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Measurement of Solar Irradiance for Determining the Optimal Tilt Angle for Photovoltaic Panels

Gbadebo I. Olatona* and Tolulope J. Fadairo
Department of Physics, Osun State University, P.M.B. 4494, Osogbo, Osun State, Nigeria.
E-mail addresses: olatonagi@uniosun.edu.ng, toluwalopefaddy@gmail.com
**Corresponding author*
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Abstract

The challenge of solar panel installers in determining the tilt angle needed to obtain optimal performance from the photovoltaic panels was the focus of this paper. The performances of two 150 W panels under varied conditions of temperature and solar irradiance on a plane at two different heights (1 m and 11.5 m) from the ground surface were determined to find the effects of tilt angle and altitude on their performances. Measurements of solar irradiance, temperature, open-circuit voltage, and short circuit current were made at various tilt angles and compared to one another based on the measured irradiance. The optimal tilt angle at the experimental site was found to be 15°SW (165°). At this angle, the irradiance was 818.05 Wm^{-2} compared to 792.26 Wm^{-2} at 15°NE (15°), 780.44 Wm^{-2} 45°NE (45°) and 767.63 Wm^{-2} at 45°SW(135°) at 1 m from ground surface, while at 11.5 m the irradiance at 15°SW was 861.99 Wm^{-2} compared to 685.98 Wm^{-2} at 15°NE, 624.33 Wm^{-2} at 45°NE and 676.49 Wm^{-2} at 45°SW. Hence the performance of a photovoltaic panel solely depends on the tilt angles relative to the height at which the panel is mounted.

Keywords: Solar, Irradiance, Photovoltaic, Panels, Tilt angle.

Introduction

All over the world, the importance of renewable energy for economic and socio-developmental processes is not in doubt and the bountiful solar energy falling on the Earth's surface is one of Nigeria's most important renewable energy alternatives. More so, solar energy is an important renewable energy source both in the generation of heat and photovoltaic electricity.

Due to the inexhaustible sunshine available all year round in Africa compared to the environmental effects of fossil fuel alternatives, the cost-effective and efficient applications of solar energy seem unavoidable. As a result, it is necessary to establish radiation estimation stations with the proper infrastructure in regions of comparative latitude all over the country in order to collect quality data on solar radiation. The measurements of solar radiation are important due to numerous applications of solar energy designs and installation to harness the sun's energy for effective uses. With a daily average solar radiation of about 5.2 $KWHrm^{-2}day^{-1}$ all year round, Nigeria receives a lot of solar energy that is available for harness and usage in various applications, according to Chineke et al. (2010). The estimation of global solar radiation obtained through the well-known Angstrom-Prescott equation in 1924 had been a choice for researchers but pyranometers are now available for direct measurement of the solar irradiance, though the setup could be very expensive and delicate, according to Olatona (2018).

As the world moves its attention away from fossil fuels towards clean and renewable energies, photovoltaic (PV) usage will continue to grow rapidly. The PV output parameters are majorly influenced by solar radiation and temperature, thus making these parameters highly significant. These two quantities (solar radiation and temperature) were measured using a hand-held solar meter and thermometer, respectively because industrial-grade devices for measuring solar radiation are delicate and expensive.

Careful observations show that the output of a PV panel is proportional to exposure to direct solar irradiance (Haider and Nader 2017). However, the panel is fixed in position while it moves relative to the Earth's rotation. Hence, the need to know the optimal tilt angle that would produce maximum PV output from an array of panels for regions or location of similar latitude. Although solar irradiance varies due to weather and climatic changes, we can categorize and measure the range using the synopsis reading obtained from the pyranometer.

Therefore, the goal of this work was to create a high-quality solar irradiance and solar PV power output resource mapping dataset at Osun State University, Osogbo, Osun State, Nigeria using two 150-Watt panels as well as developing a method for estimating solar irradiance and tilting of PV panels to get the optimal power out of solar modules.

Renewable energies are clean energies obtained from natural sources such as sunlight and wind. Their availability being dependent on time and weather. These variations are also unpredictable because they depend on synoptic weather conditions, especially at night (Mork et al. 2010). Solar energy is convertible to thermal or electrical energy. One of the best advantages of solar energy is its abundance in nature and inexhaustibility when compared to coal, gas, or any other fossil fuel. It is also more environmentally friendly. This has resulted in the rapid growth of solar installations around the world in recent years. Knowledge of solar energy, ideally gathered over a long period of time, should be valuable not just to the community where the radiation data is collected, but also to regions of the world of similar latitude (Augustine and Nnabuchi 2010). On the other hand, solar radiation is the radiant energy from the sun that supplies light, warmth and energy to the Earth. This radiant energy is necessary for the economic and natural development of the people who live on the planet. Averaged over day and night, as well as across all parts of the world, the solar radiation at the best of the atmosphere, according to Olayinka (2011) is 175×10^{15} W or 342 Wm^{-2}. Photovoltaic energy is clean, and utilized in a variety of applications. The rising usage of photovoltaic (PV) panels as energy sources and environmental friendliness call for its inclusion on national electric grids. In view of this, the estimated solar irradiance for power production is required for forecasting and power modelling.

