PERFORMANCE MONITORING OF DIFFERENT MODULE TECHNOLOGIES AND DESIGN CONFIGURATIONS OF PV SYSTEMS IN SOUTH AFRICA

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ABSTRACT: Performance monitoring of different module technologies and system configurations of Photovoltaic (PV) systems in South Africa is rare which result in few reports being published based on field results of PV systems installed and operated in South Africa. The goal of this work was to analyse and report on the performance of PV systems by evaluating the energy output of various PV system configurations and module technologies in the South African (southern hemisphere) climatic conditions. To achieve this, a 400 kWp PV Solar plant has been installed and monitored since January 2015 at the Eskom Research and Innovation Centre (ERIC) in Rosherville, Gauteng. The plant consists of polycrystalline silicon (c-Si) and copper indium gallium selenide (CIGS) thin film technologies. The plant comprises of two 25° fixed north facing inclination, north-south single axis tracking and two 10° fixed shed orientation each for both module technologies. The analysis was conducted for a period of one year. The evaluation is achieved by studying the operation of PV plant under different weather conditions and the impact of different configurations and technologies on systems overall output, and performance ratio was calculated. The CIGS module technology performed better than c-Si technology in both fixed north facing and tracking configurations. The study provides an insight to identify the optimal configuration and suitable PV technology for deployment of solar photovoltaic system in South Africa. The monitored data and operating experience of PV system can be applied for future projects.
Keywords: PV system, Performance, Analysis

1 INTRODUCTION

Amongst the various renewable energy sources, Photovoltaic (PV) technologies that convert sunlight directly to electricity are becoming a major force reshaping the future energy mix, especially in countries with high solar radiation such as South Africa. South Africa has a solar irradiation ranging from 1,700 kWh/m2 to 2,300 kWh/m2, ranking among the top countries in the world in terms of expected solar energy production. With the South African government's new drive to promote and implement renewable energy projects, the solar photovoltaic market is one of the industries with the highest growth potential in the country.

Solar PV is starting to play a substantial role in electricity generation in many countries as rapidly falling costs have made unsubsidised solar PV-generated electricity cost-competitive with fossil fuels in an increasing number of locations around the world. The cost of PV systems declined by about 75% in just less than 10 years making solar PV a cost competitive, reliable and sustainable electricity source in many countries [1]. It is estimated that at least 200 TWh, or 200 billion kWh of electricity will be produced in 2015 by PV systems installed and commissioned until January 2015 globally. This represents about 1% of the total electricity demand of the planet, though some countries have reached rapidly significant percentages. From 2000 to 2014, global solar PV deployment has increased from 0.26GW to 178 GW [2] with an annual growth rate of more than 45%, due to both technological innovations that have reduced manufacturing costs by 100 times and various government incentives for consumers and producers.

Moreover, a growing number of countries including South Africa (through its Renewable Energy Independent Power Procurement Programme (REIPPPP)) have established renewable energy targets for clean energy for a number of reasons including: to diversify energy mix, achieve low carbon emissions, and to reduce environmental issues associated with fossil energy resources such as greenhouse gas emissions and climate change. Many sources of renewable energy such as wind power, hydropower, solar energy, biomass, biofuels and geothermal energy, which come either directly or indirectly from the sun, are almost considered to be environmentally friendly and are abundantly available throughout the world.

Due to the international drive for clean energy which has seen many countries participating in renewables space and also due to the PV market growth globally and especially in South Africa over the past few years, it has become very important to compare, analyse and evaluate the performance of PV modules especially in actual South African climatic conditions. Performance monitoring of different module technologies and system configurations of Photovoltaic (PV) systems in South Africa are rare which result in few reports being published based on field results of PV systems installed and operated in South Africa. The goal of this work is to analyse and report on the performance of PV systems, by evaluating the energy output of various PV system configurations and module technologies in the South African climatic conditions and hence LCOE. To achieve this, a 400 kWp PV Solar plant has been installed and monitored since January 2015 at the Eskom Research and Innovation Centre (ERIC), Gauteng. The plant consists of polycrystalline silicon (c-Si) and copper indium gallium selenide (CIGS) thin film technologies. The plant comprises of two 25^o fixed north facing inclination, north-south single axis tracking, east-west single axis tracking and two 10° fixed shed orientation each for both module technologies. The analysis was conducted for a period of one year. The evaluation is achieved by studying the operation of PV plant under different weather conditions and the impact of different configurations and technologies on systems overall output, and performance ratio and other performance metrics were calculated to facilitate future LCOE determination.

