ASSESSMENT OF SOLAR PV OUTPUT PERFORMANCE WITH VARYING TILT ANGLES AND WEATHER DATA FROM ERA5: CASE OF MUNTINLUPA CITY, PHILIPPINES

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ABSTRACT:

Solar photovoltaic (PV) technology has been gaining popularity in the Philippines as an alternative source of sustainable energy. In such technology, module tilt angle and weather conditions are among the system parameters that have substantial impacts on PV system performance. Previous studies have considered either tilt angles or weather conditions, but not the combined impact of these two parameters on solar PV power output. The objective of this study is to examine the effects of weather variables and tilt angle on the output of solar photovoltaic (PV) systems in Muntinlupa City, the Philippines. Three 120W monocrystalline solar PV panels were used and set up to three different tilt angles (i.e., 5°, 10°, and 15°). The fifth generation of the ECMWF's global climate and weather reanalysis (ERA5) dataset was used to gather hourly weather information such as surface solar radiation, wind speed, wind direction, relative humidity, ambient temperature, and total precipitation. Three principal components (PC), which together account for 95% of the variability, were identified using principal components analysis (PCA), which was used to address multicollinearity among the weather parameters. To assess the effects of tilt angle, time, and PCs on solar PV production, analysis of covariance (ANCOVA) was carried out. Results show that all weather variables, except for wind speed and total precipitation, have a significant impact on solar PV production with configuration producing the best results. Moreover, a significant difference in mean solar PV production was observed among the three tilt angles. From 6:00 AM to 2:00 PM, solar PV output gradually increases and declines thereafter. Outputs this study can help in optimizing the design and configuration of solar PV systems in the Philippines by considering weather variables and module tilt angle. Lastly, this study provides useful information for system designers, installers, and policymakers in improving energy generation and utilization, encouraging the use of renewable energy sources, and advancing sustainable energy objectives.

1. INTRODUCTION

In the Philippines, solar photovoltaic (PV) technology has gained significant interest and actual utilization as a sustainable energy source. However, there are various factors that may limit PV power output. For instance, by setting the angle at which the PV modules are inclined relative to the sun's path, the tilt angle plays an important role in maximizing solar radiation capture (Yadav and Chandel, 2013). Furthermore, environmental parameters such as wind speed, ambient temperature, relative humidity, solar irradiation, and total precipitation can all have a significant impact on the overall performance of solar PV systems. Understanding how the interaction of tilt angle and weather parameters affects [1]solar PV output performance is crucial for improving energy conversion.

Studies by Mamun et al., (2022) and Mansour et al., (2021) investigated the effects of tilt angle on solar PV output but did not get a full grasp of its interactions with the aggregate influence of meteorological conditions. Similarly, Agarwal et al., (2022), Benitez et al., (2022), Principe et al., (2023), and Waterworth and Armstrong, (2020) focused only on weather conditions without taking into account varied angle configurations. This work fills in a research gap by evaluating the combined effect of tilt angle and weather parameters on solar PV output performance in Muntinlupa City, Philippines utilizing the ECMWF's reanalysis of the world's climate and weather (ERA5) dataset for weather parameters.

Maximizing the tilt angle of PV systems is crucial because the Philippines has an abundance of solar resources. The two main goals of this study are to first determine how different tilt positions affect solar PV system performance and then to determine how weather factors affect the overall system output. The best tilt angles for solar PV systems in the Philippines under various weather conditions can be determined by considering these variables. This knowledge will make it possible to design and modify PV systems to accommodate site-specific environmental conditions, which will facilitate the effective utilization of solar energy.

The objective of this study is to enhance comprehension regarding the utilization of renewable energy, with a specific focus on solar photovoltaic (PV) systems, within the context of Muntinlupa City, Philippines. The study investigates the connections between meteorological conditions and different tilt angles, utilizing the ERA5 global reanalysis dataset. The results of this study will contribute to the development of more efficient systems, enhancing energy utilization, and facilitating the wider adoption of solar photovoltaic (PV) technology in the Philippines. Stakeholders can choose wisely when it comes to

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system design, installation, and operational strategies by understanding how tilt angle and weather parameters interact and their impact on solar PV power generation. The output of this study may help in developing national policies and regulations for a more efficient and strategic use of solar energy. The Philippines can further reduce its reliance on fossil fuels and make significant progress toward achieving its renewable energy targets by supporting the efficient utilization of renewable energy sources such as solar.

