PERFORMANCE ANALYSIS FOR A PHOTOVOLTAIC SYSTEM WITH SOLAR TRACKING

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Abstract

Solar tracking is used on photovoltaic systems to minimize the incident angle between the panels and incoming sunlight. This offers the advantage of improved harvesting of solar energy. However, there are no extensive qualitative and quantitative data from studies to elucidate the extent of this improvement. This paper presents the performance analysis for a 11.52 kW PV system with solar tracking installed as a pilot project in Limpopo, South Africa. The data collected from the site are analysed in this paper and results for the energy yield and system efficiency are presented. These results indicate that solar tracking improves the daily energy yield of the PV system by 18% on average, over a 10-month period and over 30% during summer.

Keywords: Solar tracker, Photovoltaic System, Performance Analysis, Energy Yield Map.

1. Introduction

Solar energy has been established as a firm favourite, amongst other renewable energy sources, in South Africa due to high year-round insolation levels and ever-increasing economic viability of associated technologies. It is therefore necessary to explore different methods which may better exploit this abundant resource. One such method is the use of photovoltaic systems with solar tracking which offers the advantage of improved harvesting through minimising the incident angle between the incoming sunlight and panels. This paper presents the performance analysis for a 11.52 kW PV system with single-axis tracking installed as a pilot project in Limpopo, South Africa. To the best of the authors' knowledge, no such extensive investigation/analysis regarding the performance of this new-generation solar technology, especially in Africa, has been presented. Therefore, this paper will assist researchers, and decision- and policy-makers in the energy sector in better understanding the effectiveness and applicability of solar trackers.

2. Solar Tracking

The energy harnessed from solar PV depends on the solar insolation. Diurnal and seasonal movement of the earth affects the irradiation levels received by the solar PV at a particular location. In order to extract maximum solar energy the PV panels should be positioned such that the incident radiation is always normal to the panel's surface [1]. Solar tracking enables the PV panels to follow the trajectory of the sun thereby maintaining an optimum tilt angle. The relationship between the incident angle (θ) and power yielded (P) is given by (1), where η is efficiency, Φ is the irradiation and A is area of the solar panel. Figure 1 shows the incident angle of the incoming radiation on the solar panels.

$$P = \eta \Phi A cos\theta \qquad (1)$$

In Fig. 1, α is the azimuth angle, β is the angle of inclination of the panel (equivalent to acute angle between normal to surface and normal to earth's centre), and γ is the altitude/elevation.

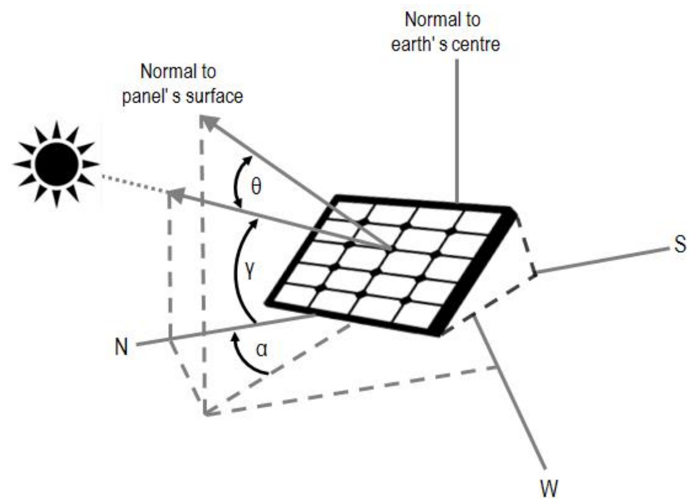

Figure 1: Incident angle of incoming sunlight on solar PV panel

Figure 2: Pilot PV system with single-axis solar tracking installed in Limpopo, South Africa

Two-axis/dual-axis and single-axis trackers are used to direct the panels towards the sun hence optimising the amount of solar energy harvested for the day. The presented solar-tracking PV system is equipped with a single-axis tracker which guides the PV array along a single axis as shown in Figure 2.