2 ERIC SOLAR PV SYSTEM FACILITY

2.1 FACILITY DESCRIPTION

The ERIC Solar PV System facility is a 400kWp PV plant localised at Eskom Research and Innovation Centre (ERIC), south of Johannesburg, South Africa. The facility is geographically located at 26°5'5" South, 28°58'1" East and approximately 1625 m above sea level. The site generally has a flat terrain and the facility occupies a total surface area of approximately 1 hectare.

Figure 1: Ariel View of ERIC Solar PV System Facility

The PV plant utilizes ground mounted, multi-configuration PV systems comprising of crystalline and thin film technologies. It consists of four sections of 100kWp of installed capacity each. Figure 1 shows an aerial photograph of the PV facility. Figure 2 is a close zoom illustrating the various orientations available at the ERIC Solar PV plant.

The various PV configurations are subject to the same environmental conditions in terms of temperature, radiation, humidity and wind speed. South Africa, in general, has excellent solar resource providing a favourable condition for the development of solar projects. The facility has annual average global horizontal solar irradiation (GHI) of 2,400 kWh/m^2. The minimum and maximum monthly average temperature is estimated at 10.4°C and 21.7°C respectively. The long term monthly average wind speed is approximately 4 m/s.

Figure 2: Aerial Photograph of ERIC Solar PV Facility

The various PV configurations at the facility are illustrated in Table 1.

Table 1: ERIC PV System set-up

PV System Number	**Orientation**	**Sub-orientation**	**Total kWp of modules at STC** (kWp)	**Tilt Angle** (°)
1	North facing fixed Crystalline		100.80	25
2	North facing fixed Thin film		102.66	25
3	Fixed E/W Crystalline			
		West Tilted Crystalline	33.60	10
		East Tilted Crystalline	33.60	10
4	Fixed E/W Thin film			
		West Tilted Thin film	17.11	10
		East Tilted Thin film	17.77	10
5	Tracking E/W Crystalline		33.60	
6	Tracking E/W Thin film		33.60	
7	Tracking N/S Crystalline		34.22	

2.2 SYSTEM DESCRIPTION

The PV Systems 1 and 2, north facing fixed multi crystalline and north facing fixed thin-film, are adjacent to each other within the facility as illustrated in Figure 1. The PV modules are ground mounted with a tilt of 25° and azimuth angle of 0°. The modules are mounted on a portrait layout along the width of the structure. The row to row distance for the multi crystalline configuration is 3.39 meters with a pitch of 6.4 meters. The pitch for thin film configuration is 4.5 meters and row to row distance is 2.3 meters. Both, tilt angle and row to row distance are selected in order to optimize the performance (minimize near shading effect) and installed capacity.

PV System 1, north facing fixed multi-crystalline PV system layout consists of 4 strings of 14 multi-crystalline silicon modules in series. Four strings are connected to one 15kW inverter. A basic section of mounting structure consists of 14 modules of two rows in portrait layout, this arrangement makes 28 modules (for c-Si) mounted per section of structure. Fourteen modules are connected in series to make one string for c-Si modules. Hence, a basic section of mounting structure consists of two complete strings. The multi-crystalline PV module configuration is illustrated in Table 2.

Table 2: Fixed Tilted Crystalline - North Facing configuration

Inverter No.	No. of strings	No. of modules/string	DC (kWp)	Number of modules
1 (15kW)	4	14	16.8	56
2 (15kW)	4	14	16.8	56
3 (15kW)	4	14	16.8	56
4 (15kW)	4	14	16.8	56
5 (15kW)	4	14	16.8	56
6 (15kW)	4	14	16.8	56
Total AC = 90kW		Total DC = 100.8kW		
Array to inverter ratio (AIR) = 112% (16.8/15)				336

PV System 2, north facing fixed thin-film PV system is 102.66 kWp and each thin film PV module can generate 140Wp with 7.71 A of IMP and 29.25 VMP. The thin film PV system layout consists of 2 different string configurations which are both connected to the same inverter. Configuration 1 consists of 2 strings of 9 thin film modules in series and configuration 2 of 10 strings of 10 thin film modules in series. A basic section of mounting structure for configuration 1 consists of 9 modules of two rows in portrait layout, this arrangement makes 18 modules (for thin film) mounted per section of structure. 9 modules are connected in series to make one string for thin film modules. Hence, a basic section of mounting structure consists of two complete strings. A basic section of mounting structure for configuration 2 consists of 10 modules of two rows in portrait layout, this arrangement makes 20 modules (for thin film) mounted per section of structure. 10 modules are connected in series to make one string for thin film modules. Hence, a basic section of mounting structure consists of two complete strings. The thin film PV module configuration is illustrated in Table 3.

