ASSESSMENT OF POTENTIAL SOLAR PV OUTPUT DERIVED FROM REMOTELY-SENSED SOLAR IRRADIANCE DATA AND DIFFERENT TILT ANGLES

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ABSTRACT: Solar photovoltaic (PV) systems are one of the most utilized renewable energy sources for households and commercial spaces which are primarily installed on rooftops. Such systems can be considered as an appropriate response to support the United Nations' sustainable development goals (SDGs), particularly goals 7, 11, and 13. However, the maximum energy utilization in these spaces is affected by factors such as solar irradiance, tilt angles, temperature, and dust. Power generated by solar PV systems depends highly on solar irradiance that reaches the solar panels. This study assessed the difference between the actual and estimated potential solar PV power output (PPV) at varying tilt angles of 5°, 10°, and 15° from the horizontal plane. The calculated PPV used the remotely-sensed (RS) AHI-8/9 Shortwave Radiation (SWR) product adjusted for high temperature and dust effects. The said adjustment used other RS data, including temperature, precipitation and other meteorological factors. To investigate the effect of different module tilt angles on solar PV power production, solar radiation reaching the surface ($R_{surface}$) was estimated using the adjusted SWR data, the latitude of the location and the day of year. The potential solar PV output at three different tilt angles was then compared using two methods. First, the analysis of variance (ANOVA) was used to assess if there exists a significant difference between the actual and potential solar PV output for the three tilt angles. Second, a t-test was employed to determine whether there is a significant difference between the actual and potential solar PV output at each tilt angle. Solar PV power output from April to May was estimated at 2.76 W to 951 W, with a mean of 505.30 W for different tilt angles. Meanwhile, the actual PV outputs ranged from 300.96 to 1118.53 with a mean value of 772.233 W. Moreover, the p-values obtained from a two-sample t-test at a 95% confidence level per angle also showed no significant difference between the actual and potential solar PV output values. This signifies that theoretical values of PV power potential (PPV) can substitute for the unavailable in situ data. Results show that the seasonal fixed optimum tilt angles are 15°, 10°, and 10° tilt angles for the cool dry season, hot dry season and rainy season, respectively and the annual fixed optimum tilt angle is computed to be at a 10° tilt angle. In conclusion, changing the tilt of the panel to the optimum tilt will produce a higher solar PV output than directly installing panels on rooftops or terrains. For future works, a validation of the PPV using actual data with a longer time horizon on multiple locations and a cost-benefit analysis of optimizing the tilt vs. directly installing on the terrain may be considered.

1. INTRODUCTION

Solar photovoltaic (PV) systems are one of the most utilized renewable energy sources for households and commercial spaces, primarily installed on rooftops (Yao & Zhou, 2023). Such systems can be considered as an appropriate response to support the United Nations' sustainable development goals (SDGs), particularly on affordable and clean energy (SDG 7), sustainable cities and communities (SDG 11), and climate action (SDG 13). The deployment of rooftop solar PV systems has also spread rapidly through net metering and fiscal incentives (IRENA, 2019). In the Philippines, the market for rooftop solar PV systems is nascent and is projected to reach a total installed capacity of 300 megaWatts (MW) by 2025 (Lackovic & Ruiz-Cabrero, 2021). By maximizing the country's RE potential, including the utilization of rooftop solar PV, could help reach its renewable energy (RE) capacity goals of 35% RE share by 2030 (PNA, 2021). However, rapid deployment of this technology doesn't necessarily translate to optimum utilization of the energy resource since the maximum energy utilization of solar PV systems is affected by: (1) meteorological factors such as solar irradiance (Sotto et al., 2023), temperature (Principe & Takeuchi, 2019), dust and precipitation (Bauzon et al., 2022a), and (2) geomorphological factors such as tilt angles (Yunus Khan et al., 2020). Literature shows that while solar PV power output depends on meteorological factors (Das et al., 2018; Harrou et al., 2020; Paulescu et al., 2013), panel tilt also matters and varies per location (Yadav & Chandel, 2013; Yunus Khan et al., 2020). Although the performance of a solar PV installation depends on its tilt angle with respect to the horizontal and orientation with respect to the equator (Soulayman & Sabbagh, 2015), fixed solar PV panels are still the most widely used technology due to its lower capital, operations and maintenance costs compared to solar tracking installations (Diaz et al., 2014). Therefore, finding the optimum tilt angle for fixed solar PV panels is important to maximize solar energy production. Yunus Khan et al. (2020) provided a comprehensive review of the optimum tilt angle obtained daily, monthly, and annually and they found that instead of constantly changing the tilt angle daily, the monthly average tilt angle provides a similar level of solar radiation throughout the year.