The energy produced from the PV panel is influenced directly by solar irradiation, which means during cloudy weather, the PV module produces little power and does not generate electricity at night (Ibrahim et al. 2019). Over the years, photovoltaic (PV) usage has grown significantly in Nigeria, with environmental benefits such as no air or water pollution, very little water use, abundance as a resource, silent operation, long lifetime, and low maintenance in contrast with other alternative sources. The measurements, however, may be impacted by (unnoticed) control actions (Akinyele et al. 2015).

The degree of tilt of photovoltaic panels facing south or north should easily slide west or east around a horizontal axis, which would receive more incident radiation than panels mounted horizontally. A panel mounted at an optimal tilt angle that swivels evenly around a horizontal axis is a question for modellers and installers (which allows both the vertical and horizontal axis of the PV to track the sun during the day). Estimates derived by NREL PV Watts in the range of 1–4 regions in some countries around the globe (NREL 2017) use the nearest meteorological stations to evaluate tilt angles in each country examined. These tilt angles are assumed using meteorological conditions from a specific location (Jacobson and Jadhav 2018). As a result, installers would have to perform precise calculations, at each location, and keep records for specific regions of comparable latitude to determine the best tilt angle.

In order to account for the high inter-annual variability of the data, PV Watts, a tool that evaluates the annual-averaged solar production in all countries that permit slanted panels, relies on each station's average year meteorology.

Materials and Methods

Description of study area

The study area of the research is located at the roof of the 11.5 m tall College of Basic and Applied Sciences, Osun State University, Osogbo Campus latitude 7.762°N and longitude 4.601°E, in the southwest region of Nigeria.

Data collection

The following instruments were employed in collecting the data: digital pyranometer (solar power meter), thermometer, and multi-meter. Also, the solar panels were mounted at two different levels to obtain the daily solar irradiance, air temperature current, and voltage using the range of the peak sunshine hours in Nigeria (6 hours) WAT GMT + 1 on a horizontal surface and different panel tilt angles (180°, 15°NE, 45°NE, 15°SW and 45°SW).

Method of experimentation

The fieldwork comprises primarily two PV modules of the same model and ratings placed at different heights of 1 m and 11.5 m from the ground surface, 1 m, being the lowest distance, a solar farm can be installed while 11.5 m is the height of the tallest building at the experimental site. The setups at the two locations, 1 m and 11.5 m were shown in Figures 1 and 2, respectively. Both setups were free from shadows from buildings during the period of the experiment. The test was carried out by connecting the measuring meter to the positive and negative ends of the photovoltaic panel while measuring the voltage and current using an AVO meter. A thermometer and pyranometer were used to measure the temperature and solar irradiance from daytime hours of 10 to 16, West African Time, at various tilt angles (15°, 45°, 135°, 165°, and 180°) against the sun. The measurements were carried out over a period thirty days and the readings were averaged. This study is limited to two experimental heights due to the limitation of available resources.

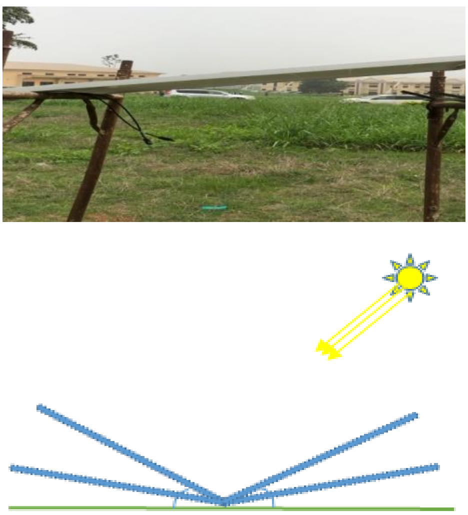

Figure 1: Experimental setup at 1 m from the ground.

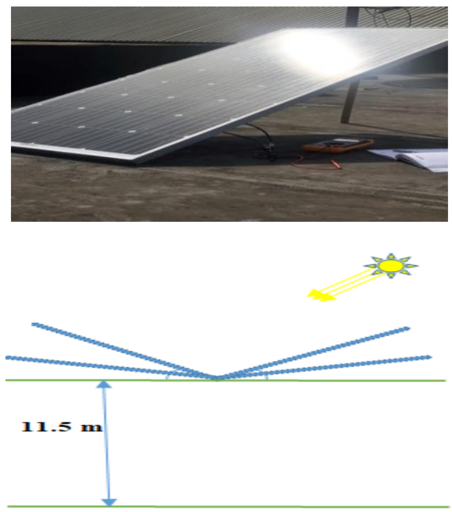

Figure 2: Experimental setup at the roof of the building 11.5 m.