2. METHODOLOGY

2.1 Data

This study analyzed the effects of weather conditions and tilt angles on the output performance of solar PV systems in Muntinlupa City, the Philippines.

2.1.1 Solar PV Output Data

Fig. 1 shows the schematic diagram of the experimental setup used in this study. The setup consists of solar PV panels at different tilt angles—5°, 10°, and 15°. Using three 120W monocrystalline solar PV panels, the effects of varying tilt angles on solar PV systems were observed. These panels were specifically oriented to the south to maximize solar irradiance and configured the vertical orientation to correspond to the various tilt angles being studied.

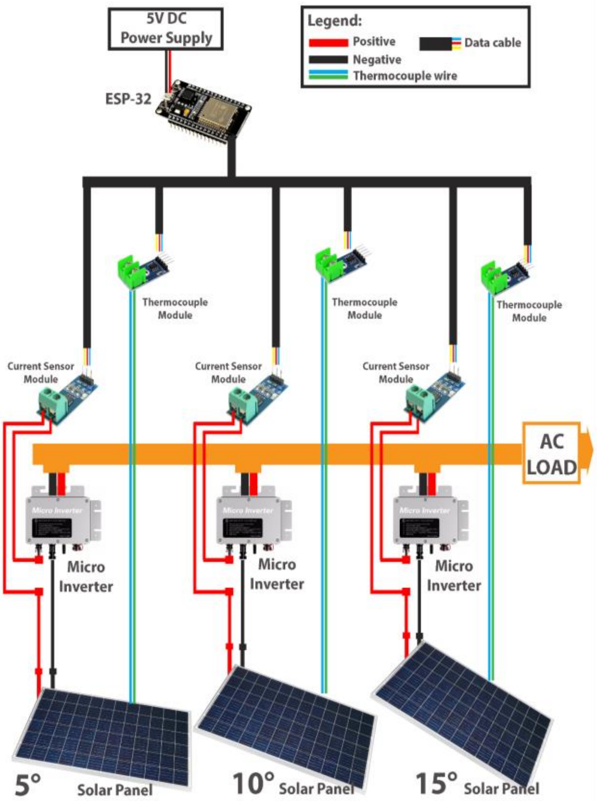

Figure 1. Schematic diagram of the experimental setup.

The solar PV output data was gathered from April 20, 2023, to May 19, 2023, over a 30-day period. The generated output power and back cell temperature (BCT) of solar PV systems were measured hourly from 6:00 AM to 5:00 PM. These measurements are used to assess how solar PV systems performed at various tilt angles.

2.1.2 Weather Data

The surface solar radiation (SSRD), wind speed (WS) and direction (WD), relative humidity (RH), ambient temperature (AT), and total precipitation (TP) hourly data from the ERA5 dataset were the weather parameters used in this study. ERA 5 is a dataset of global climate and weather reanalysis for the last 70 years (Hersbach et al., 2020). Understanding the impact of meteorological conditions on solar PV output performance required knowledge of these weather parameters. SSRD was converted from J/m^2 to W/m^2, and the ambient temperature was converted from Kelvin to Celsius. WS, WD, and RH were computed using Equations 1 to 3, respectively.

$$ws = \sqrt{u^2 + v^2} \tag{1}$$

where u^2 = u component of wind
v^2 = v component of wind

$$wd = mod\ [180 + \frac{180}{\pi}\ atan2\ (v, u), 360] \tag{2}$$

$$rh = 100 * [exp(\frac{17.625 * td}{243.04 + td})\ /\ exp(\frac{17.625 * t}{243.04 + t})] \tag{3}$$

where td = dew point temperature
t = ambient temperature

2.2 Statistical Analysis

Weather parameters may be correlated to each other and/or are affected by external factors. Principal components analysis (PCA) was therefore used to address potential multicollinearity issues among the weather parameters. PCA is a statistical method for breaking down a large set of correlated variables into a more manageable set of uncorrelated variables (Jolliffe and Cadima, 2016). This strategy ensures that subsequent analysis is only using key weather factors and avoids redundant data. Since weather parameters have different units of measurement, PCA uses the standardized variables. Correlation analysis based on Pearson correlation coefficient was employed to detect such significantly correlated factors.

