

GLOBAL IRRADIANCE ON PHOTOVOLTAIC ARRAY

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Abstract

The amount of available solar irradiance is the most important parameter to determine solar energy generation for any given location. Satellite-based irradiance data is often used as a basis for predicting the energy generation for any location, as ground-based irradiance data is only available for specific sites. This paper presents a comparison of ground-based measured irradiance and satellite-based predicted irradiance and the corresponding modelled alternating current (AC) energy generation from a photovoltaic power plant. The 558 kW DC single-axis tracked photovoltaic (PV) plant located at the Council for Scientific and Industrial Research (CSIR) Pretoria campus is used for the case study.

This paper briefly describes the techniques used to determine the Plane of Array (POA) irradiance from the Global Horizontal Irradiance (GHI) as well as the theory of operation for ground-based GHI sensors. The annual ground-based measured GHI at two locations with the CSIR campus were 3.1% and 4.9% lower compared to PVGIS Typical Meteorological Year (TMY) (1998-2011) and 1.9% and 3.6% lower compared with Meteonorm TMY (1960-2000) data, respectively. System Advisor Model (SAM) was used to model the AC energy output from the PV system. A strong correlation between the POA irradiance and alternating current (AC) power generation was calculated (R-squared = 0.987). The annual AC energy generation based on ground-based GHI measurements predicted 3.6% and 5.9% lower compared to PVGIS and 2.4% and 4.7% lower compared to Meteonorm TMY data, respectively.

Keywords: Solar irradiance; GHI; PV system; Pyranometer; Satellite data and POA irradiance

1. Introduction

Accurate solar energy input data is necessary to predict precise energy yield from a solar PV plant. The measurement of solar irradiance is also essential to monitor the solar PV system performance over its operational period. There are two primary pathways to quantify the global irradiance i.e. satellite-based and ground-based. A hybrid method that uses ground-based

measurements to calibrate and improve satellite-based models can also be used when ground-based data is available [1]. Satellite-based data is typically used for predicting energy yield of a PV system. There are several sources for satellite-based GHI data for most regions of the world either free of cost or through paid services. Ground-based measurements are only useful for limited areas from where a physical measurement is carried out by radiation sensors.

2. Satellite and ground-based irradiance measurement

The amount of solar irradiance received per unit area by a horizontal surface is termed as Global Horizontal Irradiance (GHI) [2]. GHI is the sum of Diffuse Horizontal Irradiance (DHI) and the product of the Direct Normal Irradiance (DNI) and cosine of the zenith angle (θ). GHI can be measured directly with a horizontally mounted sensor or it can be computed from DHI and DNI as per equation (1):

$$\text{GHI} = \text{DHI} + \text{DNI} \times \cos(\theta) \quad (1)$$

Satellite-based GHI measurement involves measurements of irradiance at the top of the atmosphere. A clear sky model is fit to the satellite data, and then the cloud effect is modelled to arrive at Global Horizontal Irradiance (GHI) on the surface [3].

The POA irradiance is modelled from GHI in two steps; decomposition and transposition models. First, the GHI is decomposed into DNI and DHI and then the DNI and DHI are transposed with a mathematical model to arrive at POA irradiance [4]. In this study, System Advisor Model (SAM) was used for predicting the POA using the Perez transposition model. Figure 1 presents the flow diagram of the transposition models.

Ground-based data is measured at the earth's surface, ideally at the location of a PV plant. At a minimum, GHI is measured and modelled to arrive at the POA irradiance using the same methods for satellite-based GHI irradiance. Once the PV plant is built, a sensor should be installed in the POA, maintained, and recorded for performance monitoring. A Pyranometer is an important component of ground-based irradiance monitoring system.

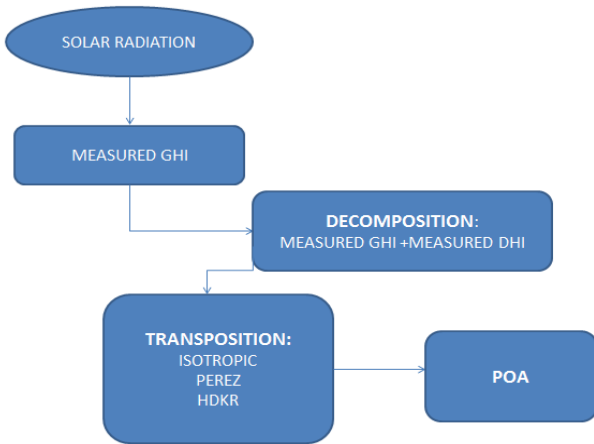


Fig. 1. Flow diagram of Transposition model

Figure 3 shows a Pyranometer which measures the GHI at every hemispheric angle. Figure 4 shows the thermal sensing element (thermopile) under a glass dome which responds to the total energy absorbed by the black surface coating [5].