Results and Discussion

Figure 3 shows hourly data obtained between the hours of 10 and 16 local time for 30 days at two different heights of 1 m and 11.5 m, at latitude 7.762°N and longitude 4.601°E as a case study in this region. It shows that on sunny days the direct irradiance received is high though about 40% were reflected on an hourly average. It is evident from the readings that there is a better reception of solar irradiance hitting the panel at 11.5 m with an average of +5.6% compared to that at 1 m.

Observed solar irradiance synopsis

The data of solar irradiance taken from the experimental site used to analyse the observed synopsis in this study is on average hourly and daily time-series measurements. These synopses when compared to the measured data could predict the output current of panels with a similar rating.

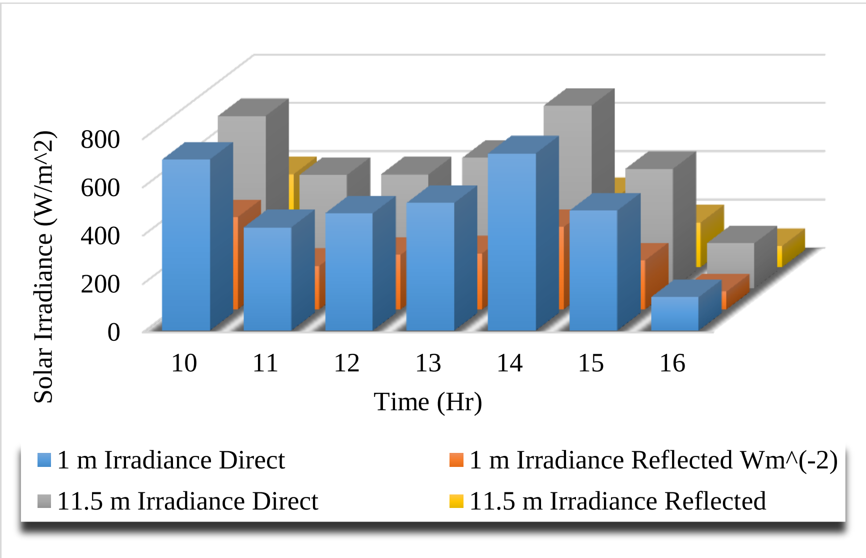

Figure 3: Direct and reflected irradiance at 1 m and 11.5 m on a sunny day.

Rainy weather irradiance synopsis (0–100 Wm^{-2})

The rainy weather could range from minor drizzling to heavy rainfall, and clouds with 4 to 7 oktas associated with the rainy season, moving over the panel, typically diminish significantly the amount of solar irradiation that reaches the Earth's surface. During this period, the irradiance obtained was in the range of 0–100 Wm^{-2}, and the current output was between 0.5 A and 2 A.

Overcast/Cloudy synopsis (101 Wm^{-2}–300 Wm^{-2})

During the overcast weather when the cloud was between 1 to 3 oktas, solar irradiance ranged from 100 Wm^{-2} to 300 Wm^{-2}. Due to the sheer clouds, solar radiation on a cloudy day varies more than on a clear day; current outputs on a cloudy day range from 2 A to 4 A.

Clear sky synopsis (301 Wm^{-2}–500 Wm^{-2})

When there are clear skies for instance when the cloud is 0 okta, it was observed that across the entire sky dome, there were no clouds seen, the solar irradiance rose to a range between 301 Wm^{-2}–500 Wm^{-2}, while the current ranged from 4 A to 6 A.

Sunny synopsis (500 Wm^{-2}–1000 Wm^{-2})

Solar radiation varies greatly on a sunny day, ranging from 500 Wm^{-2} to 1000 Wm^{-2}. This is lower than the maximum recommended maximum solar radiation measured on the ground surface which is

1122.2 Wm^{-2} according to Mayfield (2012). However, the daily mean solar radiation is 630.0 Wm^{-2} (from sunrise to sunset) for 30 days. Current at this irradiance level ranged between 6 A and 11 A. Solar irradiance transmittance increased to the peak between local noon, corresponding to 12 hours, and 14 hours then dropped linearly, which was due to rising cloud fractions. Solar panels only produce energy when the light is partially or fully incident on the cells. Hence, when it is cloudy, stormy, and rainy, only a little parcel of light is incident on the cells. As a result, PV cells are not able to create as much power as on clear sky and sunny days.