Analysis of covariance (ANCOVA) was carried out to investigate the effects of tilt angles and time on solar PV production. A statistical technique called ANCOVA combines regression analysis and analysis of variance (ANOVA) (Van Breukelen, 2006). While accounting for the effects of the PC-transformed weather covariates, ANCOVA enables the evaluation of the effects of tilt angles. The ANCOVA model with PC-transformed covariates are defined as follows:

$$Prod_{ijk} = \mu + \tau_i + \delta_j + (\tau\delta)_{ij} + \beta_1 * PC\_1_{ijk} + \ldots + \beta_r * PC\_r_{ijk} + \varepsilon_{ijk} \tag{4}$$

where $Prod_{ijk}$ = solar PV production of the ijk^{th} observation
μ = overall mean
τ_i = fixed effect of i^{th} tilt angle (i = 1, 2, 3)

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δ_j = fixed effect of j^{th} time point (j =1, 2, …, 12)
$(\tau\delta)_{ij}$ = interaction effect of i^{th} tilt angle and j^{th} time point
$\beta_1, \beta_2, \dots, \beta_r$ = linear regression coefficient for $Prod$ on $PC\_1, PC\_2, \dots, PC\_r$, respectively
$PC\_1_{ijk}, \dots, PC\_r_{ijk}$ = fixed PC-transformed covariate scores of the ijk^{th} observation
ε_{ijk} = error component

The model assumes statistical independence of the predictors, linearity and homogeneity of within-group regressions, normality of conditional $Prod$ scores with a common variance σ^2, and fixed and continuous covariates (Keppel and Wickens, 2004). The error components are assumed to have a normal distribution with zero mean and variance equal to σ^2. Furthermore, analysis was conducted on the interaction among tilt angles, time, and weather parameters, and their combined impact on solar PV output performance.

3. RESULTS AND DISCUSSIONS

Based on the data collected, the overall mean solar PV production was 772.23 ± 156.06 W. Comparing the performance of solar PV systems by tilt angle, the 10° configuration yielded the highest production of 784.10 ± 158.63 W, followed by the 15° configuration with 776.57 ± 158.63 W, and lastly, the 5° configuration with 756.03 ± 149.82 W. In terms of performance considering time of the day, the solar PV production is steadily increasing from 6:00 AM (with 618.34 ± 38.54 W), peaked at 2:00 PM (with 916.11 ± 51.33 W), and thereafter decreased drastically until 5:00 PM (with 410.49 ± 54.27 W). Meanwhile, in terms of back cell temperature, the overall mean measured BCT was 36.70 ± 4.38 °C. The 15° configuration yielded the highest BCT value of 36.82 ± 4.35 °C, followed by the 10° configuration with 36.65 ± 4.45 °C and the 5° configuration with 36.62 ± 4.34 °C. Considering the time of measurement BCT peaked at 1:00 PM (with 42.38 ± 1.24 °C).

Furthermore, weather data within the same time frame were analyzed. Table 1 shows the summary statistics of the weather parameters. It can be observed that among the weather parameters, TP has the smallest variability (SD = 0.53), followed by WS (SD = 1.34) and AT (SD = 1.73). This follows that these variables may have low predictive power in explaining changes in solar PV production. In order to confirm this, preliminary analysis was performed to assess the predictive power of the weather parameters prior to performing PCA.

Preliminary analysis includes correlation analysis that is to detect significantly correlated variables. The sample correlation coefficients (r) between solar PV production and various weather parameters at various tilt angles are shown in Table 2.

At a 5° tilt angle, solar PV production correlates positively with AT (r = 0.501), SSRD (r = 0.735), and TP (r = 0.088). This means that as AT, SSRD, and TP values increase, so will solar PV production. The positive correlations between solar PV production and AT (r = 0.522), SSRD (r = 0.752), and TP (r = 0.082) become slightly stronger when the tilt angle is increased to 10°, indicating a more significant impact of these weather parameters on solar PV production. The pattern continues at a 15° tilt angle, with similar positive correlations observed for AT (r = 0.52), SSRD (r = 0.751), and TP (r = 0.083).