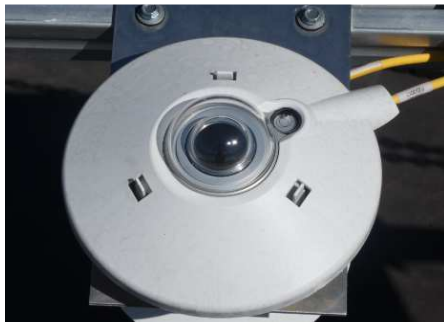


Fig. 3. Image of Pyranometer mounted at CSIR, Pretoria campus

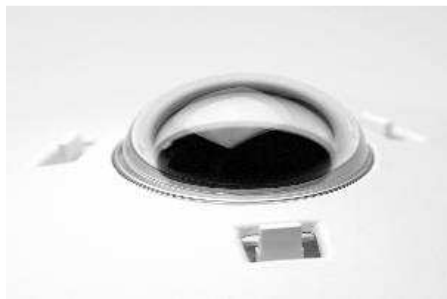


Fig. 4. Black surface coating under the domes

The thermopile is made of a thermocouple junction pair (hot and cold junctions). The hot junction absorbs the thermal radiation which increases the temperature in the junction. The cold junction is kept at a fixed temperature. The temperature difference between the two junctions will create an electromotive force (EMF) with an output voltage [5]. The irradiance measured by the device can be calculated by the

equation (2):

$$E_{solar} = EMF/s \quad (2)$$

Where ‘Esolar’ is the irradiance in Watts per square meter (W/m^2), ‘EMF’ is the measured output voltage (μV) and ‘s’ is the sensitivity of the device ($\mu V/W/m^2$).

A Pyrheliometer may be included in a ground-based monitoring system to measure DNI. A Pyrheliometer operates in a similar way as the Pyranometer since it has the same sensing element. However, the DNI sensor must be mounted on a dual axis tracking system so that it constantly tracks the sun movement, and the sensor is always in line with the sun light beam. Figure 5 shows the Pyrheliometer installed at the CSIR on the roof of Building 34. The Pyrheliometer measures the DNI from the sun arriving at the earth’s surface within a 5 degree field of view and an uncertainty of +/- 2% on an hourly basis as stated by Kipp and Zonen [5].



Fig. 5. Pyrheliometer CHP1 mounted on Dual axis tracker at CSIR, Pretoria campus

3. Results and discussion

3.1 Predicted and Actual GHI measurements

The CSIR Energy Centre has three Pyranometers to measure GHI: two on the roof of Building 34 and one located adjacent to the Single Axis Tracker (SAT) PV plant. The CMP21 on Building 34 was installed as part of Weather Station 1 in 2016 and measures the solar irradiance every 5 seconds. The SMP10-V on Building 34 was installed as part of Weather Station 2 in November 2017 and measures every 30 seconds. The SAT has an SMP10-A Pyranometer measuring GHI. The measured insolation for the two Pyranometers on Building 34 (GHI 1 and GHI 2) for a single day on 02 March 2018 from 6AM to 7PM is $542.9 W/m^2$ and $543.2 W/m^2$, respectively. The difference between GHI 1 and GHI 2 is observed to be very low, approximately 0.04% on that day. These two sensors are mounted approximately 2 meters apart and the calibrations are nearly identical. The difference between GHI measured at

Building 34 and SAT is approximately 2.5% on the same day. Building 34 and the SAT plant are approximately 1.2 km apart. Figure 6 presents the measured GHI data by CMP21, SMP10-V and SMP10-A Pyranometers on a clear sky day (02 March 2018).

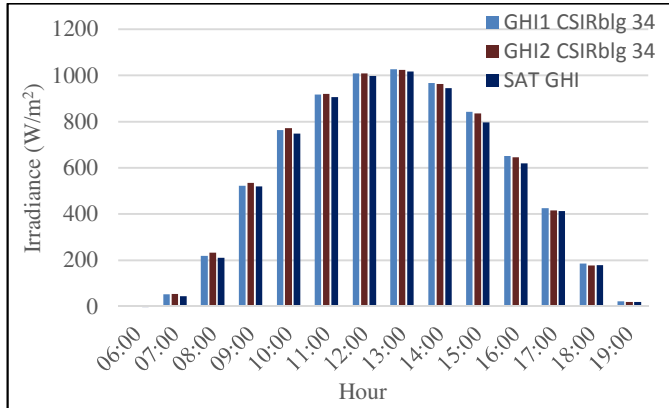


Fig. 6. Measured GHI by CMP21, SMP10-V and SMP10-A

Satellite irradiance data is available from many sources: PVGIS, Meteonorm, Solar GIS etc. PVGIS (1998-2011) and Meteonorm (1960 – 2000) provides TMY irradiance data free of cost on their respective websites derived from satellite measurements interpolated for any region with a resolution of 3 km in Africa [10].

