\% \tag{10}$$

where $E_{DC,d}$ = Total daily DC output energy.

4.5.1. Inverter efficiency

The instantaneous inverter efficiency (η_{inv}) is given below:

$$\eta_{inv} = \frac{E_{AC}}{E_{DC}} \tag{11}$$

where E_{AC} = Output energy of the inverter and E_{DC} = Energy at the input of the inverter.

The monthly inverter efficiency ($\eta_{inv,m}$) considered over the data recording period is calculated as follows:

$$\eta_{inv,m} = \frac{E_{AC,d}}{E_{DC,d}} * 100\% \tag{12}$$

4.5.2. System efficiency (ηsys)

The efficiency of the entire SPV system is defined as the ratio of the energy generated ($E_{AC,d}$) to the global horizontal solar irradiation (H_t) at the SPV array area (A_a). By applying equation (13) the system efficiency was calculated.

$$\eta_{sys} = \frac{E_{AC,d}}{(H_t * A_a)} * 100\% \tag{13}$$

4.6. Performance Ratio

The performance ratio (PR) is the quality factor of a SPV plant that shows the magnitude of the plant output energy in percent. The performance ratio defines the relationship between the SPV plant's final yield and the reference yield. It is the quantity of energy fed into the grid after deduction of energy losses and operational energy consumption [13].

$$PR = Y_F - Y_R \tag{14}$$

4.7. Capacity Factor

The capacity factor (CF) of a SPV power plant is the ratio of the annual AC energy output to the AC energy generated by the SPV system when it operates at full rated power ($P_{SPV,\ rated}$) throughout the same period. The SPV system's annual capacity factor is determined by the following equation:

$$CF = \frac{E_{AC}}{P_{PV,rated} * 8{,}760} \tag{15}$$

The performance parameters mentioned above provide the overall system performance in terms of energy production, meteorological resource, and overall system loss effect.

5. RESULTS AND DISCUSSION

The output energy generated by the SPV system was measured at the DC/AC inverter at 5 minutes intervals. Figure 7 shows the total monthly energy generated by the SPV system, which ranged from 220.6 kWh in June to 415.7 kWh in January during the monitored period. The SPV system generated a total annual energy yield of 16.178 MWh as measured by the inverter.

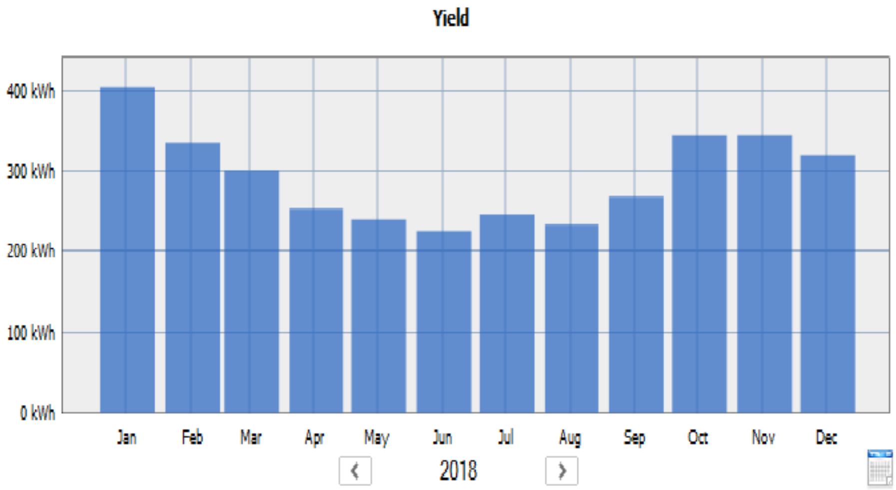

Figure 7 Total monthly energy generated by the SPV system.

The SPV system monthly average daily final yield, reference yield, and array yield monitored within January to December 2018 is presented in figure 8. The minimum and maximum values recorded vary between June and January from 3.59–5.84 kWh/kWp/day, 4.15–7.02 kWh/kWp/day, and 3.33–6.2 kWh/kWp/day for the final, reference and array yields respectively. This is attributed to the fact that the minimum average horizontal solar irradiation was received in June at 3.68 kWh/m^2/day and maximum 6.13 kWh/m^2/day in January with an annual average value of 4.52 kWh/m^2/day. From figure 8, it can be seen that the system yields relate in variation over the monitored period. It is found that they are directly proportional to the horizontal solar irradiation