Traditionally, two types of tracking systems are used – i.e. single- and dual-axis. It has been reported that a single-axis solar tracking system can increase the energy output of a photovoltaic collector of approximately 30% versus a fixed tilt [2, 3], and dual-axis tracking can increase the photovoltaic output to 50% [4]. However, the extent of the improvement is strongly dependent on the location and climate conditions at the site. Seasonal variation impacts the performance of trackers which tend to perform significantly better in summer than winter for clear sky countries. In cloudy conditions where there is a high volume of clouds in the sky the system would collect around 35% in summer and 5% only in winter [5]. Additionally, it should be noted that the use of solar tracking devices in certain conditions can actually diminish the performance of the system [6]. It is therefore crucial to obtain reliable information regarding the performance of tracking in a specific area over an adequate period of time to investigate the additional cost-benefit trade-off. Although there is some performance information available from investigations carried out in Asia, Europe and North America, there is insufficient data available for the African continent [7].

The presented solar PV system was installed in Limpopo, South Africa as a pilot aimed at determining the performance of the tracking system. Although single-axis tracking is not a novel concept, the technology employed in the presented system enables flexible mounting and accurate tracking for much larger PV arrays. Hence, this new-generation tracking technology offers the benefits of both improved harnessing of solar energy and economy of scale.

3. Performance Analysis

The purpose of this work is to investigate the performance of the aforementioned new-generation solar tracking technology and to determine its effectiveness and applicability in a Southern African context. Significant measures of performance are presented with two main areas of focus - i.e. energy yield of the system and surplus yield made available through solar tracking. The solar-tracking PV system was monitored for a year and measurements were obtained for the total energy yield and irradiation at the site. An algorithm was designed for pre-processing and processing large amounts of three dimensional data (day, time and the parameter of interest) to analyse daily, monthly and seasonal performance characteristics. The surplus energy generated by the system is considered as the key performance indicator of the solar tracker and is determined using the irradiation data obtained from tracking and fixed sensors. The average efficiency (η) of the system is also estimated. The system is rated at approximately 11.52 kW at peak production, consists of two 4m by 10m monocrystalline PV arrays and is equipped with single-axis tracking. The observation period is from October 2014 to October 2015 with some measures of performance analysed between the period from February 2015 and November 2015, due to the availability of continuous solar irradiation data.

3.1. Energy Yield

Energy yield is simply the usable energy produced by the system. The plot presented in figure 3 is a 'heat map' which allows one to view three dimensional data in a two dimension plot. The map consists of a number of rectangular rows and columns that represent data values against a colour scale. In this case, the quantified energy yield of the system is displayed in terms of both the hour of the day and the day. This allows the monthly and daily performance trends of the system to be viewed together with seasonal influence on yield. The y-axis represents the time of the day, x-axis represents a day during the observation period and the colour scale represents the energy yield (in kWh) measured at 15 minute intervals.

3.2. Surplus Energy Yield

The main indicator of the solar tracker's performance is considered here as the surplus energy generated by the entire system. Essentially, the surplus energy generated is the difference between the energy yield of the system and the energy yield of similar system without tracking. The observation period used here is between 11 February 2015 and 18 November 2015. Figure 4 gives a stacked histogram of the daily energy yield showing the estimated surplus energy yield component. Figure 5 gives heatmap of the estimated surplus energy over the same period.