Results of direct and reflected solar irradiance data at the experimental station

Solar irradiance from the experimental site varies over the day while peaking within the hours of 10 to 14. At this time, the weather is sunny and from the synopsis observed, the radiance received is above 500 Wm^{-2}. The reflected irradiance is as a result of the scattered radiation being a component of the total global radiation including the ground reflected radiation (albedo). The direct irradiance received is more than the reflected. This allows the PV to absorb more irradiance that enabled a better performance of the PV.

Figure 4 shows the differences between the received irradiance on the PV and that of the reflected irradiance on a clear sky day on an hourly basis from 10:00 hours to 16:00 hours and it was compared with the measurement at heights 1 m and 11.5 m, respectively to show the surface which received more irradiance.

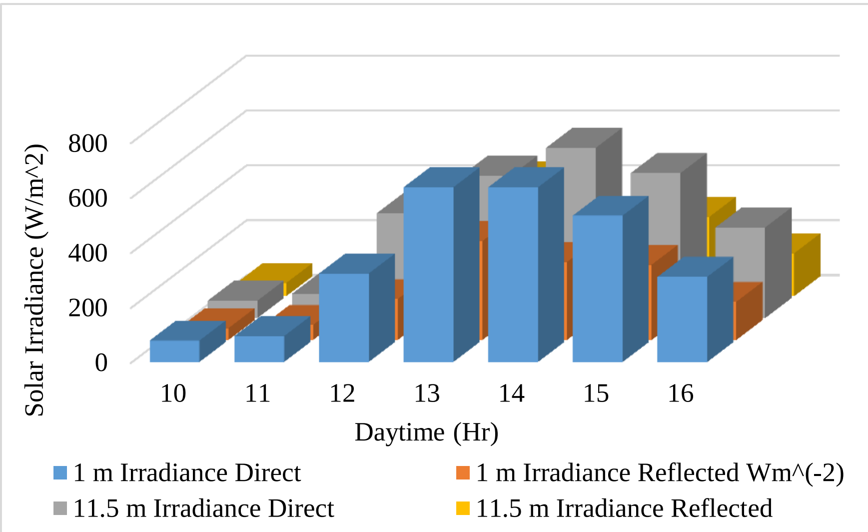

Figure 4: Comparison of direct and reflected irradiance on a clear sky day at 1 m and 11.5 m.

Temperature at different heights considered

Figure 5 shows the variations of temperature per hour of the two heights (1 m and 11.5 m) recorded in the region. From this, it is evident that the average hourly temperature at 1 m decreases by 2.42% compared to 11.5 m

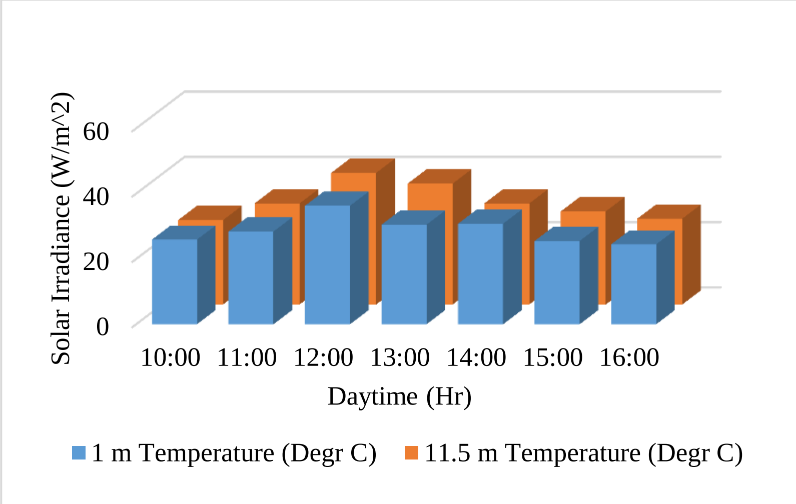

Figure 5: Solar irradiance variations with temperature at 1 m at 11.5 m heights.

Effect of temperature rise on PV panel's voltage and current

Heat can reduce the output efficiency of photovoltaic panels rated at a temperature of 10–25% standard test condition (STC) depending on the installed areas. The voltage output which is expected to reduce linearly did not due to the cool weather (cloudy) around that period of the year (May–July) at the experimental site and hence, the effect on the panel's power production is not as expected. This is because the current also increased significantly during the period of the experiment. The temperature increased to about 40 °C which is equivalent to +10% of the actual rating.

When the temperature reaches 40 °C, the voltage V_{oc} , dropped from the rated 22 V to 20.2 V. That on a daily average indicates a decrease of 4.44%, but because the drop is still within the ±5 % of the voltage rating, the drop was not enough to affect the performance of the PV.

