Effect of Using Global Horizontal or Plane of Array Irradiance for Monitoring Sun Tracking Solar Photovoltaic Plants Performance

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ABSTRACT

The performance ratio (PR) is a metric commonly used for assessing the performance of a photovoltaic (PV) plants worldwide. The standard PR calculation method (PR_{PoA}) used in solar PV industry as per the International Electro-technical Commission (IEC) standard uses the solar irradiance in the Plane of Array (PoA) as reference. The CSIR PR calculation method (PR_{GHI}) used Global Horizontal Irradiance (GHI) as a reference for the first phase of PV plants realized as part of the Energy Autonomous Campus program. The PR_{GHI} holds the EPC contractor liable for any underperformance due to poor layout or tracker operations. The PR_{GHI} is variable in the short term and highly variable across the seasons compared with the PR_{PoA}. The temperature corrected PR_{GHI} and PR_{PoA} are calculated to minimize any biases due to temperature which may arise from different weather conditions. The PR_{PoA} is less variable in the short term and across the seasons, so any loss or gain in performance is more easily identified for both the single axis and dual axis tracker systems. The seasonal effect on PR_{GHI} is larger for the dual axis tracker system compared to single axis tracker PV system. The increasing PR_{GHI} between summer and winter solstice for the dual axis tracker system is due to a decrease in the reference irradiance caused by the higher angle of incidence of the sun on the GHI reference sensor and is not due to an increase in PV electrical output. The predicted and actual PR_{GHI} and PR_{PoA} are compared for the single and dual axis tracker systems for a period of one year without temperature correction. The absolute delta between the predicted and actual PR for the single axis tracker was -10% for PR_{GHI} and -4.5% for PR_{PoA}. The absolute delta for the dual axis tracker was -4.5% for PR_{GHI} and +0.4% for PR_{PoA}. The large absolute PR_{GHI} delta between the actual and predicted PRs for the single axis tracker is investigated and this paper focuses only on the tracker performance. The actual tracker tilt angle performed optimally during the summer solstice period but sub-optimally during the early morning and late afternoon between the summer and winter equinoxes. Future work will characterize the effect of the sub-optimal tracker performance in terms of PoA irradiance and energy production.

Keywords: Solar PV system; GHI, PoA, Single axis; dual axis; Performance ratio

1. INTRODUCTION

There is a pressing need worldwide to accelerate the development of advanced clean energy technologies in order to address the global challenges of energy security, climate change and sustainable development. Solar Photovoltaic (PV) energy systems offer a key technology option to realize the shift to a decarbonised energy supply, and they are projected to emerge as an attractive alternate electricity source. The annual global PV market grew significantly to at least 96 GW in 2017 taking the total capacity to 402.5 GW. Solar PV secured first place in 2017 for new capacity added within the renewable energy technologies, ahead of wind, hydro and CSP [1]. The monitoring and assessment of solar PV plant performance is important to determine how the PV system is performing in comparison to expected output and in comparison to similar plants in similar climates. A change in the system performance may be detected during assessments; usually there will be a decrease in performance thus allowing the system owner to investigate and potentially perform cost effective maintenance. PV modules form a major part of the PV systems. PV module performance is determined using an indoor sun simulator at standard test conditions (STC): PoA irradiance is 1000 W/m^2, cell temperature is 25 °C and Air Mass 1.5. PV system performance is determined by comparing the measured energy output relative to the measured irradiance. Irradiance in the field is typically measured with pyranometers or silicon reference cells. A sensor installed in the same plane as the PV modules measures the Plane of Array irradiance, and a sensor mounted in the horizontal plane measures the Global Horizontal Irradiance. The PR is the ratio of the actual energy output versus the theoretically possible energy output, and it is commonly used for assessing PV system performance. PR_{POA}

is largely independent of the orientation of a PV system and the incident solar insolation on the PV plant. PR_{GHI} is highly dependent on these two factors, so a comparison with other PV plants is impossible. Design, functional and environmental factors will also influence the PR value. The PR_{POA} calculation identifies functional losses arising from PV module quality, cabling, soiling and shading, inverter and transformer issues. However, the PR_{POA} is less effective than the PR_{GHI} at identifying sub-optimal module layout and tracker operational issues. The PR_{GHI} will encourage an Engineering Procurement and Construction (EPC) contractor to take responsibility for all design and operational issues [2].