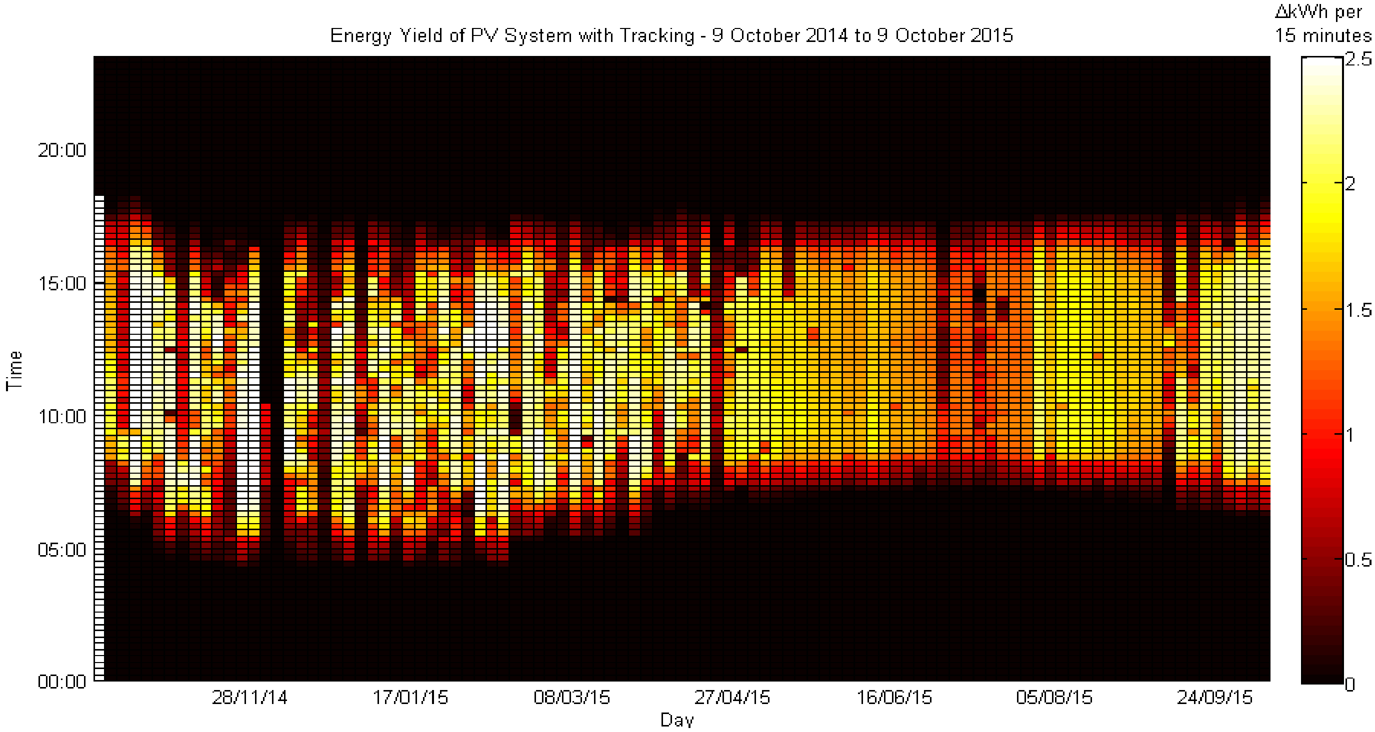

Figure 3: Energy mapping for one year observation period 9 October 2014 to 9 October 2015 (incremental energy yield - measured in kWh - over 15 minute intervals)