Note: The output current of a solar panel increases as the temperature of the panel rises, even though the voltage output should decrease.

Characteristics of current, voltage, and power of the photovoltaic panel

The characteristics of current and voltage on the photovoltaic panel give a series of information on the power production and performance of the panel as shown in Figures 6a to 6e for the two heights considered and at various tilt angles. The output parameters examined are open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), and maximum power (P_{max}) then the optimal tilt angle was obtained to be 165°.

Figures 6a to 6e indicate that the solar panel installed at 11.5 m outperforms the solar panel mounted at 1 m. The short-circuit current (I_{sc}) at both heights increases in value from 9 A which was the actual rating under STC to 11A, respectively due to the irradiance. The high rate of solar radiation absorbed causes an increase in short circuit current I_{sc}.

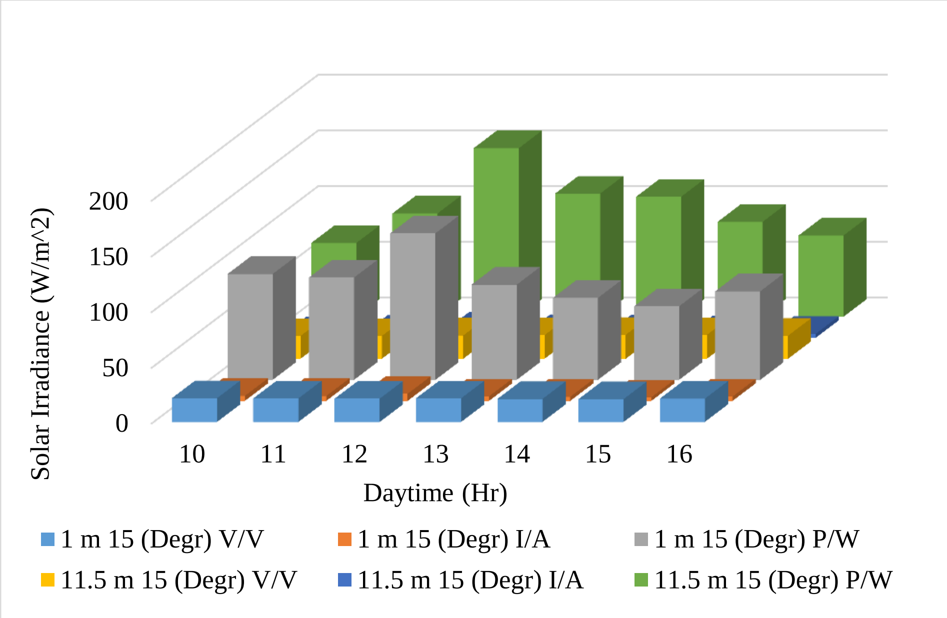

Figure 6a: Comparison of voltage, current, and power datasheet for 15° tilt angle at 1 m and 11.5 m.

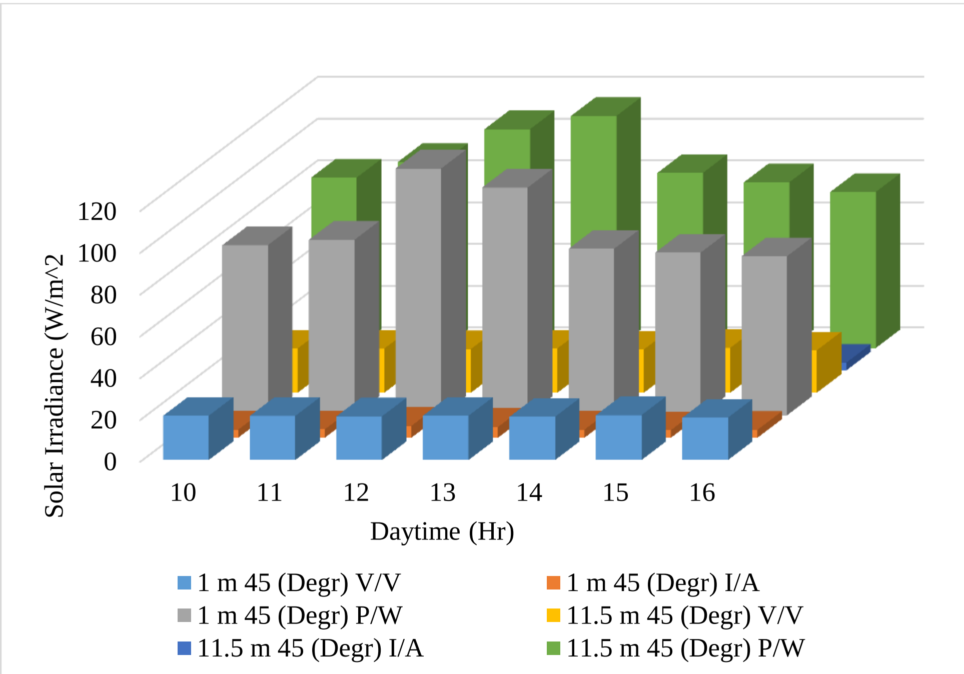

Figure 6b: Comparison of voltage, current, and power datasheet for 45° tilt angle at 1 m and 11.5 m.