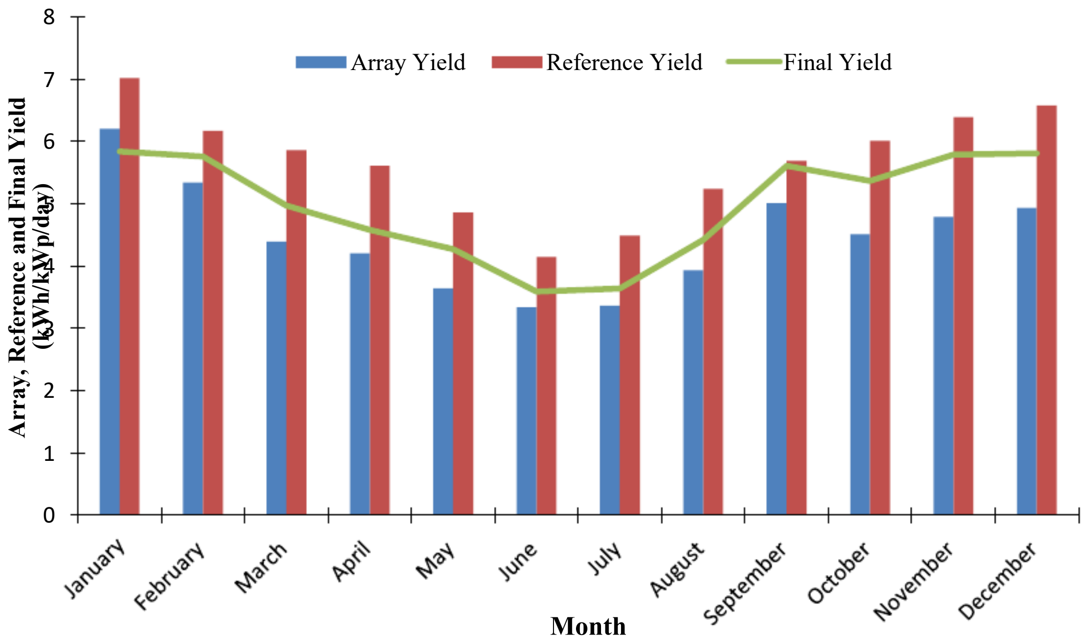

Figure 8 Monthly average daily SPV system's array yield, reference yield and final yield over the monitored period.

Figure 9 shows variations in the monthly average daily performance ratio and the capacity factor of the SPV system over the period monitored. The performance ratio ranged from 81.4% in July to 93.7% in February and the average annual performance ratio was 87.1%. The monthly average daily capacity factor ranged from 17.1 percent in December to 20.1 percent in June with a 10.1 percent annual average. The capacity factor varies depending on the final yield that usually vary alongside the generated AC energy. The maximum value of the average monthly capacity factor was 19.97 percent in January, where the final yield is also high at 5.84 (kWh/kW_p/day) and the lowest value was 16.57 percent in June, where the final yield was comparatively low at 3.59 (kWh / kWp / day).

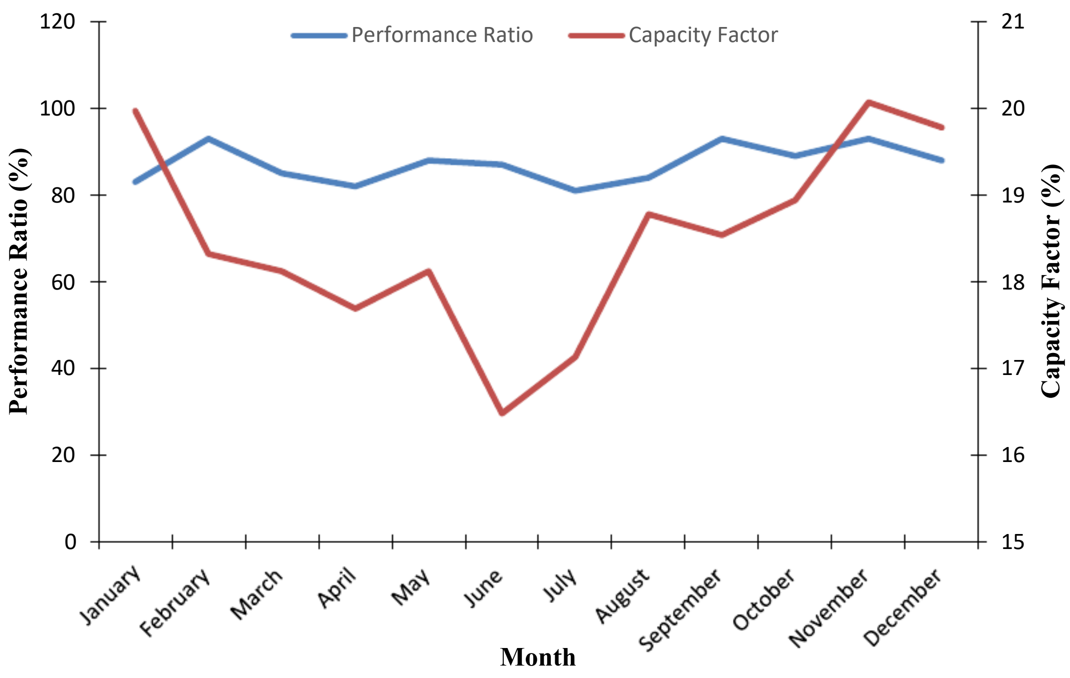

Figure 9 Monthly average daily performance ratio and capacity factor.