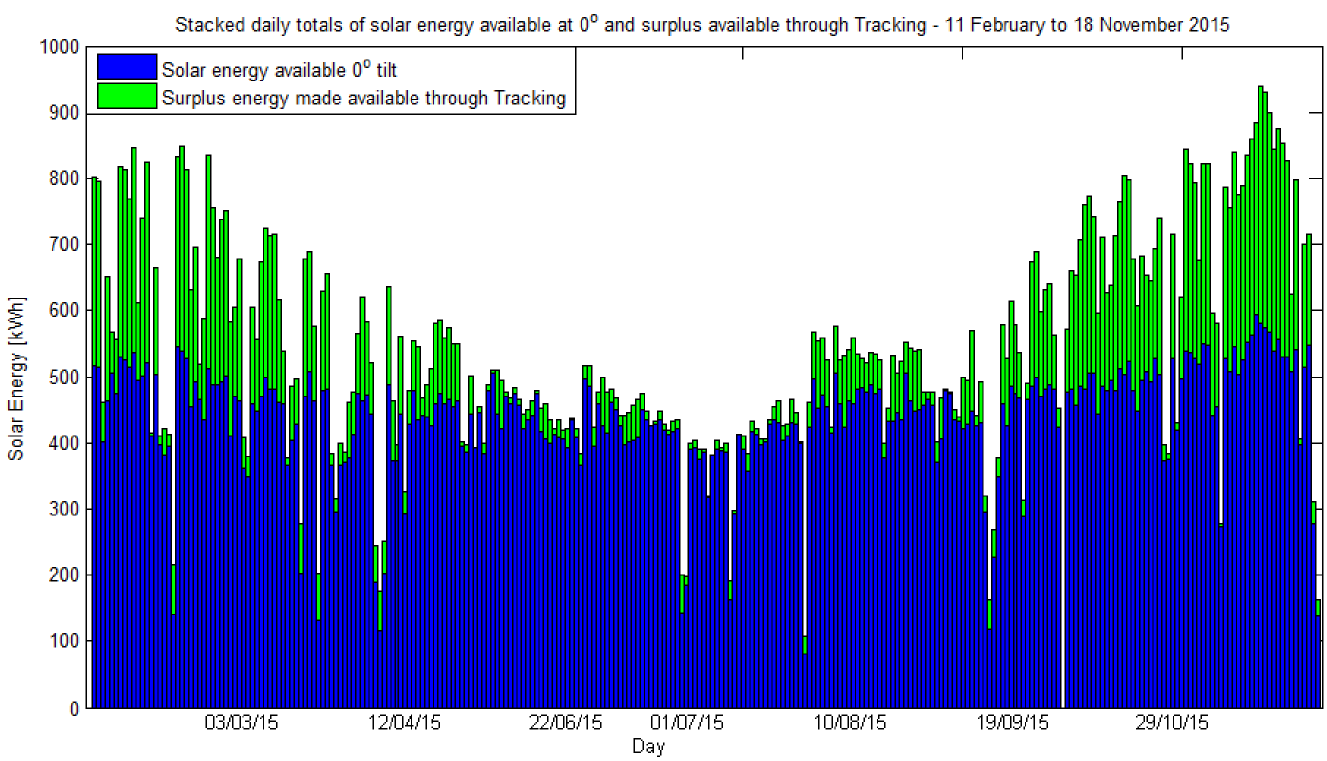

Figure 4: Daily Solar Energy available horizontally and surplus made available through Tracking for observation period 11 February 2015 to 18 November 2015 (estimated for PV panel area)