The PV Systems 3 to 4 are crystalline silicon modules and thin film modules mounted on a fixed structures with half of the modules at an azimuth angle of 90° (Due West) and the other half of the modules at an azimuth angle of -90° (due East). The inclination angle of these modules is 10° in order to maximise annual energy yield. The modules are mounted on a portrait layout along the width of the structure.

The PV Systems 6 to 7 crystalline silicon and thin film modules mounted on single axis tracking structures. The tracking structures have the following orientations:

a) 1-axis trackers installed in an E-W direction with a N-S tracking function.

b) The rest of this sub-section consist of 1-axis trackers installed in a N-S direction with an E-W tracking function.

Table 3: Fixed Tilted Thin Film - North Facing configuration

Inverter No.	No. of strings	No. of modules per string	DC (kWp)	Number of modules
1 (15kW)	2	9	2.61	18
	10	10	14.5	100
2 (15kW)	2	9	2.61	18
	10	10	14.5	100
3 (15kW)	2	9	2.61	18
	10	10	14.5	100
4 (15kW)	2	9	2.61	18
	10	10	14.5	100
5 (15kW)	2	9	2.61	18
	10	10	14.5	100
6 (15kW)	2	9	2.61	18
	10	10	14.5	100
Total AC = 90kW		Total DC = 102.66kW		
Array to inverter ratio (AIR) = 114%				708

PV Systems 1 & 2 which are fixed north facing orientations are preferred in South Africa as observed from most large scale IPP plants.

The PV Systems 6 to 7 are tracking systems and these are expected to indicate the maximum possible energy yield. The PV System number 7 (tracking N/S Crystalline) has been included for comparison reasons. These systems are generally horizontal during the day and their tracking movement is significant only in the morning and evening. These systems are normally not installed, as they tend to lose their performance very fast due to dirt, which cannot be readily washed away by rain.

The PV module properties for the multi-crystalline and thin film modules installed at ERIC Solar PV Facility are shown in Table 4.

2.2.1 DC SYSTEM

The DC system comprises of the following; PV modules, DC cabling, combiner boxes, protective devices and disconnect switches. PV modules were first connected in series to make a string. A group of strings (arrays) was then connected to an inverter through combiner boxes. For the ERIC PV Solar system multi-crystalline modules were not connected to the combiner boxes, strings were connected directly to the DC side of the inverter. The combiner boxes were utilized by the thin film modules only.

Table 4: ERIC Solar PV module properties

Specifications	**Technology**	
	Poly-crystalline Silicon	Thin film (CIGS)
Manufacturer	Astronergy	tsmc solar
Model	CHSM6612P-300	TS-145C2
Maximum Power	300Wp	145Wp
Voltage at Pmax	8.91V	63.6V
Current at Pmax	34.74A	2.28A
Nominal Operating Cell Temp	46°C	

The combiner box collects individual strings to form an array. It houses the fuses for overcurrent protection of individual strings, on-load disconnect switch for isolation and surge arrestors for over voltage protection. The combiner box is located between the solar field and the inverter. Combiner box is utilized thin-film technology only because strings need to be combined in order for the minimum inverter voltages and currents to be met. Poly crystalline technology is connected directly the inverter as it satisfies the minimum requirements for voltages and currents.