The study of Chinchilla *et al.* (2021) evaluated 2,551 locations worldwide and provided location-specific models that calculate the optimum annual tilt angles as a function of latitude, which helped designers conveniently identify optimum tilt angles in the absence of meteorological data, often the case for small installations and locations globally. Jacobson & Jadhav (2018) also estimated the optimal solar PV tilt angles for all 195 countries in the world using PVWatts (NREL, 2017) and taking into account temperature, wind speed, solar panel characteristics, and panel orientation. Their study identified that for the Philippines, the optimal tilt angle is at 9°, but was rounded to 10° following the general industry practice which allows the rain to wash them naturally. They also recommended that installers calculate the optimal tilt angles for their location to ensure greater accuracy. Meanwhile, Gharakhani Siraki & Pillay (2012) emphasized the importance of taking into account the climate condition and latitudes when calculating for the optimal panel tilt. Regarding climate conditions, the Philippines has a tropical climate that can be divided into two major seasons according to DOST Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA, 2015). The rainy season occurs from June to November while the dry season can be further categorized to cool dry season from December to February and hot dry season from March to May. From the study by Bauzon et al. (2022b), it can be observed that the highest and lowest solar radiation values are received during the months of March and December, respectively. Regarding latitude, Philippines, with a latitude ranging from 4°23' and 21° North (N), is located in the tropics where the sun hits the ground almost perpendicularly most of the year (Reppert & Seman, 2021). Due to the spherical shape of the earth, greater amounts of radiation per unit area and unit time are received in tropical regions compared to areas at higher latitude (Levin, 2013).

Following the recommendation of Jacobson & Jadhav (2018), this study assessed the optimal tilt for the Philippines using estimated potential solar PV power output (PPV) derived from remotely-sensed solar irradiance data, and were calculated based on the work of Principe & Takeuchi (2019) which accounts for the effects of meteorological parameters on solar PV output. To validate the estimated PPV performance and its usability for future work, this study compared it using actual data from a rooftop solar PV installation at different tilt angles which will be further discussed in Section 2. Furthermore, this work utilized meteorological data with the highest spatial and temporal resolution for the Philippines, ensuring location-specific accuracy. The main objective of this study is to develop a methodology for finding the monthly, seasonal, and annual fixed optimum tilt angles in the Philippines while accounting for the dust and high temperature effects on solar PV panels.

2. MATERIALS AND METHODS

This study assessed the difference between the actual and estimated solar PV power output (PPV) at varying tilt angles of 5°, 10°, and 15° from the horizontal plane. 10° tilt angle was used as the base angle for the experimental procedure (Jacobson & Jadhav, 2018). With a ±5° tolerance to observe the behavior of the actual PPV output as the tilt changes, 5° and 15° tilt angles were set as the lower and upper limit of this study. Figure 1 shows the workflow diagram of the solar radiation incident to the module surface ($R_{surface}$) in watts per square meter (W/m^2) and solar PV power output (PPV) in megawatts(MW) processing using QGIS, a free and open-source geographic information system (GIS) software (QGIS, 2023).

2.1 Materials

2.1.1 Remotely-sensed Data

This study used Year 2020 Level 2 FengYun-4A (FY-4A) Surface Solar Irradiance (SSI) from China Meteorological Administration (CMA) National Satellite Meteorological Center (NSMC). FY-4A is a Chinese geostationary meteorological satellite with an advanced geosynchronous radiation imager (AGRI), geostationary interferometric infrared sounder (GIIRS), and lightning mapping imager (LMI) instruments onboard (NSMC, 2023). Meanwhile, SSI is an AGRI product of FY-4A with a 4000x4000m spatial resolution and a 15-minute temporal resolution. To extract the solar irradiance data, the full disk NetCDF SSI data was converted and georeferenced to the WGS84 geographic coordinate system to make it parallel with other datasets.