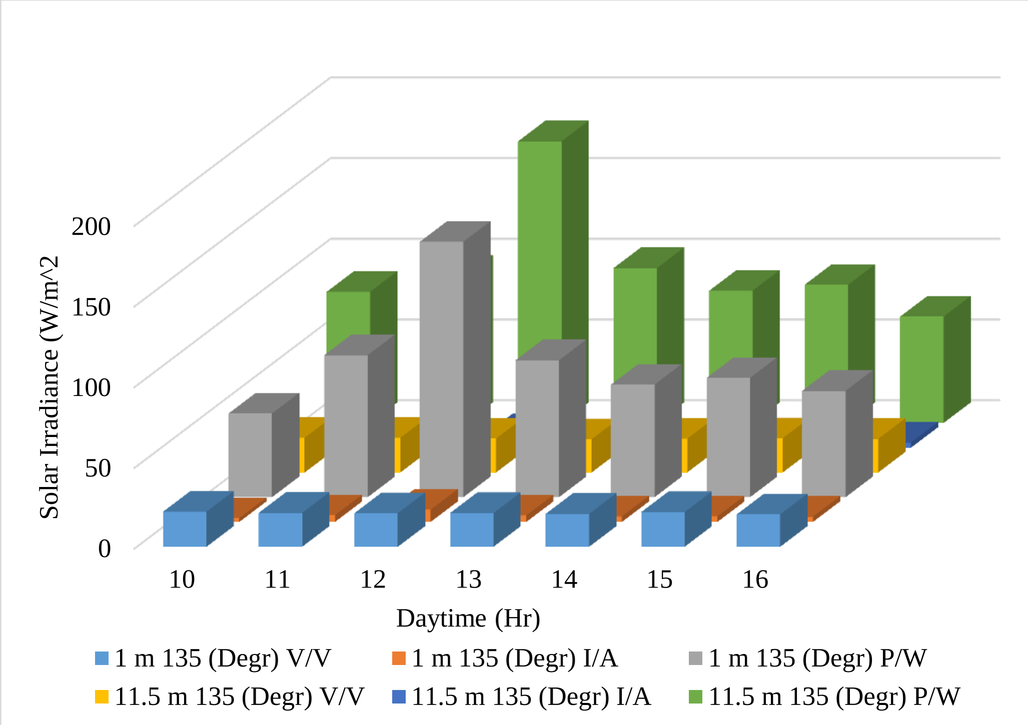

Figure 6c: Comparison of voltage, current, and power datasheet for 135° tilt angle at 1 m and 11.5 m (V = Voltage in Volts; I = Current in Ampere, A; P = Power in Watts, W).

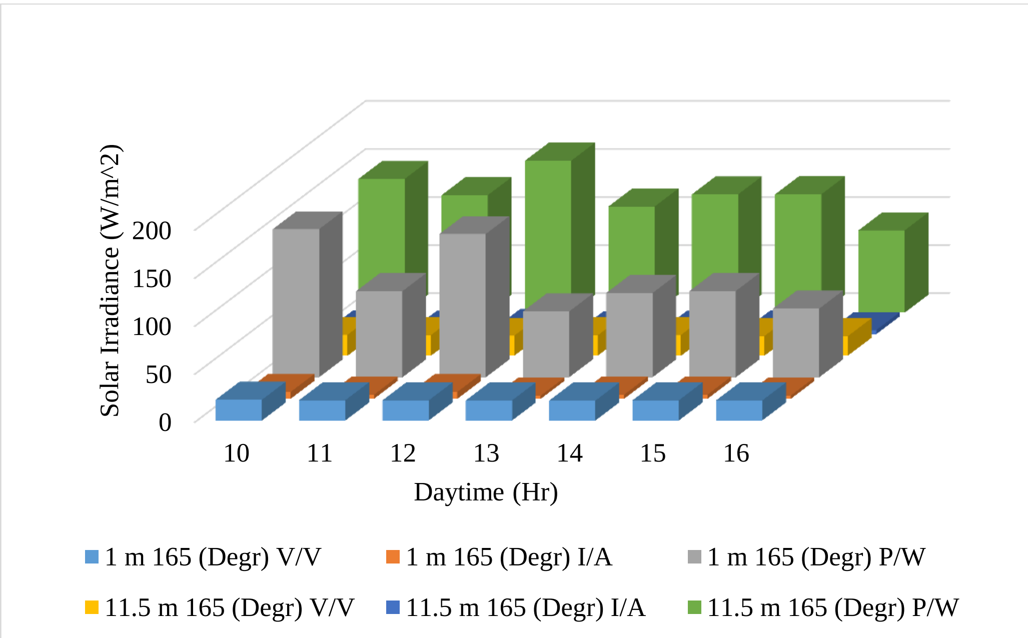

Figure 6d: Comparison of voltage, current, and power datasheet for 165° tilt angles at 1 m and 11.5 m.