1.1 SUN TRACKING PV PLANTS AND BACK TRACKING

A PV system sun tracker follows the movement of the sun across the sky so that the maximum possible sunlight is directed on to the PV modules throughout the day. A sun tracker will attempt to move to the best angle of exposure of light from the sun with the support of a motor to produce maximum power output. The movement is either controlled based on solar algorithm or through sensors. The solar algorithm controls the tracking of a system based on models of the position of the sun in the sky for the given site geography. The algorithms are based on astronomical data and can predict or estimate the position of the sun with an accuracy of 0.01° [3]. The sun position changes throughout the year depending on the season and might vary from year to year on long term factors. The algorithm based control systems require accurate measurement of both the elevation and the azimuth angle of the modules in order to function correctly and are not affected by passing clouds or largely cloudy conditions. The sensor based systems detect the position of sun relative to the position of PV modules and adjust them to an optimum position. The sensors will be typically photosensitive devices and operate on a step drive system where the module position will be adjusted in steps as the sensor detects the movement of sun. In comparision with a fixed tilt installation, the annual energy production of a sun tracking plant may increase up to 50% depending on the type of tracking system and the location of the plant.

The CSIR Pretoria campus installed a horizontal single axis tracker (HSAT) PV system with back tracking and an Azimuth-Altitude dual axis tracker (AADAT) PV system without back tracking adjacent to each other as part of the Energy Autonomous Campus plan. In the HSAT system, the axis of rotation is horizontal with respect to the ground. The posts of horizontal single axis tracker at either end of the axis of rotation are shared between trackers. Vertical pylons are used on which bearings are mounted for supporting a long horizontal torque tube. The tube axis is on a North-South line and the modules are installed on the tube. The pre-programmed solar algorithm developed by PIA Solar rotates the tube from east to west, tracking the sun through the day. The AADAT system has its primary axis vertical to the ground and the secondary axis is perpendicular to the primary axis. The self-shading risk is high in this case and requires efficient optimization of the ground cover ratio to minimize the plant size and avoid energy loss from self-shading. The photosensitive devices mounted on the vertical and horizontal axis of each PV array control the motor drive to align the array with the brightest spot in the sky throughout the day.

A back tracking algorithm is implemented to avoid row-to-row shading effects from the adjacent PV arrays when the sun is at low elevation during early morning and late afternoon. Backtracking moves the PV array away from the optimal position relative to the sun position, but eliminates the self-shading effects that would otherwise reduce the energy production even further. Backtracking is used to balance the ground cover ratio with energy output. Figure 1 presents the PV arrays without a backtracking algorithm. The high inclination angle of the PV array is causing a shadow on the adjacent array.

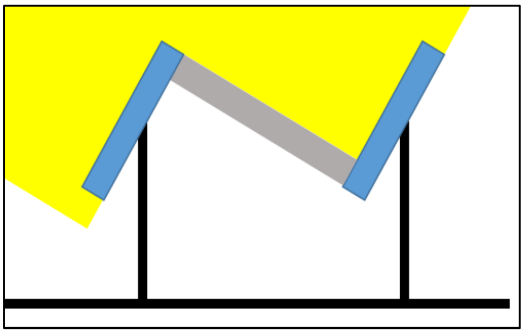

Figure 1: PV Arrays without back tracking algorithm

Figure 2 presents the PV arrays with a backtracking algorithm. The shade from the adjacent array is avoided by reducing the inclination angle and moving slightly away from the sun. This position is not the optimum inclination angle to generate the maximum power in the absence of shading, but the tracker position should be optimized to generate maximum power by reducing the row-to-row shading. The back tracking algorithm is more useful in horizontal single axis and more efficient when applied in the primary axis of two axis tracker [4, 5].