Other data products used were ERA5 Reanalysis Temperature and Wind Speed datasets (2020) (Hersbach et al., 2020; Setchell, 2020), and Angstrom Exponent, Aerosol Optical Thickness and Precipitation datasets from JAXA Himawari (2017-2021) (Bessho et al., 2016; EORC & JAXA, 2022). ERA5 is a product European Center for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate from 1940 to present. It provides hourly estimates of multiple atmospheric, land and oceanic climate variables. (Hersbach et al., 2020; Setchell, 2020) JAXA Himawari aerosol and precipitation products were used for the computation of meteorological effects due to its high spatiotemporal resolution compared to FY4A and ERA5 products. (Bauzon et al., 2022a; EORC & JAXA, 2022) All datasets used in this study were resampled to 5 km spatial resolution and hourly temporal resolution raster data in GeoTIFF format for uniformity in the next processing stages.

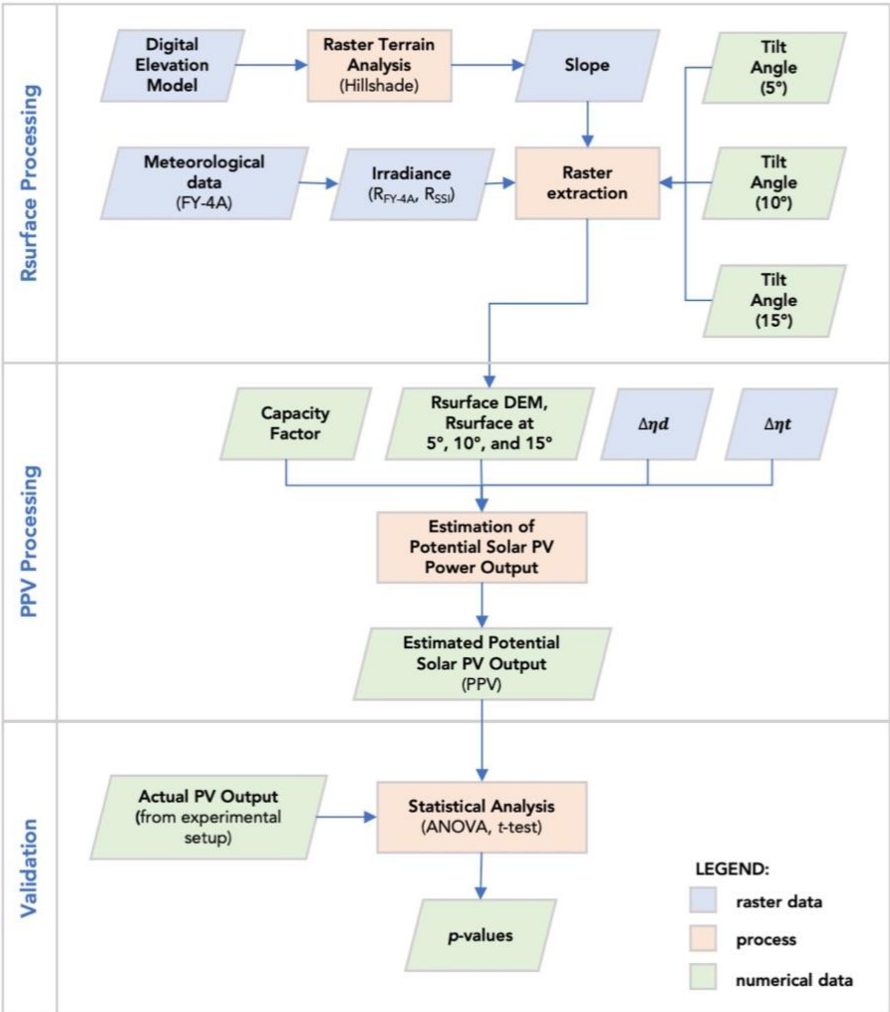

Figure 1. Workflow diagram of $R_{surface}$ and PPV Processing using QGIS.