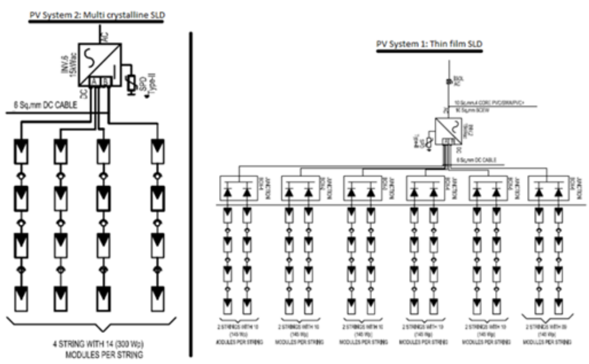

Figure 3: Typical SLD for PV System 1 and PV System 2

2.2.2 INVERTER DESCRIPTION

As an example, the DC design includes 14 modules per string for multi-crystalline (PV System 1) and 9 and 10 modules per string for thin film technology (PV System 2). The number of modules per string is selected based on the module characteristics and inverter mppt input voltage range. The configuration is made in such a way that the string voltage will always be within inverter's mppt operating voltage range.

The same type of inverter is used at ERIC Solar PV Facility, which is a three phase SMA Sunny tripower 15000TL. The Sunny Tripower 15000TL has new features, such as the integration of grid management functions, including Integrated Plant Control, which permits the inverter to regulate reactive power at the grid-connection point. Consequently, upstream regulator units are no longer needed. Inverter maximum efficiency is 98.2 %. It also provides design flexibility with the two MPP inputs in connection with a broad input voltage range. DC input voltage of up 1000V is achievable [3].

All Inverters communicate via RS485 to the Webbox which is installed inside the Server Panel. The SCADA then communicates to the Webbox via Ethernet to read all information from the Inverters.

Figure 4: Typical Thin Film Configuration for the Inverter at ERIC

Figure 5: Typical Multi Crystalline Configuration for the Inverter at ERIC

2.2.3 METEOROLOGICAL MONITORING EQUIPMENT

Measurements of the meteorological parameters, such as global horizontal irradiance (GHI), ambient and module temperature were done at the facility weather station. All meteorological parameters were measured for each PV system orientation and transmitted to the server via a RS485 to the MOXA serial to Ethernet converter cards. The SCADA then read the information via Ethernet from the MOXA cards.

All pyranometers are secondary standard (i.e. Compliant with ISO 9060) with an accuracy of at least +/- 3%. The pyranometer measurements are sampled at

60 second intervals and averaged and recorded at 15 minute intervals [4].

The temperature sensors are PT 100 sensors which measure the ambient temperature as well as the PV module temperature. The temperature sensors have a minimum accuracy of +/- 1˚C [4]. The temperature sensor measurements are recorded at 15 minute intervals.

The orientation and inclination (tilt) of PV modules determines the average daily irradiation on the system. The irradiation is directly linked with the power generation of the PV system through size and efficiency of the modules.

3 PERFORMANCE METRICS

The performance metrics used for the comparison are: final yield, reference yield and performance ratio.

3.1. Final yield

The final yield (Y_f) is defined as:

$$Y_f = \frac{E}{P_{STC}} \qquad (1)$$

where:

E is the total energy output of the PV system measured in kWh AC;

P_{STC} is 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.

The reference yield (Y_r) is given by:

$$Y_r = \frac{H_m}{G_{STC}} \qquad (2)$$

where:

is the equivalent hours of STC experienced by the site;

H_m is the total in-plane solar radiation in kWh/m²;

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

3.2 Performance ratio

The PR is defined in accordance with IEC 61724 as the ratio of energy fed into the grid to the energy that the system could have produced had it operated at STC of 1 kW/m².

The PR is given by:

$$PR = \frac{Y_f}{Y_r} \qquad (3)$$

3.3 Yield gain

The yield gain Y_{Gain} of a tracking system versus a fixed tilt is defined as:

$$Y_{Gain} = \frac{Y_{f,tracking} - Y_{f,fixed}}{Y_{f,fixed}} = \frac{Y_{f,tracking}}{Y_{f,fixed}} - 1$$

where:

$Y_{f,tracking}$ is the monthly specific yield of a tracking system;

$Y_{f,fixed}$ is the monthly specific yield of a fixed system.

4 APPROACH FOR PERFORMANCE COMPARISON

The approach used in comparing the system performance was to keep the system design parameters constant as far as possible and to only consider variables which are pertinent to the specific system. Table 6 show the module technology (2) and design configuration used for comparison of performance in this study.