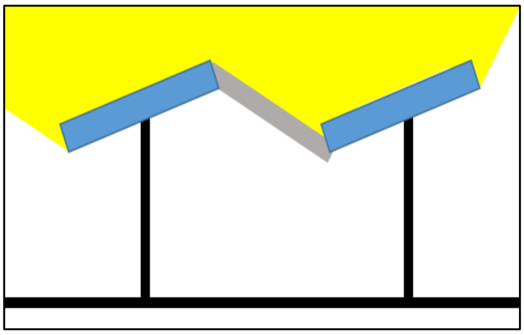

Figure 2: PV Arrays with back tracking algorithm

1.2 PR CALCULATION METHODLOGY

The performance ratio (PR) is defined in the IEC 61724-1 standard for PV System Performance - Monitoring [6]. The PR is a commonly used metric to measure solar PV plant performance for acceptance testing and for monitoring over its lifetime. The PR measures how effectively the plant converts sunlight collected by the PV modules into AC energy delivered in relation to what is expected from the module nameplate rating and the plane of array insolation. The PR calculation as per IEC 61724 is defined using the PoA irradiance, and this is widely used throughout the solar PV industry. However, the standard accepts the use of GHI irradiance in place of PoA irradiance if PoA irradiance is not available [6]. The CSIR implemented the performance ratio based on GHI rather than POA in order to facilitate the procurement process based on the lowest levelized cost of electricity (LCoE). The bidders were given the same historical baseline for GHI insolation and asked to design the optimal system based on a minimal system size. The winning contractor is held accountable to demonstrate the guaranteed performance ratio during first 3 years of operations to ensure the LCOE and pay liquidated damages if the plant produces short of the guaranteed value. Figure 3 explains PR calculation using GHI and PoA scenarios in a flow diagram.

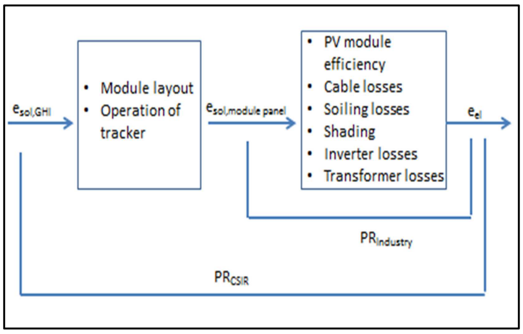

Figure 3: Flow diagram of PR calculation using Industry and CSIR methodology

In this study, the PR is calculated using both GHI and PoA as measured by a calibrated secondary-standard pyranometer. The single axis tracker PV system has two CMP11 pyranometers (PoA reference sensor) mounted in the same plane as the modules measuring PoA irradiance. The average of two pyranometer measurements is used to calculate PR at PoA for the single axis tracker. For the dual axis tracker, there are no irradiance sensors in the plane of array, so the POA insolation is estimated with a transposition model using ground-based irradiance measurements. The Direct Normal Irradiance (CHP1 Pyrheliometer mounted on Solys 2 dual axis tracker) and the Diffuse Horizontal Irradiance (shaded CMP21 Pyranometer under a tracking ball) measured within CSIR Pretoria campus is input to the System Advisor Model (SAM) model, and the PoA insolation for the dual axis tracker PV system is determined. One additional CMP11 Pyranometer (GHI reference sensor) installed adjacent to the single axis plant is used for both single axis and dual axis tracker PV plants to calculate the PR at GHI.

The calculated PR is the quotient of the system's final yield Y_f relative to the reference yield Y_r, and indicates the overall effect of losses on the system output due to both array temperature and system component inefficiencies or failures, including balance of system components. The PR_{GHI} and PR_{POA} are calculated as per equation (1) using the global horizontal and plane of array insolation.

$$PR = \frac{Yf}{Yr} \tag{1}$$

Where,

$$Yf = \frac{Egrid}{PSTC} \tag{2}$$

Y_f is the final yield measured in kWh/kWp, E_{grid} is the AC energy output measured in kWh and P_{STC} is rated DC power of installed capacity measured at standard test conditions (STC)

And

$$Yr = \frac{H}{GSTC} \tag{3}$$

Y_r is the equivalent hours of STC irradiance experienced at the location, H is the total insolation measured in the plane of horizontal (GHI) or in the plane of array (PoA) with a secondary standard pyranometer in kWh/m², G_{STC} is the reference solar irradiance at STC which is 1 kW/m².