2.1.2 Experimental Data

The actual solar PV production was extracted from an experimental setup in Muntinlupa City, Philippines from April 20, 2023 to May 19, 2023 and measured hourly from 6:00AM to 5:00 PM. Figure 2 shows the experimental setup diagram, having three 120W monocrystalline solar PV panels at three different tilt angle configurations (5°, 10°, and 15°). Each panel was connected to its micro inverter and current sensor module. The whole set-up was attached to an ESP-32 microcontroller and a 5V DC power supply.

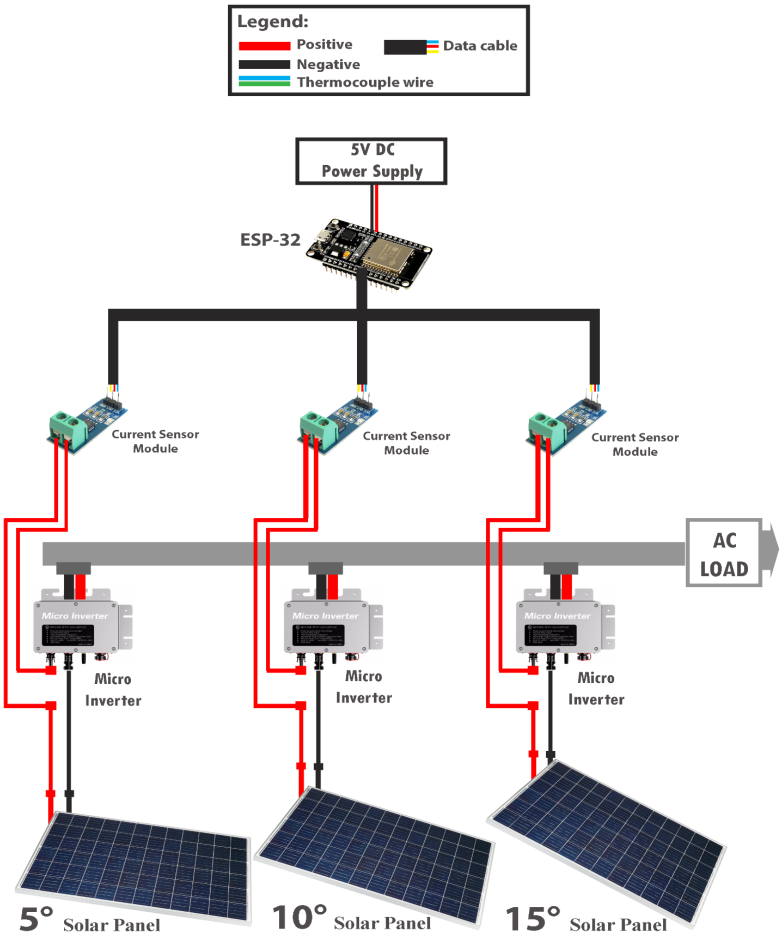

Figure 2. Diagram of Experimental Setup.

2.2 Estimation of $R_{surface}$

This work estimated the solar radiation reaching the surface ($R_{surface}$) to investigate the effect of different module tilt angles on solar PV power production. $R_{surface}$ was computed using Eq. (1):

$$R_{surface} = R\left(sin\left\{90^{\circ} - \phi + 23.45^{\circ} sin\left[\frac{360}{365}(284 + d)\right] + \beta\right\}\right) \quad (1)$$

where ϕ means latitude, *d* means day of the year, and β stands for module tilt angle. (Liu et al., 2017; Principe, 2019).

The 1x1 m spatial resolution slope was derived from a digital elevation model(DEM) using Hillshade Raster Terrain Analysis. The DEM-derived slope, referred to as actual slope ($Slope_{act}$), was used as the module tilt angle assuming that the panels will be installed directly on the angle of the roof surface or the ground. $R_{surface}^{Slope_{act}}$ was then calculated using the surface solar irradiance (SSI) data from FY4A, latitude of the location and slope as the module tilt angle.