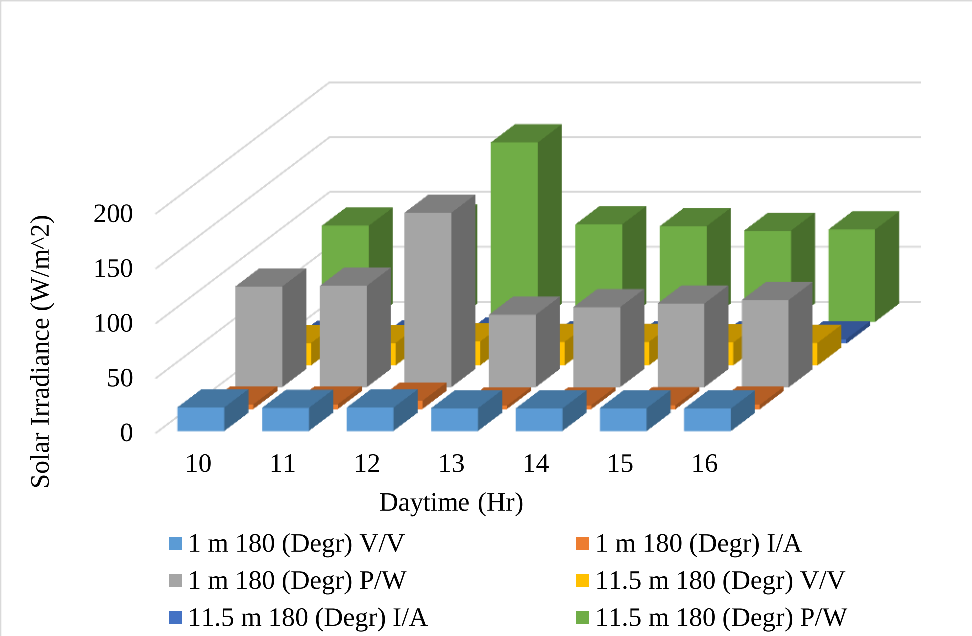

Figure 6e: Comparison of voltage, current, and power datasheet for 180° tilt angles at 1 m and 11.5 m.

Tilting at different heights

It is known that there is a dependence of direct irradiance on the angles when the panel is tilted to produce maximal power; Tables 6a to 6e show the results of the measured power at each considered tilt angle.

Figure 7 shows a comprehensive datasheet showing the direct and reflected irradiance, the various experimental angles and their respective power outputs, for the two heights, which would be beneficial in helping those specialized in the field and installers to determine the optimal tilt angle to use in the site for installation and what to expect as power production for efficient uses at Osogbo, South West, Nigeria.

$$P = \frac{1}{h \sin\theta (Rd + Rr)} * e + IV$$

Where: R = Total radiation;
R = Rd + Rr;
Rd = Measured direct irradiance;
Rr = Measured reflected irradiance;
I = Current; V = Voltage; h = Height;
e = Efficiency of the panel; and
θ = Tilt angle.

$\text{Sin}\ \theta = \frac{Opposite}{Hypotenuse}$ of tilted panel

$\text{Sin}\ \theta = \frac{38.5}{148} = 0.2601$

$\theta = \sin^{-1}(0.2601)$

$\theta = 15°$

I and V vary as a result of measured R.

Experimental validation

The results from the experiments showed that the optimal tilt angle was 165° (15°SW) at the experimental site, 7.762°N, 4.601°E. The temperature increases with irradiance, for example, the temperature at 11.5 m is more than at 1 m. Since there is no solar farm or photovoltaic power station connected to the national grid in Nigeria, the optimal tilt provides PV potential acceptable for stand-alone system configurations. Due to the change in latitude, the PV panel output of various tilt angles will be different, hence knowing the estimate of solar radiation will now be easy with the synopsis observed and grouped. This estimate is valid for use in any region but the tilt angle can never be the same. Mohammed (2019) obtained an optimum tilt angle of 35° for all day in the year for panels facing south installed in Baghdad. However, Raptis et al. (2019) found the optimum tilt angle to be 30° for model calculations for various tilt angles in Greece on year basis, while Masili and Ventura (2019) simulated the optimal tilt angle for the city of Sao Carlos, Brazil (-22° 01' 03 '' S longitude -47° 53' 27 '') and obtained 23.22° for all year round. These results confirm that optimal tilt angle is region specific.