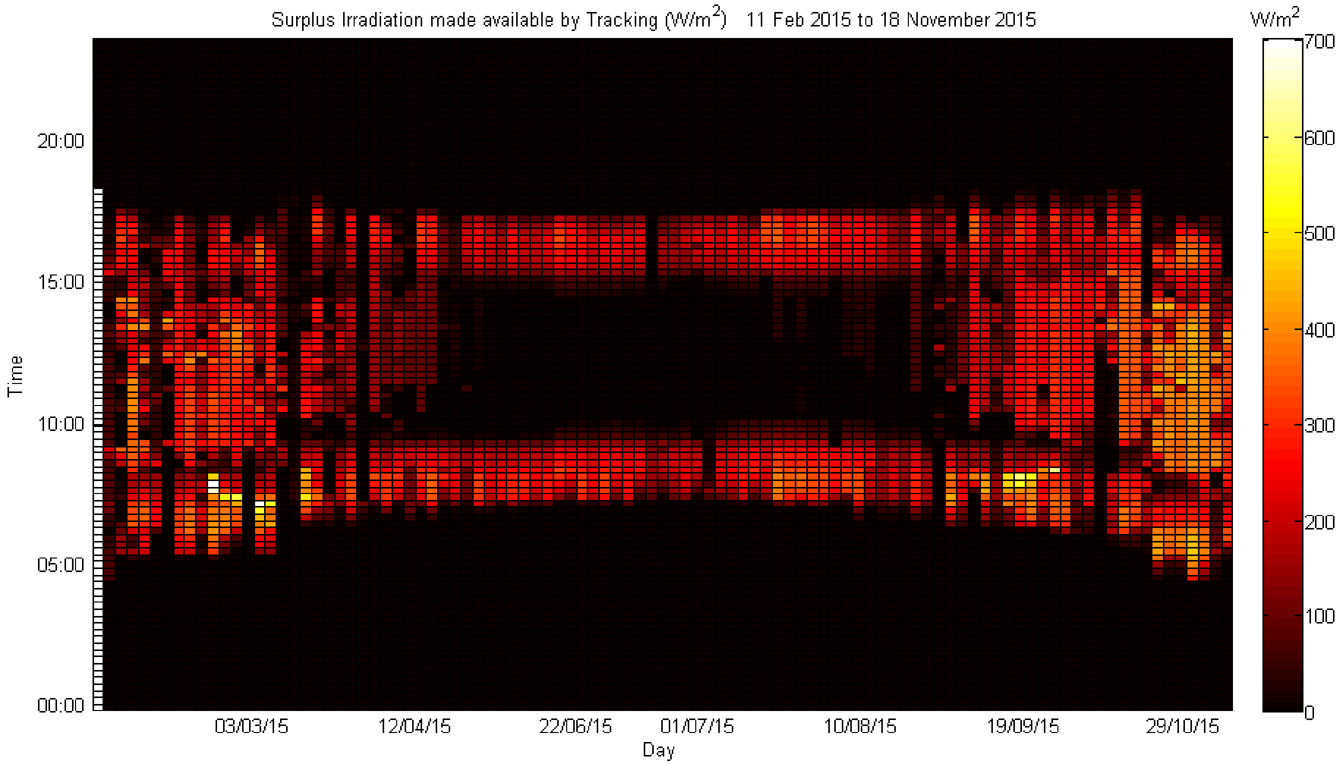

Figure 5: Mapping of estimated surplus energy made available through tracking for observation period 11 February 2015 to 18 November 2015 (estimated for PV panel area)

3.3. Surplus Energy and Efficiency Estimation

In general, efficiency (η) may be defined as the ratio of useful energy output to energy input. For the presented case, the available data consists of average solar irradiation (Φ_T) over 15 minute periods and energy yielded in 15 minute intervals. Therefore, the estimated efficiency (η) of the system must be determined using the estimated average of the total solar energy input and the total energy yielded. It should be noted that the total energy input to the system is an estimate of the total solar energy irradiated over an area of $80m^2$ for the observation period as it is based on the solar irradiation measurements from the sensor mounted on the tracking system. Simply put, the energy input used to estimate the efficiency, in the presented analysis, is the solar energy made available (through tracking) for harvesting over an area of $80m^2$.

In order to estimate average efficiency of the system and tracking performance - the solar irradiation must be converted to solar energy (kWh) available for harvesting over an area of $80m^2$ in a 15 minute period (as given by sensor measurements - i.e. 15 minutes or 0.25 hours) as follows:

$$\Phi_T = \phi_T \times 0.25\text{h} \times 80m^2 \times 10^{-3} \quad (2)$$

$$\Phi_H = \phi_H \times 0.25\text{h} \times 80m^2 \times 10^{-3} \quad (3)$$

where,

E - Measured energy yield per 15 minutes [kWh],
$\emptyset_T$ - Solar irradiation tracked (sensor fixed on tracker) [W/m^2],
$\emptyset_H$ - Solar irradiation at 0˚ (sensor fixed horizontally) [W/m^2],
Φ_T - Solar energy irradiated over the tracked $80m^2$ area for 15 minute period [kWh],
Φ_H - Solar energy irradiated at 0˚ over the $80m^2$ area for 15 minute period [kWh].

Therefore, the surplus solar energy made available for harvesting over an area of $80m^2$ by tracking system (in kWh) is estimated as given by (4).

$$\Phi_S = \phi_T - \phi_H \quad (4)$$

The ratio of additional solar energy made available for harvesting over an area of $80m^2$ by tracking system to a horizontally fixed system is given by (5)

$$\tilde{S}_{S,H} = {}^{\phi_S}/_{\phi_H} \times 100\% \quad (5)$$

Average efficiency of the system can be estimated using the energy yield measured and the estimated solar energy irradiated over the $80m^2$ tracked area, as follows:

$$\tilde{\eta} = {}^{E}/_{\phi_T} \times 100\% \quad (6)$$

For the observation period 11 February 2015 – 18 November 2015:

$$\tilde{\eta} = {E_{Total}}/{\phi_{T,Total}} \times 100\% = 11.25\% \quad (7)$$

The monthly surplus due to tracking is presented in two ways - total energy yield due to tracking ($\tilde{S}_{S,T,monthly}$), and additional energy yielded due to tracking in kWh ($E_{S,monthly}$):

$$\tilde{S}_{S,T,monthly} = {\phi_{S,monthly}}/{\phi_{H,monthly}} \times 100\% \quad (8)$$