$R_{surface}$ at 5° tilt angle ($R_{surface}^{5°}$), $R_{surface}$ at 10° tilt angle ($R_{surface}^{10°}$), and $R_{surface}$ at 15° tilt angle ($R_{surface}^{5°}$) were also calculated to compare PV power output of directly installing the panels on the ground or roof surface vs optimizing the tilt angle of panel installations. $R^{5°}_{surface}$, $R^{10°}_{surface}$ and $R^{15°}_{surface}$ were computed using Eq. (1) by substituting the predetermined 5°, 10° and 15° tilt angles to the module tilt angle ($\boldsymbol{\beta}$). $R_{surface}$ for the actual slope, 5°, 10° and 15° tilt angles were extracted and graphed vs. the corresponding day of year to show the variation of daily optimum tilt angle. Estimated $R_{surface}$ in each of the 4 cases($Slope_{act}$, 5°, 10°, and 15°) were averaged into monthly data for the year 2020.

2.3 Estimation of PPV

Solar PV power output (PPV) was obtained using Eq. (2) where the R used is the $R_{surface}$ defined as the solar radiation reaching the surface, A_{cell} is the total area of the study site and η is the capacity factor of the solar panel. (Liu et al., 2017; Principe, 2019) Estimated PPV was computed by subtracting combined effects of high temperature ($\Delta\eta_t$) (Principe & Takeuchi, 2019), dust and precipitation ($\Delta\eta_d$) (Bauzon et al., 2022a) to the theoretical PPV.

$$PPV = A_{cell}\eta R\ (1 - \Delta\eta_t - \Delta\eta_d) \tag{2}$$

2.4 Estimated PPV and Tilt Angles

The estimated potential PPV at three different tilt angles were compared using two methods. Firstly, the one-way analysis of variance (ANOVA) was used to assess if there exists a significant difference between the actual and potential solar PV output for the three tilt angles. It has a null hypothesis which states that there is no difference between means. Having a *p*-value greater than 0.05 means that the PPV can be used as an alternative should the actual solar PV output be unavailable. Secondly, a two-sample *t*-test was employed to determine whether there is a significant difference between the actual solar PV output and estimated PPV at each tilt angle. It has a null hypothesis that both are equal. Having a *p*-value less than 0.05 means that they are different and that the estimated PPV can be used as an alternative should the actual solar PV output be unavailable.

3. RESULTS AND DISCUSSION

3.1 Tilt Angles and Estimated $R_{surface}$

In order to investigate the effects of tilt angle, the $R_{surface}$ was calculated for different installation tilt angles. Figure 3 shows the normalized effect of change in tilt angle installation to the $R_{surface}$. Variation of monthly mean daily solar SSI radiation with different tilt angles for Colegio de Muntinlupa, Sucat is shown in Figure 4. Results show that for the study area, the average values of $R_{surface}$ range from 553.62 to 924.78 W/m^2 with the minimum irradiance occurring during the month of December in the cool dry season and the maximum during April for the hot dry season.

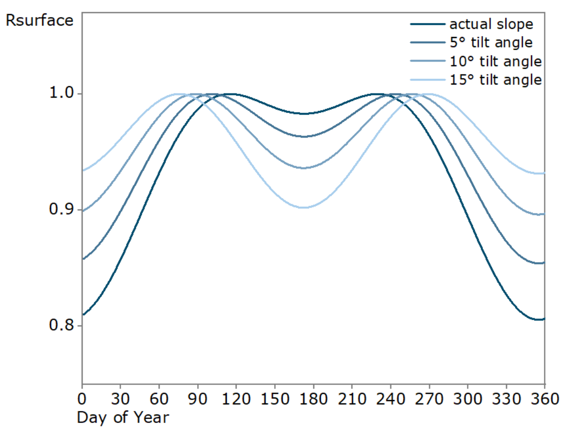

Figure 3. Day of Year vs Tilt angle.

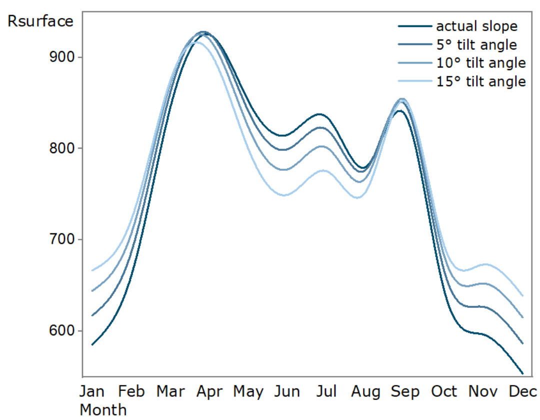

Figure 4. Monthly SSI at varying tilt angles of Colegio de Muntinlupa for Year 2020.