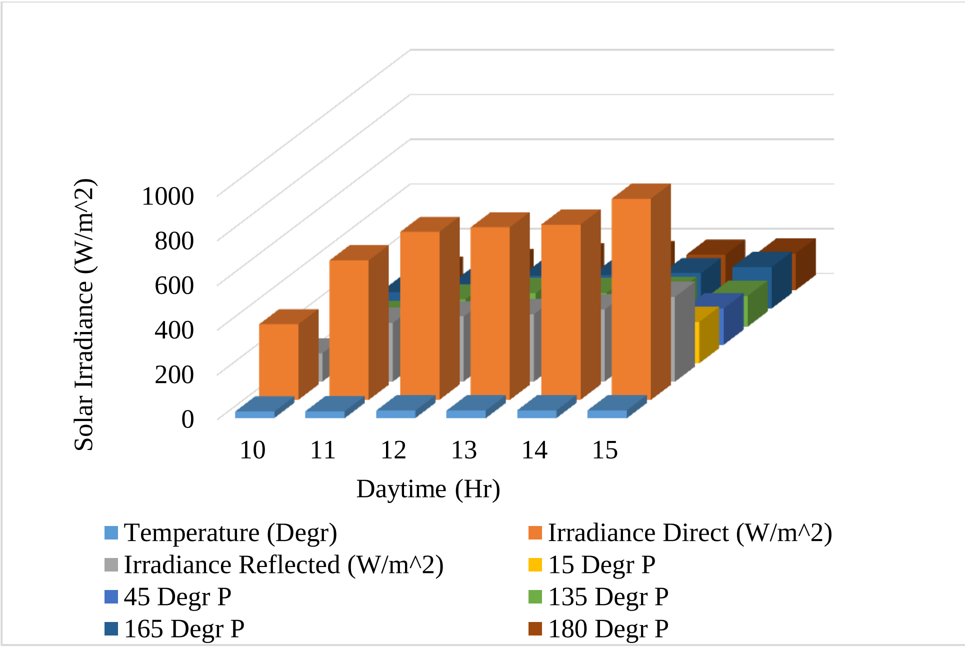

Figure 7: Solar irradiance and PV power output dataset for 15°, 45°, 135°, 165° and 180°.

Conclusion and Recommendation

This real-time experiment contributes to the study of parameters that determine a photovoltaic module's performance in a real-world application. The two 150 watts panels were subjected and tested under two weather conditions which served as our input parameters to determine and analyse the solar irradiance received which were grouped into rainy, cloudy, clear sky and sunny synopses.

It was observed that as the temperature increases, both the direct and reflected irradiance increase irrespective of the tilting angle. Also, the power derivable from the solar panels is dependent on the tilting angle. At 165°, the power is more at 11.5 m than at 1 m. The utilization of these observations as proxy measurements or as training data for PV forecasting would have significant impacts on PV state estimation and system performance prediction, respectively. Weather conditions (solar irradiance: as grouped into synopsis, temperature) tilt angles: as considered in this paper, and inappropriate ratings such as using different panels of different wattages, current and voltages are all factors that might influence PV performance and prevent an installer or an engineer to determine the optimal tilt angle for installation. As a result, the impacts of these variables on the solar panel should be assessed alongside the analysis of temperature variability and expected trends.

The investigation shows minor seasonal variations in the average temperature on a monthly time frame. Solar irradiance analysis shows that the radiation received on a plane varies inconclusively due to weather conditions. Despite that fact, we foresee an abundance of solar irradiance within the dry season; tilt angles ought to be considered for the optimal generation of power when using the PV, while installers should use the optimized tilt angles in their respective region and also regions of similar latitudes with Osun State University, Osogbo Campus and environs should use the optimized angle of 15°SW when installing their PVs'.

The study's measurement methods and analysis help to better understand the performance of the mounted and tilted PV modules. The paper also discusses the effects of temperature on the surface of a tilted PV module. The results of the measurements revealed that the PV modules specified ratings are achievable. The cause of the power loss in the PV system is as a result of 11.8% increase in the panel temperature that led to a decrease in solar irradiation absorption, which in turn led to a decrease in power output.

The real-time experiment enhances the understanding of parameters that influence the performance of a photovoltaic module in a real application. The use of these observations as proxy measurements or as training data for PV forecasting would have great impacts on the estimation of the PV state and prediction of the system performance, respectively.

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