From the South African Radiometric Network (SAURAN) database, the GHI data measured at the University of Pretoria (UP) was analysed to verify the quality of the CSIR ground-based GHI measurements. Figure 7 presents monthly ground-based GHI measured at CSIR Building 34 and UP.

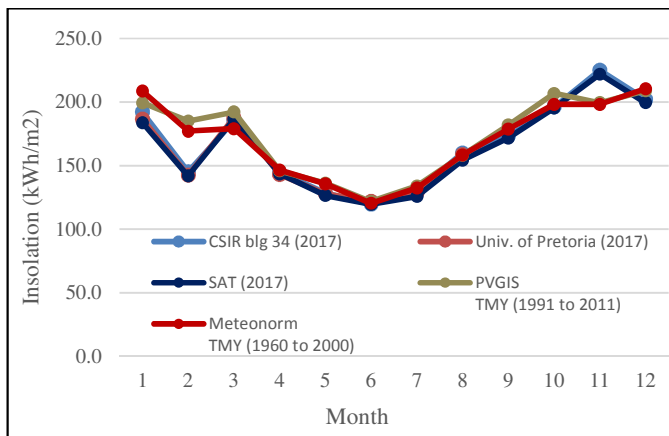


Fig. 7. Measured GHI from ground-based Pyranometers and satellite based TMY data

The GHI measured data for a period of 8 months during the calendar year 2017 at UP weather station was found to be

concordant approximately 1.4 % and 1.3% with Building 34 and SAT GHI measurements respectively. The difference in measured GHI between CSIR Building 34 compared to PVGIS and Meteonorm data was observed to be 25% and 21% lower in February and 12% and 13% higher in November. This might be due to changed sky conditions during the reference year i.e. 2017.

Table 1 presents the annual insolation from PVGIS and Meteonorm satellite-based data with the ground-based data measured at CSIR, Pretoria during the calendar year 2017. The annual total insolation of satellite-based data is observed to be higher than the ground-based measurement data carried out at CSIR Pretoria campus.

GHI Data Source	Total Insolation (kWh/m2)
CSIR Building 34 CMP21 Pyranometer	2006
Single Axis Tracker SMP10 Pyranometer	1970
PVGIS TMY data (1998 - 2011)	2069
Meteonorm TMY data (1960 - 2000)	2044

Table 1: Annual insolation measured by ground-based Pyranometers and satellite-based TMY data

Table 2 presents the relative difference between ground-based and satellite-based GHI measurements. Building 34 measured GHI irradiation was 1.8% higher compared to the measured GHI at the SAT. Meteonorm satellite-based GHI annual insolation is 1.9% higher compared to the measured GHI at Building 34. The reported uncertainty for yearly GHI insolation measurements from Meteonorm is +/- 3% [6]. PVGIS satellite-based irradiation is higher by 3.1% and 4.9% compared to ground-based GHI measurements at Building 34 and SAT, respectively.

Description	% difference
PVGIS / Building 34	+ 3.1
Meteonorm / Building 34	+ 1.9
PVGIS / SAT	+ 4.9
Meteonorm / SAT	+ 3.6
Building 34 / SAT	+ 1.8

Table 2: Annual relative difference between satellite-based TMY data and ground-based GHI measurements

3.2 Importance of POA

A Pyranometer mounted in the same POA as the PV modules is shown in Figure 8. To monitor the PV modules performance efficiently, the irradiance sensor should be mounted at the same orientation of the modules so it measures the same irradiance hitting the active cells on the module. It is necessary to know the electrical energy output and the solar energy input measured at POA irradiance to determine the conversion efficiency of a PV power plant. One should be cautious using GHI to monitor PV modules on a tilted rack or tracker since GHI measurements are taken at a horizontal surface and do not accurately reflect the solar energy input to the PV system.



Fig. 8. SMP 10 on the 20 degree tilt

The POA irradiance data is the key input to predict the electrical energy output from a solar PV plant. Software models take solar resource data and a host of additional parameters such as geographical location, weather parameters and components configuration and efficiencies to estimate AC energy output. Figure 9 shows the correlation between hourly AC power output from the 558 kW DC single axis tracker plant at the CSIR versus POA irradiance for a period of one year.