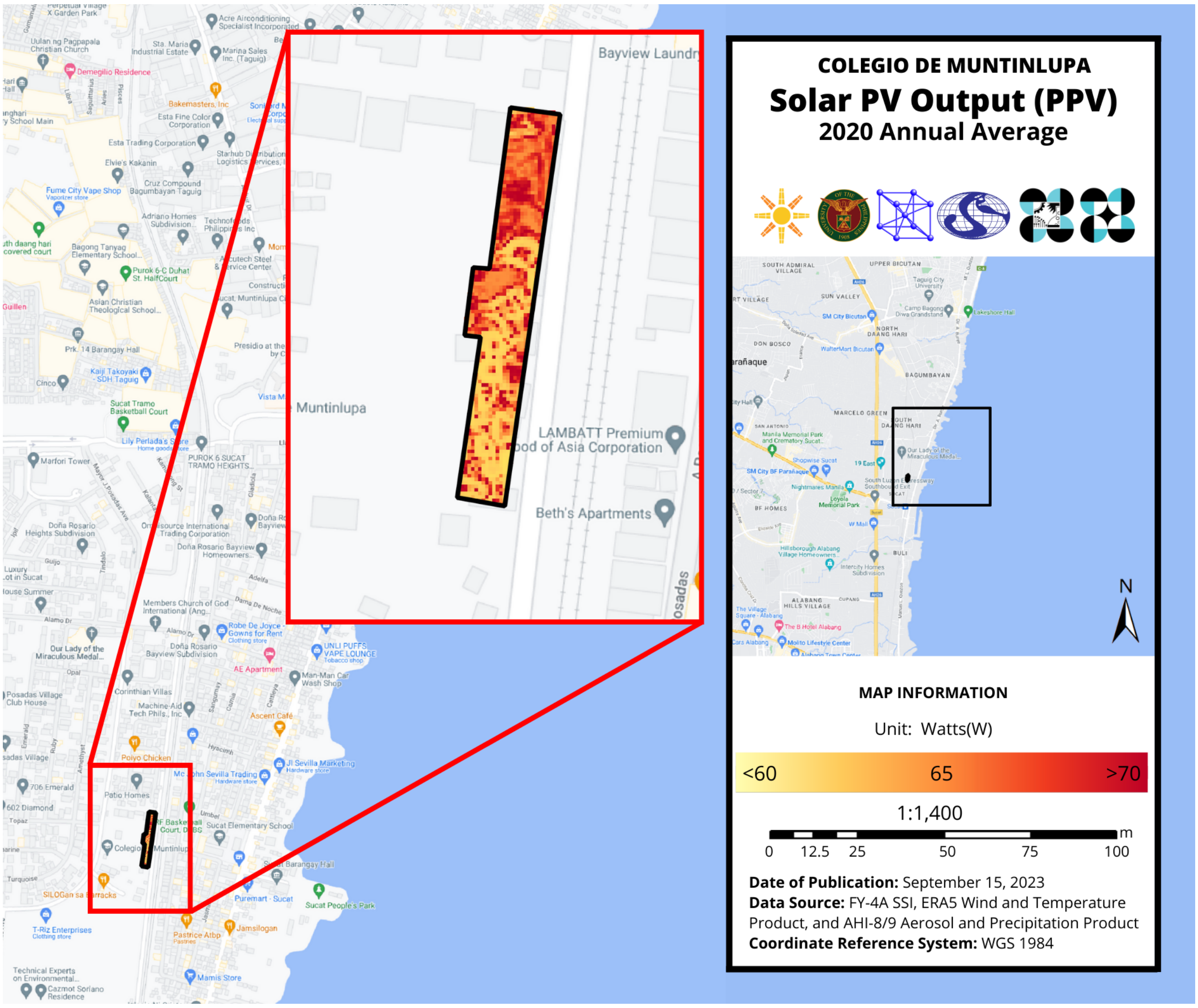

Figure 5. Estimated Potential Solar PV Output (PPV) for Colegio de Muntinlupa

3.2 PPV Processing

The estimated PPV for Colegio de Muntinlupa using $R_{surface}^{Slope_{act}}$ is shown in Figure 5. It is the computed annual average of the mean monthly PPV raster data for 2020 using raster calculation in QGIS. Areas with yellow symbology indicate less than or equal to 60 watts estimated potential solar PV power output while areas with red indicate greater than or equal to 70 watts. Figure 5 shows that the northern part of the building has higher potential than southern areas. This may be due to obstruction and shading at the location of the installation. At the current roof inclination of the study area, the estimated output PV is 19.44% lower compared to when installed at 15° optimum tilt angle.