1.3 TEMPERATURE CORRECTED PR

The temperature corrected performance ratio (PR) is also defined in the IEC 61724-1 standard for PV System Performance - Monitoring [6]. This correction removes any biases which may arise from different weather conditions. This creates a more stable metric throughout the year, allowing its use as a metric for performance guarantees while still retaining the familiarity this metric brings to the industry and the value of its use in predicting actual annual system yields [7]. Both tracker plants did not have valid measured module temperature for a full one year; hence the below equation (4) was used to calculate the module back temperature.

$$T_m = G_{POA}\left(e^{(a+b*WS)}\right) + T_a \tag{4}$$

Where T_m is the module back-surface temperature (°C) , G_{POA} is the solar irradiance incident on module surface (W/m^2) on the studied system, T_a is the ambient temperature (°C) of the system which was measured, *WS* is the measured wind speed corrected to a measurement height of 10 meters (m/s), *a* is the empirical constant reflecting the increase of module temperature with sunlight (a = -3,56) for glass-cell-polymer sheet open mounted rack, *b* is the empirical constant reflecting the effect of wind speed on the module temperature (b= -0.075 s/m) for glass-cell-polymer sheet open mounted rack, *e* is the Euler's constant and the base for the natural logarithm [7].

The cell operating temperature is calculated using Equation (5):

$$T_{cell} = T_m + \left({G_{POA}}/{G_{STC}}\right)(\Delta T_{cnd}) \tag{5}$$

Where Tcell is the predicted operating cell temperature (°C), Tm is the predicted module surface temperature as determined in Equation (4), G_{POA} is the PoA irradiance as described earlier, G_{STC} is reference irradiance (1,000 W/m^2), ΔTcnd is the conduction temperature drop for glass-cell-polymer sheet open mounted rack (3 °C) [7].

The Temperature corrected PR value is then given by the following equation as defined by Dierauf et al [7], substituting cell temperature for module temperature (6):

$$PR_{Tcorr} = \frac{\sum_i EN_{ACi}}{\sum_i [P_{STC}(\frac{G_{POAi}}{G_{STC}})(1-\frac{\delta}{100}(T_{cell_{avg}}-T_{cell}))]} \tag{6}$$

Where EN_{ACi} is the measured AC electrical generation, P_{STC} is the nameplate power of the studied system, G_{POAi} is the POA irradiance, G_{STC} is the standard testing condition irradiance and $T_{cell_{avg}}$ is the average cell temperature for one year and δ is the temperature coefficient for power of the studied module [7]. The temperature corrected PR (PR_{Tcorr}) value gives the ability to remove the irradiance and temperature effects on the performance of the system. The temperature correction is carried out for both PR_{GHI} and PR_{PoA}.

2. RESULTS AND OBSERVATIONS

The daily monitored data for energy generation, GHI and PoA insolation (PoA was modelled for dual axis) of the 558 kWp single axis tracker (SAT) and the 202.3 kWp dual axis tracker (DAT) installed at CSIR Pretoria campus for a period of one year is presented in Figure 4 and 5, respectively.