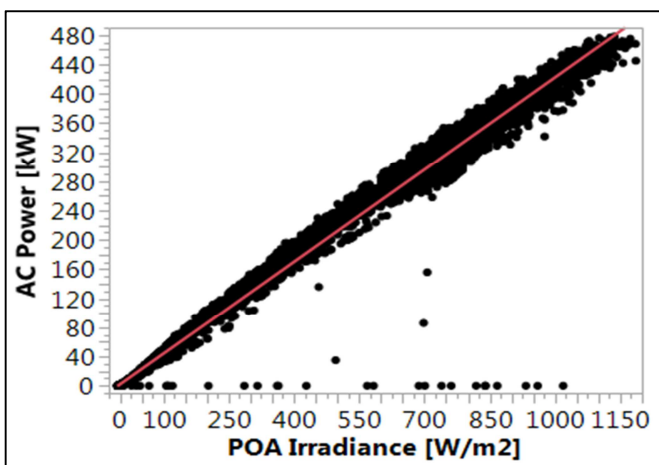


Fig. 9. Correlation between AC power output and POA irradiance

Nearly 99% of the variability in the AC power output can be explained by the POA irradiance (r -squared = 0.987) without consideration for any other inputs. While the relationship between AC power and POA irradiance can be established easily with historical data and a statistical model, predicting the output of new PV systems requires a more complicated physical model.

3.3 Solar PV energy generation prediction

In this study, the energy yield predictions for the 558 kWp single axis tracker PV plant was modelled with ground-based and satellite-based GHI data using SAM. A weather file was created from the measured GHI, DHI, DNI, Wind speed and direction and Ambient temperature measured at Building 34 and SAT for the calendar year 2017. The weather file was uploaded into SAM and the Perez transposition (Sky Diffuse model) was selected for modelling for its high accuracy POA irradiance [6, 13]. A 558kWp single-axis tracker consisting 1800 BYD PV modules (310 Wp), 8 SMA inverters (60 kW), 20 modules in series per string, 90 strings in parallel, and an annual soiling loss of 5% was considered in the modelling. Figure 11 presents the results of the model.

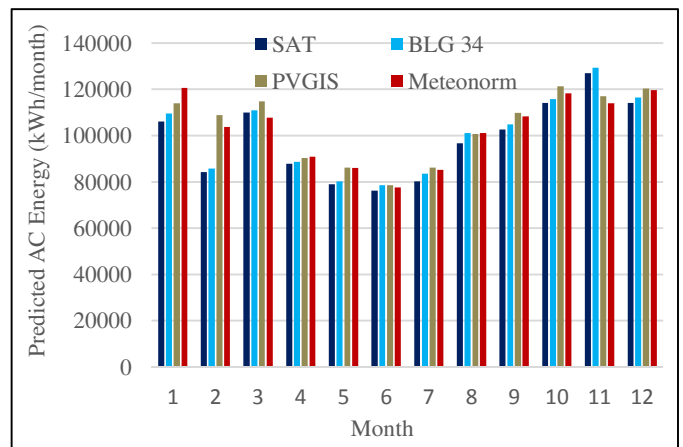


Fig. 11: Predicted AC energy for the CSIR single-axis PV plant from four GHI estimates

The modelled AC energy correlates to the GHI data observed in Figure 7. In the month February, the predicted AC energy from satellite-based GHI is higher compared to ground-based GHI and lower in November, which is in line with the GHI input data. The annual predicted AC energy using GHI from Building 34 and SAT is 3.6% and 5.9% lower compared with using PVGIS and 2.4% and 4.7% lower compared with using Meteonorm data, respectively.

4. Conclusion

In this study, the satellite-based TMY data is compared with ground-measured GHI data. Two pyranometers installed at CSIR Pretoria campus for ground measurement are compared and observed with an average difference of 0.04% on a single clear sky day. The ground measured GHI data at CSIR was compared with another ground measurement station for GHI at UP in Pretoria and observed a relative difference of 1.4% in the total insolation measured for a period of 8 months. The satellite-based PVGIS and Meteornorm TMY data is 4.9% and 3.6% higher in comparison with measured ground-based GHI data measured adjacent to the PV plant at the CSIR Pretoria campus during the calendar year 2017. Nearly 99% of the variability in AC power can be explained by the plane of array irradiance using simple linear regression. The DC energy output was predicted using SAM for both satellite-based and ground-based GHI data. The annual AC energy generation based on ground-based GHI measurements predicted 3.6% and 5.9% lower compared to PVGIS and 2.4% and 4.7% lower compared to Meteornorm TMY data, respectively. The AC energy predictions correlate with the insolation data input to SAM.

Acknowledgements

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