Comparing the average 2020 monthly mean PPV, the overall mean monthly efficiency of the system has increased by 1.82% at $Slope_{act}$ vs 5° tilt angle, 2.86% $Slope_{act}$ vs 10° tilt angle and 3.11% at $Slope_{act}$ vs 15° tilt angle as presented in Table 1. Drastic change in efficiency can be observed at 15° tilt angle with an increase of 15.40% during the cool dry season (December) and a decrease of 8.08% during the start of the rainy season(June).

Table 1. Summary of Monthly Increase in efficiency at $Slope_{act}$ vs tilt angles

Month \ Tilt Angle	5°	10°	15°
January	5.44	10.07	13.87
February	3.88	6.96	9.23
March	1.93	3.09	3.47
April	0.08	-0.60	-2.04
May	-1.32	-3.39	-6.20
June	-1.95	-4.65	-8.08
July	-1.61	-3.98	-7.07
August	-0.39	-1.55	-3.45
September	1.36	1.95	1.76
October	3.33	5.88	7.63
November	5.10	9.40	12.86
December	5.95	11.10	15.40

3.3 Validation

Solar PV power output from April to May was estimated between 2.76 W to 951 W with a mean of 505.30 W at different tilt angles. Meanwhile, the actual PV outputs were ranging from 300.96 W to 1,118.53 W with a mean value of 772.233 W. Using one-way ANOVA, results showed that with the F-value (0.36) and *p*-value (0.50), the tilt angle has no statistically significant effect on solar PV production both on theoretical values. Meanwhile, the actual PV production shows statistically significant effects on the production in relation to tilt angle having F-value (3.13) and p-value (0.04). The F-value indicates that the variation in solar PV production between tilt angles is significant when compared to the variation within each tilt angle group. Table 2 shows the summary of analysis of covariance for estimated PPV while Table 3 for the actual solar PV output.

Moreover, the *p*-values obtained from a two-sample *t*-test at 95% confidence level per angle also showed no significant difference (p = 0.00) between the actual and estimated PPV values. This signifies that the estimated PPV values can substitute for the unavailable actual solar PV output data. Results also show that the 15° tilt exhibited the best annual efficiency with only 4.20% loss of surface solar irradiance reaching the panel compared to 5° and 10° with 5.05% and 4.26% loss.

Table 2. Summary of Analysis of Covariance for estimated PPV.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Angle	2	54,792	27,396	0.36	0.695
Error	1077	80,996,478	75,206	-	-
Total	1079	81,051,270	-	-	-

Table 3. Summary of Analysis of Covariance for actual solar PV output.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Angle	2	152,001	76,001	3.13	0.044
Error	1077	26,125,178	24,257	-	-
Total	1079	26,277,179	-	-	-

Figure 6 shows the comparison between solar PV output from actual solar PV installations (PPV_{actual}) and the estimated PPV for 5°, 10° and 15° tilt angles (PPV5, PPV10, and PPV15, resp.). Based on the results, the actual values yield higher production than PPV_{actual} (% difference vs PPV 5 = 32.29%, PPV10 = 34.87%, and PPV15 = 33.72%) as compared to the estimated values. When examining the differences in PPV_{actual} output based on different angles, it becomes evident that a minimal range of output changes exists, ranging from 0.97% to 3.63%. There is also minimal output variability across different angles when comparing the estimated PPV values , which ranges from 0.22% to 0.98%.