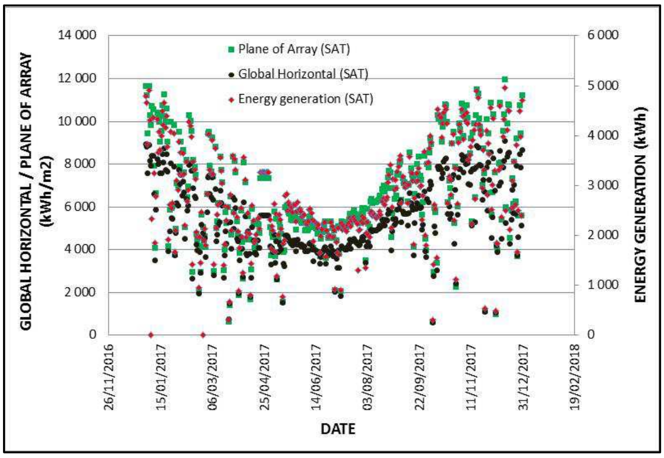

Figure 4: Daily Energy generation, GHI and PoA data for the Single Axis Tracker

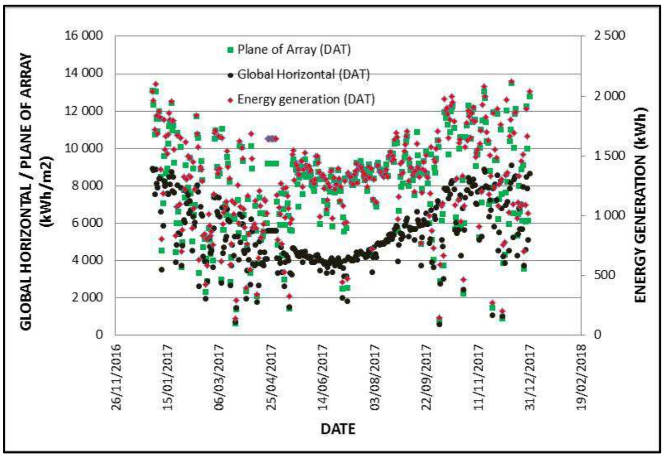

Figure 5: Daily Energy generation, GHI and PoA data for the Dual Axis Tracker

The dip in GHI observed during the winter months is due to both decreased sun hours and the increased angle of incidence between the sun and the GHI sensor. The dip in energy generation and PoA insolation for the SAT is due to both decreased sun hours and increased angle of incidence between the sun and the PV array. The dip in PoA insolation and energy generation for the DAT is less pronounced because the angle of incidence between the sun and array is always zero. Thus, the dip is primarily due to shorter day.

From the simulated and measured data, the daily predicted and actual performance ratios (PR_{GHI} and PR_{PoA}) are calculated for a period of one calendar for the single and dual axis tracker systems using equation (1) to (3). The cosine law and the direct beam component of the available sunlight are the key inputs for understanding the effect of using GHI and PoA for the PR calculations. The number of photons from the direct beam that strike the surface of the array decreases by the cosine of the angle between the array and the sun, given a constant intensity. When the sun is normal to the array, the angle of incidence is 0, cosine (0) = 1, and there is no cosine loss for direct beam light. When the sun is marginally off normal relative to the PV array, the number of direct beam photons hitting the panel is reduced because the effective surface area of the array is reduced. For example, if the incident angle is 20 degrees, cosine (20) = 0.94, and the direct beam photons that strike the array is only 94% relative to a PV array normal to the sun. The orientation of the GHI sensor never changes throughout the year. However, the orientation of the SAT and the DAT are constantly changing. For example, at solar noon the angle of the sun position relative to the plane of array is same for the SAT and the GHI reference sensor, whereas it diverges for rest of day and throughout the year. On the DAT, the angle of the sun relative to the array is never the same as the angle of the sun relative to the GHI sensor, at least in Pretoria, South Africa.

The temperature also has an effect on the output of the PV modules and hence on the PR. Generally the PR increases as the module temperature decreases and the vice versa depending on the seasonal conditions. In order to remove the season based temperature effects; using equations (4) to (6), the temperature corrected PR ($PR_{GHI\,Tcorr}$ and $PR_{PoA\,Tcorr}$) is calculated for the single and dual axis tracker. The graph in Figure 6 and 7 presents the temperature corrected actual $PR_{GHI\,Tcorr}$ and $PR_{GHI\,Tcorr}$ for the single and dual axis tracker for a period of one year. The sharp decline in SAT $PR_{GHI\,Tcorr}$ and $PR_{PoA\,Tcorr}$ between May and August months in figure (6) is due to soiling. The performance gain is noticed in both cases as soon the cleaning of PV array is carried out. The $PR_{GHI\,Tcorr}$ fluctuates more from day-to-day compared to$PR_{PoA\,Tcorr}$. Thus the temperature corrected $PR_{PoA\,Tcorr}$ is the preferred metric for PV plant monitoring. The $PR_{GHI\,Tcorr}$ for the dual axis tracker varies seasonally (Figure 7) due to changing angle of incidence relative to the GHI reference sensor. Hence PV array performance losses due to soiling or gains due to cleaning go un-detected when the angle of incidence is changing rapidly for the GHI sensor. The losses when soiled and the gain after cleaning are difficult to see in the trends unless it is communicated. The cosine angle impact is associated to solar irradiance measurements and not to the PV array performance. The $PR_{GHI\,Tcorr}$ for the dual axis tracker changes more drastically within a year compared to the single axis tracker because the plane of array on the dual axis tracker deviates more relative to the horizontal GHI sensor than the single axis tracker, as shown in figures 4 and 5 above.