Table 6: Module technology and design configuration used in this study

Module technology
• c-Si vs CIGS: Fixed tilt
• c-Si vs CIGS: E-W tracking
Design configuration
• Fixed vs E-W tracking
• Fixed vs E-W fixed

5 PERFORMANCE RESULTS AND DISCUSSIONS

5.1 Comparison of module technologies

5.1.1 Fixed tilt orientation

In order to compare the outputs from different PV module technologies, the monthly specific yield (in kWh/kWp) is calculated and the results are shown in Figure 6. It can be noted that throughout the year, the thin film produced more energy when compared to the c-Si modules. It is worth mentioning that the specific yield during winter time seems to be lower compared to other seasons. However, one has to take into consideration when comparing the month to month yield data since the values might be affected by the data cleaning process and the duration of operation that has been considered for performance comparison. Nonethless, the physical response of different technologies will still hold true. For example, the December data was available for only half the duration of December due to power outages. May to June 2015 also experienced heavy power outages from time which affected hours of operation for the PV plant.

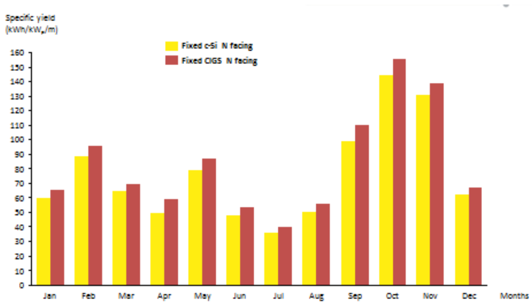

Figure 6: Monthly specific yield of c-Si module performance compared with CIGS modules on fixed tilt configuration

The comparison between the performance ratios of c-Si and CIGS modules in fixed tilt configuration is given in Figure 7. It can be seen form the figure that the PR values vary between 72 to 93 %. The highest value of PR is found to be around 93 % in the month of June for CIGS technology. It is observed that the performance ratio of CIGS thin film is higher for all of the months throughout the year.

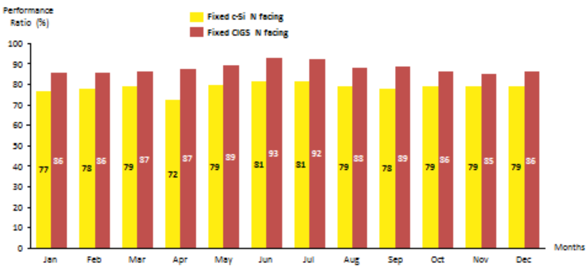

Figure 7: Comparison of monthly performance ratio of c-Si and CIGS modules

5.1.2 Tracking

Figure 8 shows the comparison between the monthly specific yield of c-Si and CIGS modules in east-west tracking configuration. From the graph one can deduce that the tracking yield more energy every month throughout the year except the August month where the tracking system malfunctioned.

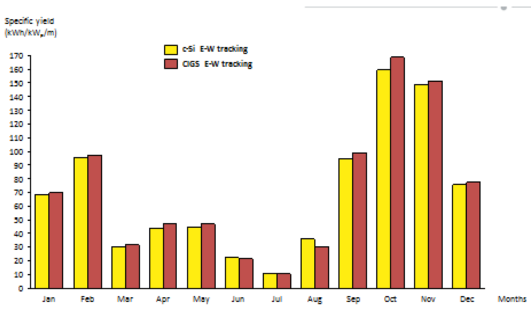

Figure 8: Monthly specific yield of c-Si module performance compared with CIGS modules on fixed tilt configuration

Figure 9 depicts the comparison of the monthly PR values for c-Si and CIGS thin films in tracking configuration. It can be seen from the figure that the PR values of the CIGS technology is higher for the whole year except the August month.

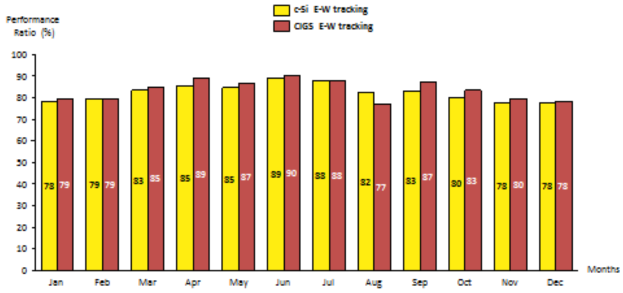

Figure 9: Comparison of monthly performance ratio of c-Si and CIGS modules

It is worth mentioning that the CIGS module technology performed better than c-Si technology in both fixed north facing and east-west tracking configurations.