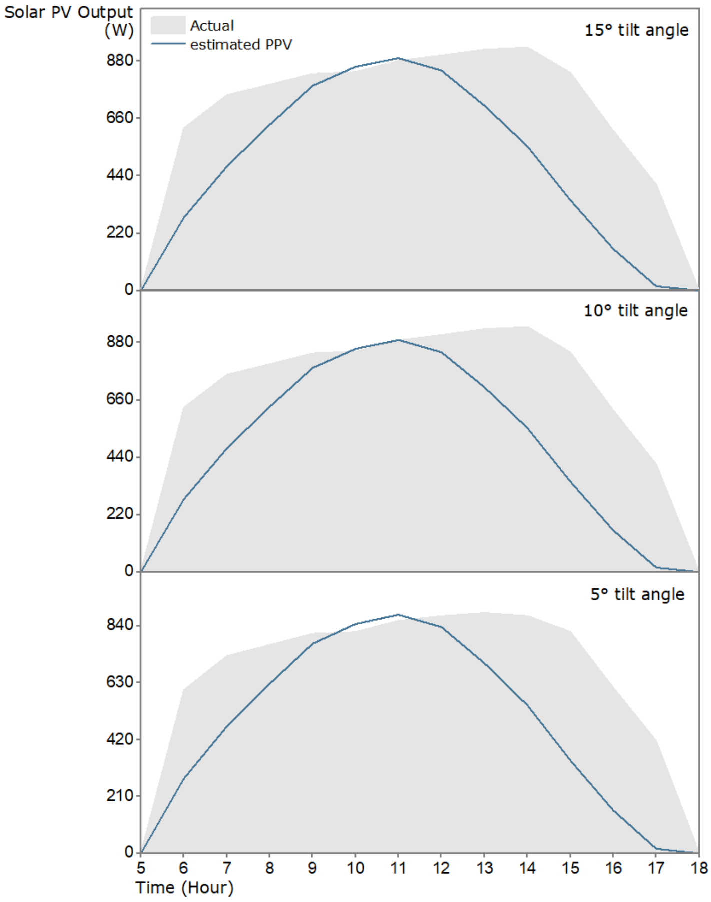

Figure 6. Comparison of actual solar PV output and estimated PPV in various tilt angles.

4. CONCLUSION

As the optimum tilt angle for a solar energy installation is site specific, the accurate determination of this angle is essential to maximize the output power production of a solar PV system (PPV). In this study, solar radiation reaching the surface ($R_{surface}$) was estimated using the adjusted SWR data, the latitude of the location and the day of year. To investigate the effect of different module tilt angles on solar PV power production, FY-4A surface solar irradiance data was used to calculate potential solar PV output, accounting for temperature and dust effects. After factoring in the magnitude of the surface solar irradiance, dust and temperature effects and the sun hours, the monthly, seasonal, and annual fixed optimum tilt angles were calculated.

The monthly fixed optimum tilt angle varies per month with 5° tilt angle for April, 10° tilt for September and 15° tilt angle for January, February, March, October, November and December, and maintaining the actual slope of the location for May, June, July and August. The seasonal fixed optimum tilt angles are 15°, 10°, and 10° tilt angles for the cool dry season, hot dry season and rainy season, respectively. Lastly, the annual fixed optimum tilt angle is computed to be at a 10° tilt angle. The utilization of the optimum tilt angles will be advantageous to solar PV system owners since solar PV generation efficiency will significantly improve. Furthermore, a solar PV installation installed with an annual optimal tilt may be used as a base load capacity to meet a constant and uninterrupted demand on the power grid.

This work also validated the calculated potential PPV using actual values, which verifies the assumptions made in the study and helps ensure that the conclusions drawn from the study align with observed phenomena. Lastly, this study demonstrates that the estimated theoretical PPV derived from remote sensing (RS) data can effectively substitute for in-situ production data.

5. RECOMMENDATIONS

For future works, a validation of the estimated PPV using actual data with a longer time horizon on multiple locations is recommended. This study only focused on the effect of tilt angles on PPV. It is therefore recommended to consider other factors such as cleaning effects due to precipitation and deposition of dust and snow. In areas with significant seasonal variations in solar irradiance, solar panels with a fixed tilt angle may not be the best option. A cost-benefit analysis can also be conducted to determine which between direct installation on the existing terrain and optimizing the tilt angle is the better option.. Lastly, assessment may also be conducted to verify if the potential increase in energy generation can justify the additional cost of installing a solar tracking system instead of adjusting the tilt angle manually per season.

6. ACKNOWLEDGMENT

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