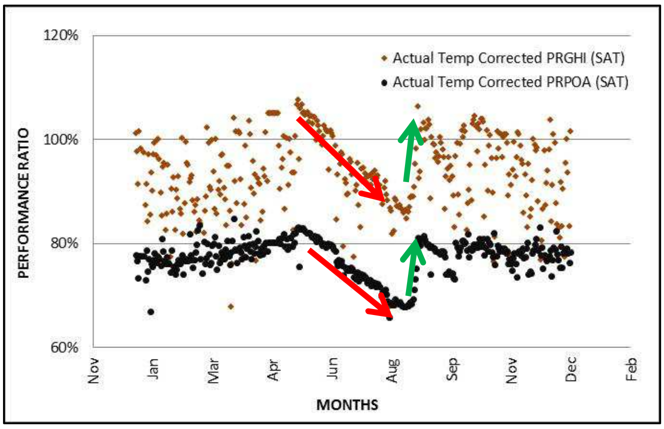

Figure 6: Temperature corrected PR_{GHI} and PR_{PoA} for Single Axis Tracker

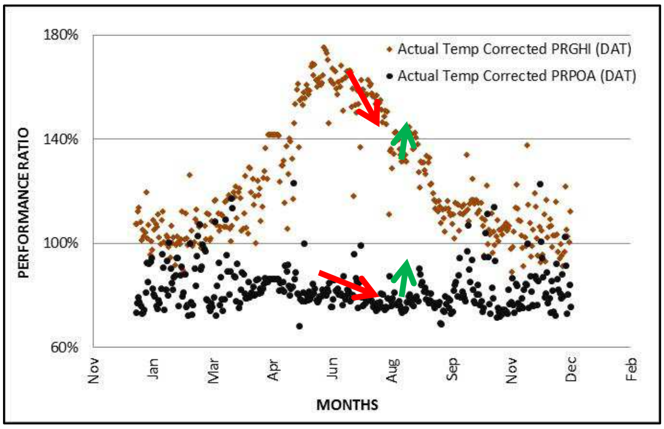

Figure 7: Temperature corrected PR_{GHI} and PR_{PoA} for Dual Axis Tracker

The cumulative average actual PR_{GHI} and PR_{PoA} without temperature correction are calculated to identify how well the PV plant is performing against the predicted for a period of one calendar year. Figure 8 presents the cumulative average actual PR_{GHI} against the cumulative average predicted for the single axis and dual axis trackers, respectively.

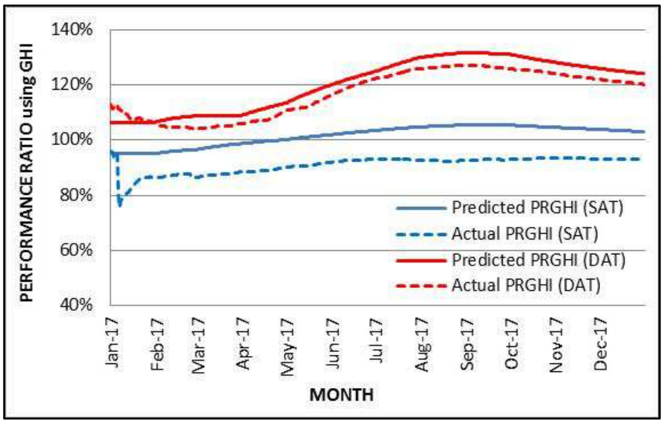

Figure 8: Annual average actual PR_{GHI} against predicted for Single Axis Tracker and Dual Axis Tracker

The annual average actual PR_{GHI} achieved 93% against the predicted 103% for the single axis tracker. For the dual axis tracker, it is 120% against the predicted 125%. The delta between predicted and actual is -10.1% absolute and -4.5% absolute for single axis and dual axis tracker, respectively. The maximum and minimum actual monthly PR_{GHI} achieved is 102% and 86% (+/-8%) respectively for single axis tracker. For the dual axis tracker, the maximum and minimum actual monthly PR_{GHI} achieved is 163% and 101% (+/-31%), respectively, within a calendar year.

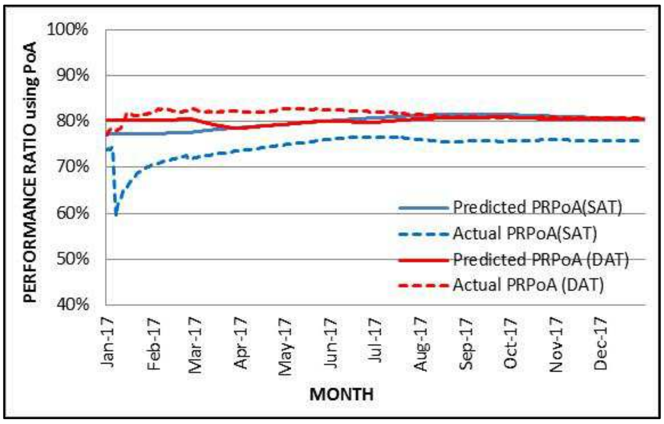

Figure 9: Annual average actual PR_{PoA} against predicted for Single Axis Tracker and Dual Axis Tracker