5.2 Comparison of different design configuration

5.2.1 Fixed vs tracking

The monthly specific yield of optimally aligned fixed tilt compared with east-west tracking for the same module technologies is shown in Figure 10. It can be seen, that the tracking configuration outperforms the fixed tilt installation in summer months (southern hemisphere), when the sun stands high in the sky and the days are long where as in winter months the fixed tilt installations perform better.

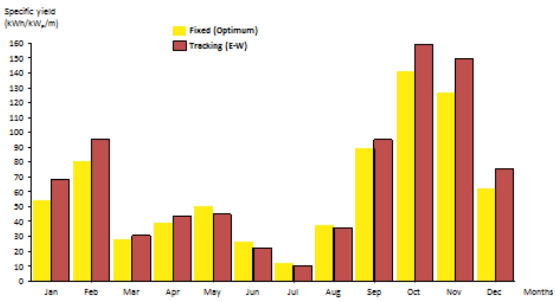

Figure 10: Comparison of fixed tilt yields with east-west tracking yields for each month of a year

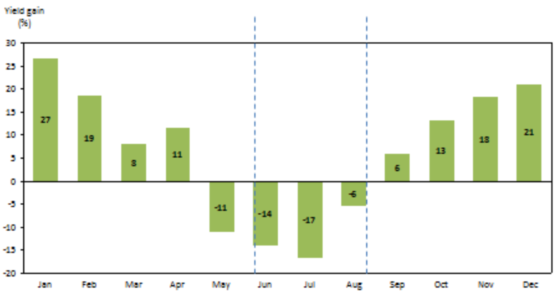

Figure 11: Monthly yield gain of tracking system with respect to the fixed tilt system

Another interesting observation is that the monthly yield gain of the tracking versus fixed installations during winter months is negative (Figure 11).

5.2.2 Fixed vs E-W

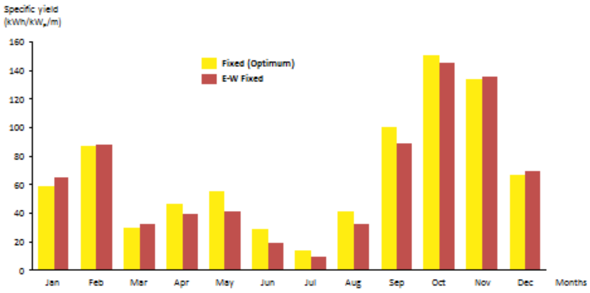

Figure 12: Comparison between fixed tilt installations and east/west tilt installations monthly specific yield

Figure 12 depicts the monthly specific yield comparison between fixed installation and east-west oriented PV system. As can be seen in Figure 12, the east/west installations produced more energy in summer months (southern hemisphere). Due to the different orientations in an east-west PV system, the solar modules are exposed to various irradiation levels which results in lower yield in other seasons. This is clearly evident in the yield gain of east/west configuration with respect to the fixed tilt (Figure 13).

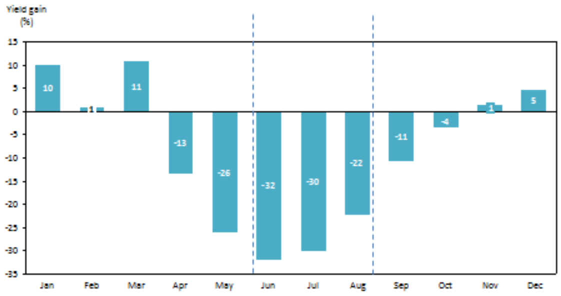

Figure 13: Monthly yield gain of east-west tilted installations with respect to the fixed tilt installations

6 CONCLUSIONS

Performance monitoring of a 400 kWp solar park installed at Rosherville, Gauteng was evaluated for a period of one year from January to December, 2015. The final yield and performance ratio were calculated. It was found that the CIGS module technology performed better than c-Si technology in both fixed north facing and east-west tracking configurations. This study provides an insight to identify the optimal configuration and suitable PV technology for deployment of solar photovoltaic systems in South Africa. This information is also useful in evaluating the operational benefits of the plant based on the net energy output. The monitored data and operating experience of the reported PV system can be applied for future projects.

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