Solar PV production has weak positive correlations with WS across all tilt angles ($0.116 \leq r \leq 0.133$). This implies that higher WS correspond to slightly higher solar PV production. WD has a weak positive correlation with solar PV production as well, but with smaller coefficients ranging from 0.03 to 0.039. This suggests that wind direction has only a minor impact on solar PV production. In contrast, RH has a negative correlation with solar PV production at all tilt angles ($-0.364 \leq r \leq -0.377$) indicating that when RH rises, solar PV output decreases. This means that high humidity levels can reduce the efficiency of solar PV systems.

Table 3 shows the sample correlation coefficients between BCT of solar panels at various tilt angles and weather parameters. These values indicate the direction and strength of linear relationship between the weather variables and the temperature of the solar panel cells BCT has a strong positive correlation with AT (0.644 < r < 0.652) and SSRD (0.761 < r < 0.766) at all three tilt angles. This implies that higher back cell temperature corresponds to higher AT and SSRD. WS, WD, RH, and TP, on the other hand, have weaker correlations with BCT at all three tilt angles, indicating a smaller influence on the panel temperature. Specifically, RH correlates negatively with BCT at all tilt angles, thus higher humidity levels may result in lower back cell temperatures. Meanwhile, WS and WD have weak positive correlations with BCT at all angle configurations. This suggests that while wind conditions influence back cell temperature, they are not the primary cause of temperature variations.

According to the results, AT, SSRD, and TP show high positive correlation to solar PV production while WD and WS have weaker positive correlation. RH, on the other hand, has a negative correlation with both solar PV production and BCT. Understanding these relationships is critical for optimizing the performance and efficiency of solar energy systems considering different weather conditions and tilt angles. By taking these factors into account, researchers and industry professionals can make informed decisions about the design and operation of solar PV systems in order to maximize productivity while mitigating the potential negative effects of weather-related factors.

Solar PV production and BCT correlations per angle indicate consistent patterns in the relationships with various weather conditions. However, the occurrence of multicollinearity, in which various meteorological indicators are closely associated with one another, makes establishing their individual impacts very difficult. Principal Component Analysis (PCA) is used to overcome this difficulty and acquire a better understanding of the said relationships among different weather parameters. By reducing the correlated weather parameters into a smaller collection of uncorrelated main components, PCA can address the issue of multicollinearity. PCA enables a more extensive examination of the correlations between weather parameters, solar PV production, and BCT, revealing the primary factors influencing these variables.

Another analysis carried out prior to PCA is the ANCOVA of solar PV production on the untransformed covariates in order to drop variables that do not significantly predict the outcome. Based on the preliminary results, WD and TP were not significant predictors of solar PV production. Also, in the

Weather Parameter	Mean	Standard Deviation	Minimum	Maximum
WS	2.90	1.34	0.13	6.70
WD	136.86	74.31	29.29	328.98
RH	67.00	8.66	46.11	86.41
AT	31.42	1.73	27.75	35.68
SSRD	485.55	269.95	37.93	969.87
TP	0.14	0.53	0.00	5.00

Table 1. Summary statistics of weather parameters

Variable	Prod (5°)	Prod (10°)	Prod (15°)	WS	WD	RH	AT	SSRD
WS	0.133	0.118	0.116	1.000	-	-	-	-
WD	0.039	0.033	0.03	-0.235	1.000	-	-	-
RH	-0.364	-0.376	-0.377	-0.497	0.315	1.000	-	-
AT	0.501	0.522	0.52	0.367	-0.041	-0.912	1.000	-
SSRD	0.735	0.752	0.751	0.206	-0.022	-0.645	0.733	1.000
TP	0.088	0.082	0.083	-0.074	-0.092	0.23	-0.19	-0.227

Table 2. Correlations between Solar PV Production and weather parameters

Variable	BCT (5°)	BCT (10°)	BCT (15°)	WS	WD	RH	AT	SSRD
WS	0.211	0.207	0.213	1.000	-	-	-	-
WD	0.113	0.105	0.112	-0.235	1.000	-	-	-
RH	-0.473	-0.468	-0.474	-0.497	0.315	1.000	-	-
AT	0.651	0.644	0.652	0.367	-0.041	-0.912	1.000	-
SSRD	0.761	0.766	0.762	0.206	-0.022	-0.645	0.733	1.000
TP	0.132	0.133	0.132	-0.074	-0.092	0.230	-0.190	-0.227