Figure 9 presents the cumulative average actual PR_{PoA} against the cumulative average predicted for the single axis and dual axis trackers, respectively. The annual average actual PR_{PoA} achieved 76% against the predicted 81% for single axis tracker. For the dual axis tracker, it is 81% against the predicted 81%. The delta between predicted and actual is -4.5% absolute and +0.4% absolute for the single axis and dual axis trackers, respectively. The maximum and minimum actual monthly PR_{PoA} achieved is 82% and 73% (+/-5%) respectively for both the single and dual axis tracker. The monthly PR_{PoA} values were around 80% for both the trackers unlike in PR_{GHI}. The PR_{PoA} shows virtually no seasonal effect, as both the PV array and reference sensor are in the same plane and the angle of incidence to the sun is the same at any given point of time over the year.

An investigation for the large delta between predicted and actual PR_{GHI} for SAT is carried out and the initial results are presented in this paper. Possible causes that affect the performance of the SAT were considered: soiling, direct to diffuse irradiance ratios, improper tracking, degradation, inverter/ transformer clipping and other issues. The soiling impact will be the focus of a separate SASEC 2018 presentation by the CSIR Energy Centre.

The impact of tracking is covered in this paper. The PR_{PoA} does not highlight tracking issues since both the AC energy output and the PoA irradiance decrease proportionally when the tracking is sub-optimal. The PR using GHI can be useful to highlight further opportunity to optimize the tracking so long as the deficiencies with the metric as described above are managed. In the SAT, two sun tracker units drive the 558 kWp PV array simultaneously throughout the day. The ground cover ratio of this plant is 50% with a 4 meter pitch between the mounting posts. The tracker rotates +/- 50° in both directions. Backtracking happens in the morning and afternoon periods and the kick start time depends upon the season. The optimum backtracking tilt angle for a ground cover ratio of 50% (CSIR single axis tracker) is determined using the SAM model and compared with the actual tracker tilt angle of the two tracker units.

Figure (10) to (13) present the actual tilt angle (°) compared against the ideal tracking and back tracking tilt angle for summer and winter solstice and equinox days. The tracker units follow the similar pattern throughout the year except the tilt angle and time stamp where the tracker turns ON and the back tracking is started. At noon, the actual tracker tilt angle is 0° which means they are in horizontal plane throughout the year.