$$E_{S,monthly} = \phi_{S,monthly} \times \tilde{\eta} \quad (9)$$

4. Analysis of Results

'Heat maps' were selected here to enable viewing of large amounts of data in a single plot. This method of presenting the data also assists in analysing significant seasonal, monthly, and daily performance characteristics of the system. In figure 3, the impact of seasonal variation of the performance of the system is evident. The energy yield is improved during summer owing to relatively higher irradiation levels and more hours of daylight. However, erratic climate conditions during summer and spring (such as increased cloud cover) causes variation in the daily and hourly yields. The estimated surplus energy yield of the system is the main performance indicator of the solar tracking. Figure 4 gives the total energy yield separated into two constituents – i.e. surplus energy yield due to tracking and fixed system energy yield. This figure shows that the tracking system performs better in summer and spring. Figure 5 confirms this observation and clearly indicates that the surplus energy yielded during autumn and winter is predominant on, and in some cases limited to, the "shoulders" of the day. Tracking is improves harvesting of the solar energy particularly during these times of the day.

Using the data presented in figure 4, the average additional energy made available by the tracking system over the observation period is determined. A daily average of 18.39% of additional energy is made available for harvesting, by tracking, than a horizontally fixed system i.e. 0˚ tilt. Additionally, it is found that the tracker performs better in the 'hotter' months than the 'colder' months. Results for the Average Daily Surplus during the specific periods during the total observation period are as follows:

- Mid-February 2015 to mid-April 2015, September 2015 to mid-November 2015 - 30.66%
- Mid-April to the end of August 2015 - 6.09%

It should be noted that the average daily yield is rendered lower because the observation period is from 11 February 2015 to 18 November 2015. It is expected to increase to a higher value (interpolated to approximately 24%) if observation period is extended to 11 February 2016 (one year) to include the subsequent summer months - which have been shown to yield better surplus due to tracking.

5. Conclusion

There are currently no substantial field data or test results available to researchers, and decision- and policy-makers in the solar industry sector that demonstrate the effectiveness and applicability of solar tracking on PV systems. Hence, this paper will assist in informing the solar industry sector in Southern Africa of the main implications of this type of technology in order to better understand and assess potential benefits/ drawbacks. Additionally, this work is intended to serve as a basis for further feasibility and viability studies into large-scale implementation within the industrial sector where there is a critical need to generate off-grid, independent power.

Two dimensional 'heat maps' are generated to enable analysis of large amounts of data using a single plot. This method of processing and presenting the data assists in extraction of important seasonal, monthly, and daily performance characteristics of the system. Various monthly and seasonal totals of the surplus energy yield are also presented. The average daily surplus energy made available by the tracking system over the observation period was found to be between 18% - 24%. Additionally, results indicate that the system harvests greater surplus energy in the summer months than winter months.

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References

[1] P. Bajpai, and S. Kumar, "Design, development and performance test of an automatic two-axis solar tracker system," *2011 Annual IEEE India Conference*, Hyderabad, pp. 1-6, December 2011.

[2] M. M. Abu-Khadera, O. O. Badranb, and S. Abdallah, "Evaluating multi-axes sun-tracking system at different modes of operation in Jordan", *Renewable and Sustainable Energy Reviews*, vol. 12, no. 3, pp. 864-873, 2008.

[3] R. Bruno, P. Bevilacqua, L. Longo, and N. Arcuri, "Small size single-axis PV trackers: control strategies and system layout for energy optimization", *Energy Procedia*, vol. 82, pp. 737-743, December 2015.

[4] N. Kelly, and T. Gibson, “Improved photovoltaic energy output for cloudy conditions with a solar tracking system”, *Solar Energy*, vol. 83, no. 11, pp. 2092-2102, 2009.

[5] G. Prinsloo, and R Dobson, *Solar Tracking: Sun position, sun tracking, sun following*, University of Stellenbosch, South Africa, 2009.

[6] R. A. Messenger, and J. Ventre, *Photovoltaic systems engineeringg*, CRC Press, London, 3rd Ed., 2012.

[7] J. F. Lee, and N. A. Rahim, “Performance comparison of dual-axis solar tracker vs static solar system in Malaysia”, *IEEE Conference on Clean Energy and Technology (CEAT)*, Lankgkawi, pp. 102-107, 2013.