Table 3. Correlations between back cell temperature (BCT) and weather parameters

Variable	PC_1	PC_2	PC_3
BCT	0.434	0.403	-0.582
WS	0.274	-0.811	-0.493
RH	-0.492	0.241	-0.505
AT	0.518	-0.001	0.384
SSRD	0.476	0.349	-0.126

Table 4. Eigenvectors corresponding to the Top 3 Eigenvalues in the Principal Components Analysis

Source	DF	Adj SS	Adj MS	F-Value	P-Value
PC_1	1	144,714	144,714	56.84	0.00
PC_2	1	223,823	223,823	87.92	0.00
PC_3	1	129,365	129,365	50.82	0.00
Angle	2	146,339	73,169	28.74	0.00
Time	11	3,598,719	327,156	128.51	0.00
Error	1,063	2,706,164	2,546	-	-
Total	1,079	26,277,179	-	-	-

Table 5. Results of Analysis of Covariance.

descriptive statistics earlier, TP was identified with low variability, therefore this result was expected. Consequently, the remaining variables were deemed as the important factors and subjected to data reduction through PCA. Based on the results of PCA, three principal components (PCs) account for approximately 95% of the variation in the weather data, hence the dimension of the weather data can be reduced to three PCs resolving the issue of multicollinearity without much loss of information. Table 4 summarizes the three principal components (PC_1, PC_2, and PC_3) derived from the analysis, as well as the loadings of the original weather parameters.

BCT, WS, AT, and SSRD all have positive loadings in PC_1. This component combines these variables and captures the overall variability associated with solar PV production. PC_2 has a dominating negative loading for WS and positive loadings for BCT and RH. The inverse relationship between WS and solar PV production is reflected in PC_2. PC_3 has negative BCT, WS, and RH loadings and positive AT loadings. This component accounts for additional variability not captured by PC_1 and PC_2. Since the issue of multicollinearity among the weather factors has been resolved, the PCs can be used as the covariates in the ANCOVA model.

The ANCOVA analysis summarized in Table 5 revealed that all three principal components (PC_1, PC_2, and PC_3) were significant predictors of solar PV production. This implies that the combined impact of the important weather parameters represented by these components has a significant impact on solar PV output. The results also show that both tilt angle and time of day are significant predictors in solar PV production after fitting the ANCOVA model in Equation 4.