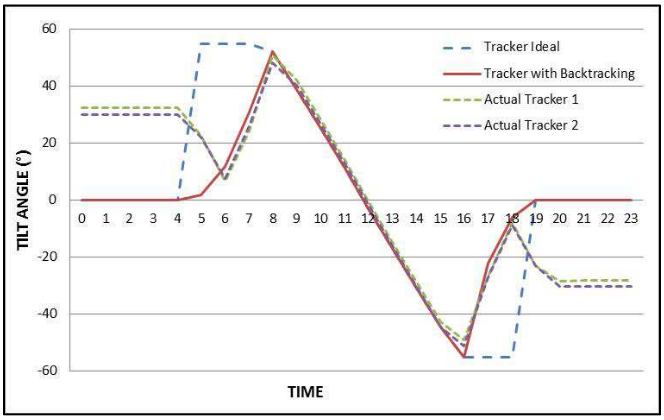

Figure 10: Actual tilt angle of Single Axis Tracker on summer solstice

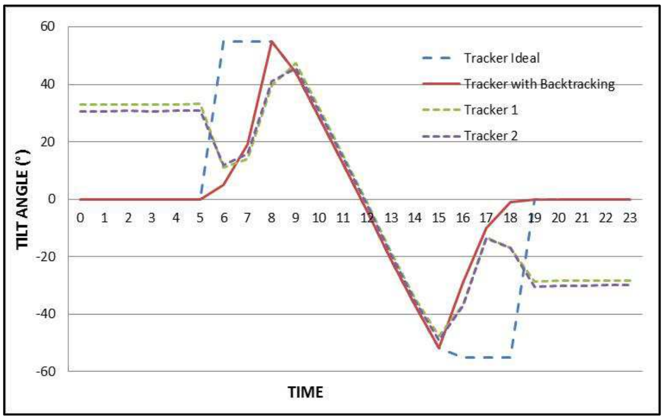

Figure 11: Actual tilt angle of Single Axis Tracker on fall equinox

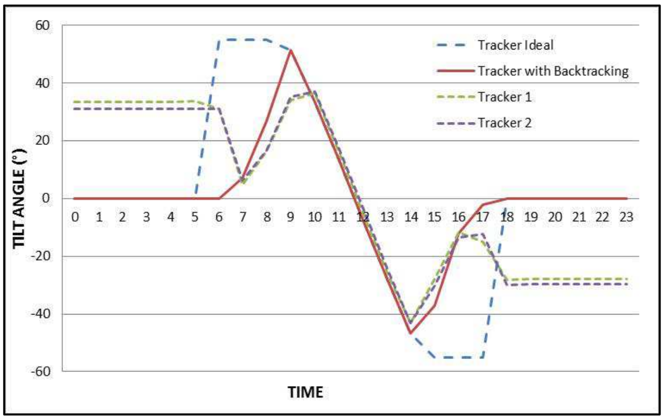

Figure 12: Actual tilt angle of Single Axis Tracker on winter solstice

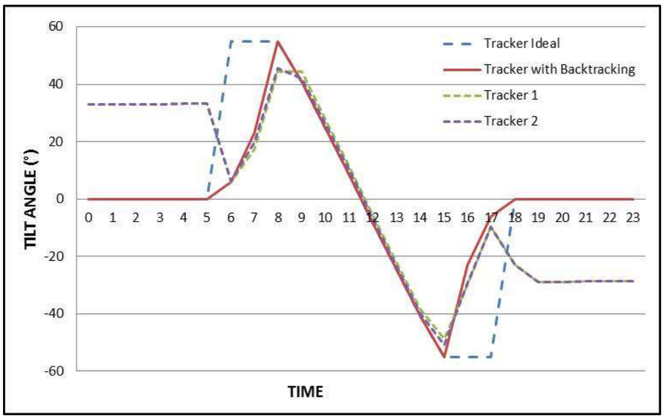

Figure 13: Actual tilt angle of Single Axis Tracker on spring equinox

The actual tilt angle of the tracker units on summer solstice follows the optimal pattern determined by the SAM program for back tracking tracker for most of the day. It only differs with the time when the tracker units turn ON and the stow position from the previous day. As the dates move towards fall equinox and further up to winter solstice, the actual tracker tilt angle during the day goes off the optimal tilt angle in the morning and afternoon periods, particularly when the backtracking is in action. The tilt angle regains as dates move towards spring equinox and summer solstice to the same point where it started. This analysis indicates room for further improvement in the algorithm to control tracker position at the most optimum tilt angle depending on the season. The total usable insolation lost at the PoA due to off tracking needs to be calculated. This is to be substantiated with further detailed analysis to determine the effective improvements particularly for the winter months where the actual tracker tilt angle is not in line with the optimal tilt angle.

3. CONCLUSIONS

The pros and cons of using GHI and PoA for calculating performance ratios (PR) for sun tracking devices is presented in this paper. The measured data for a one year period is analysed. The varying incident angle of the sun on the GHI reference sensor compared to the PV modules causes the PR_{GHI} to increase or decrease drastically depending on the season for both the single and dual axis tracker systems. For the single axis tracker, the GHI and PoA irradiance during noon periods are mostly similar as both are in horizontal plane, so the seasonal variation in PR_{GHI} is less compared to the dual axis tracker. An annual average actual PR_{GHI} of 93% and 120% is achieved for the single and dual axis tracker, respectively. An annual average actual PR_{PoA} of 76% and 81% is achieved for single and dual axis tracker, respectively. The monthly variation in PR_{GHI} was +/-8% for the single axis tracker and +/-31% for the dual axis tracker within a calendar year. The monthly variation in PR_{PoA} was +/-5% for both single and dual axis trackers. The significant monthly PR variation for the dual axis tracker using GHI hides all the performance losses or gains made during or after maintenance actions unless it is communicated. For the single axis tracker, the achieved PR_{GHI} showed a large delta between predicted and actual triggering a further investigation to analyse the tracker performance. Further investigation on tracking units leads to identification of sub-optimal tilt angle between the fall and spring equinox. Future work will focus on quantifying the usable insolation lost due to the sub-optimal tilt angle and the corresponding relative energy gain post optimization.

Acknowledgements

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