The annual average of the SPV panel efficiency, system efficiency, and inverter efficiency were found to be 13.15%, 12.06% and 96.33% respectively as illustrated in figure 10. The seasonal monthly average inverter efficiency for the summer and winter season was found to be 96.74% and 95.76% as a result of the average horizontal solar irradiation which was 6.16 kWh/m^2/day for summer and 5.37 kWh/m^2/day for winter respectively.

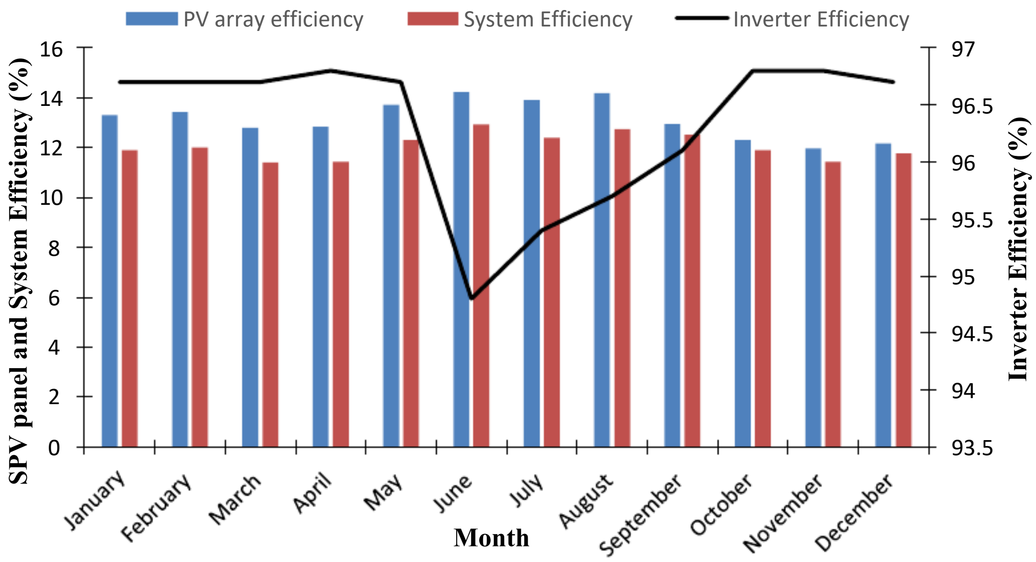

Figure 10. Monthly daily average array efficiency, system efficiency, and inverter efficiency

6. PERFORMANCE COMPARISON

Comparative analysis of performance parameters of this study with some of the existing grid-tied SPV system reported in literature is presented in Table 4. The annual daily final yield are: Dublin, Ireland, 2.47 kWh/kWp/day; Tangier, Morocco, 4.45 kWh/kWp/day; Eastern India, 3.67 kWh/kWp/day; Bhopal, India, 3.36 kWh/kWp/day; Jaén, Spain, 3.26 kWh/kWp/day and 4.93 kWh/kWp/day for this study which is greater than those reported in Morocco, India, Northern Ireland and Spain. Similarly, this study obtained the highest performance ratio.

Table 4. Performance comparison of different grid-tied SPV system in literature.

Location	Installed Capacity (kW)	Energy Output (kWh/kW$_p$)	Final Yield (kW h/ kWp-day)	SPV Panel Efficiency (%)	System Efficiency (%)	Inverter Efficiency (%)	PR (%)	References
Dublin, Ireland	1.72	885.1	2.47	14.9	12.6	89.2	81.5	[13]
Durban, South Africa	**8**	**16178**	**4.93**	**13.2**	**12.1**	**96.3**	**87.1**	**Present study**
Düzce Province Turkey	2.64	3141.15	-	11.36	11.4	90.7	81	[16]
Tangier, Morocco	5	6411.3	4.45	12.38	11.99	96.7	79	[17]
Eastern India	11.2	-	3.67	13.42	-	89.83	78	[18]
Bhopal, India	110	163100	3.36	-	-	-	71.6	[19]
Jaén, Spain	200	892.1	3.26	8.9	7.8	88.1	62.7	[20]

7. CONCLUSIONS

An 8 kW grid-tied SPV system installed in Industrial Energy Efficient Training and Resource Centre (IEETRC) of Durban University of Technology, South Africa was monitored between January 2018 and December 2018 and its performance parameters were evaluated on a monthly and annual basis. Data recorded during the monitored period showed that with increased solar irradiation, the output power of the SPV plant increases linearly. The annual average final yield and reference yield were 4.93 kWh/kWp/day and 5.59 kWh/kWp/day while the annual average of the SPV panel efficiency, system efficiency, and inverter efficiency was found to be 13.15%, 12.06% and 96.33% respectively The performance ratio ranged from 81.4% in July to 93.7% in February and the average annual Performance Ratio was 87.1%. Performance ratio is a key indicator of SPV system effectiveness therefore, performance ratio above 80% is always desired. The evaluated annual performance ratio obtained confirms the vast solar potential suitable for solar power generation in KwaZulu-Natal Province of South Africa. A comparison of this study to other studies conducted in Dublin, Morocco, India, and Spain shows that this study final yield and performance ratio of 4.93 kWh/kWp/day and 87.1% is higher than what is reported in the extant literature.

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