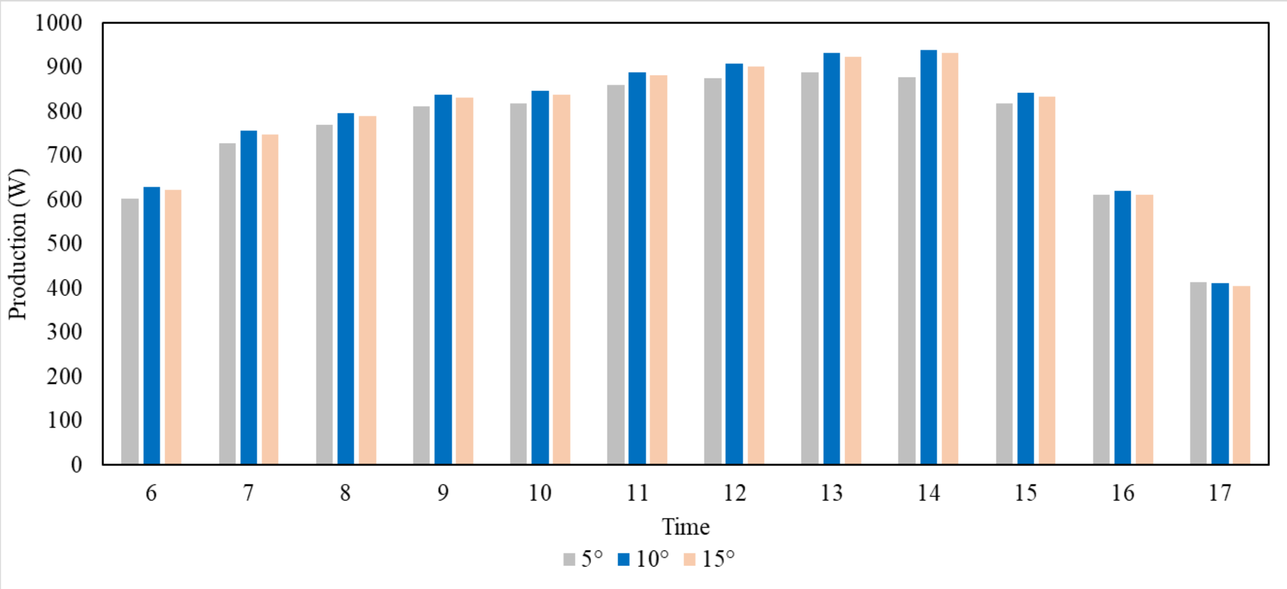

Figure 2. Hourly Average Production per Angle.

The interaction effect of tilt angle and time was not found significant. Hence, the main effects of such predictors were retained.

In terms of the covariates, all three main PCs derived from weather parameters are also significant predictors of solar PV production. With this, tilt angle and time of the day are important factors influencing solar PV output while holding the PC-transformed weather covariates constant. These findings offer valuable insights into the effects of various factors on solar PV production, allowing for better optimization and planning of solar energy systems.

Table 5 shows the results of the ANCOVA analysis for solar PV production. Here, the number of independent observations available for each factor is indicated by the degrees of freedom ("DF"). The adjusted sum of squares ("Adj SS") represents the variability that each factor or source of variation accounts for. Adjusted mean squares ("Adj MS") are computed by dividing Adj SS by its respective DF. F-values are the ratio of variability between groups to variability within groups; a higher value means that the difference between the groups is more significant. Based on the table, all the F-values are large with small p-values (i.e., $p < 0.05$), indicating that there are significant differences in solar PV production in terms of tilt angle and time of day while holding the PC-transformed weather covariates constant.

Tilt angle (Angle) significantly affects solar PV production ($F = 28.74$, $p<0.001$). 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. Furthermore, with a high F-value (128.51) and a low p-value (<0.001), the time factor (Time) has a significant effect on solar PV production. This implies that solar PV production varies significantly across time points.

Overall, the ANCOVA analysis shows that tilt angle and time have a significant impact on solar PV production. The setup with a tilt angle of 10° produces the most solar PV energy, followed by the 15° and 5° angles.
The analysis of the solar PV output with time of the day also revealed an intuitive pattern. As shown in Fig. 2, the solar PV output steadily increased from 6:00 AM to 2:00 PM, demonstrating the best use of solar radiation during this time. However, the solar PV output began to decrease from 2:00 PM to 5:00 PM, indicating a reduction in the amount of solar radiation available.

4. CONCLUSIONS AND RECOMMENDATIONS

In this study, solar PV output performance of installations located in Muntinlupa City, Philippines was examined in relation to tilt angle and weather variables. Results show how important these components are for optimizing solar PV system design and performance. Outputs of this study revealed that solar PV output is significantly influenced by tilt angle, time, and principal components derived from weather parameters. Among the three angles taken into consideration, the tilt angle configuration with a 10° tilt showed the highest mean solar PV production. The results of the analysis of covariance (ANCOVA), which showed that tilt angle and time are significant predictors of solar PV output, confirmed the statistical significance of the said factors. The dimensionality of weather parameters was effectively reduced by the principal components analysis (PCA) resolving the issue of multicollinearity and enabling a more in-depth examination of the critical variables influencing solar PV performance.

Future research can build on these findings by considering longer periods to capture seasonal variations in weather conditions. The accuracy of the analysis can also be further accessed by using in-situ weather data. Additionally, a more thorough understanding of the time-dependent variations in solar PV output would be provided by expanding the analysis to a 24-hour timeframe.

Outputs from this study provide valuable information on how to maximize the use of solar energy which may help in further advancing the design and operation of solar PV systems in the Philippines. It is hoped that these results will promote the widespread use of solar PV systems and advance the country's agenda on the use of sustainable energy resources.

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