SLOPE ANALYSIS OF CLOT-ADJUSTED SSI-FY4A DATA FOR SOLAR PV POWER POTENTIAL ASSESSMENT IN THE PHILIPPINES

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ABSTRACT:

Utilization rate of energy from solar photovoltaic (PV) systems has surged considerably with the increase in global demand for sustainable energy solutions.The angle at which panels are positioned relative to the horizontal plane must be aligned with the sun's incoming radiation to achieve optimum power production. Unfortunately, this ideal alignment is not always feasible, particularly for panels lacking tracking systems. Therefore, determining the best tilt angle becomes a key factor that significantly influences the effectiveness of solar PV systems, considering various influencing factors. The study aims to establish the relationship between different slopes and solar PV performance and to assess the impact of this on energy generation efficiency for specific locations across Luzon and Mindanao. The study focuses on determining the optimal tilt for specific locations across Luzon, Visayas, and Mindanao. Sites including Metro Manila, Cebu, and Davao were selected as representative areas for each respective island group for being the most populous cities in their respective geographical island groups. Theoretical solar energy obtained from SSI was CLOT-adjusted and incorporated with dust and temperature effects to determine the maximum solar energy resource potential within the study area. Results show that the highest solar PV potential was determined at 5° -10° tilt angle for both Metro Manila and Davao followed by 10-20° and 20-30° tilt angle with an average of 86.42 W solar PV potential (PPV). For Cebu, the highest solar PV potential was determined at 20° to 30° tilt angle with the value of 95.99 W solar PV potential (PPV). The lowest PPV was found on installations with tilt > 30° in all the study areas at an average of 65.02 W. This suggests that to maximize solar PV output in different regions, installations should be tilted according to the optimal tilt angle specific to that region. The latitude differences across the country significantly impact which tilt angle is most effective, as they influence the amount of sunlight received in each area. To improve the accuracy of future studies, it is recommended to increase the number of data points per slope interval. While the differences observed in this study were small, having more data points can enhance the precision of average values obtained from formulas.

1. INTRODUCTION

1.1 Background and rationale of the study

Utilization rate of energy from solar photovoltaic (PV) systems has surged considerably with the increase in global demand for sustainable energy solutions. The installation of solar panels has gained popularity as communities around the world transition to eco-conscious practices using eco-friendly technologies. The angle at which panels are positioned relative to the horizontal plane must be aligned with the sun's incoming radiation to achieve optimum power production (Ibrahim and Ibrahim, 2021). Unfortunately, this ideal setup is not always feasible, particularly for panels lacking tracking systems. Consequently, the pursuit of an optimal tilt angle emerges as a pivotal determinant, profoundly impacting the effectiveness of solar PV systems amidst various influencing factors. Furthermore, the assessment of potential PV output takes into account both dust and temperature effects. Research conducted by Bauzon et al. (2022) reported a 20-30% decrease in solar PV power output due to dust deposition in the Philippines. Moreover, under controlled steady-state conditions, experimental observations indicate a gradual decline in voltage, current, and power as the PV panel's temperature rises (Thong et al., 2016). This temporal effect ultimately decreases the PV module's efficiency (Thong et al., 2016). In Saudi Arabia, a study recommended the adoption of a site suitability criterion, involving a slope factor of 5 degrees or less. This parameter notably contributed to an enhanced performance of solar PV systems, particularly on flat or gently sloping terrains (Al Garni et al., 2017). Consequently, the study of Al Garni et al. (2017) considered distinct slope ranges of less than 5^0, 5^0 to 10^0, 10^0 to 20^0, 20^0 to 30^0, and greater than 30^0. These slope ranges serve as an essential factor for determining the optimal value during solar PV installation and output estimation.

1.1 Objectives of the study

The study aims to determine the optimal tilt or slope angle for maximum power generation from solar PV systems in the Philippines. It aims to assess the impact on power generation efficiency and establish the relationship between different slopes and system performance. Moreover, this study provides stakeholders in the renewable energy industry useful information on tilt angles during solar PV system installation based on empirical data and satellite-derived measurements of Surface Solar Irradiance (SSI) from Fengyun-4A (FY-4A), taking into account both dust and temperature effects.

1.2 Study area

The study focuses on determining the optimal tilt for specific locations across Luzon, Visayas, and Mindanao. Sites in Metro Manila, Cebu, and Davao were selected as representative areas for each respective island group for being the most populous

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cities in their respective geographical island groups based on the Philippine Statistics Authority Census (2020).

Slope analysis will look into the optimal tilt angles tailored to the unique solar conditions of these prominent urban centers.

2. MATERIALS AND METHODS

2.1 Materials

The utilization of SSI satellite data is essential not only for optimizing the planning and functioning of solar energy installations but also for its potential application in climate monitoring and analysis (Muller and Pfeifroth, 2022).

According to the National Aeronautics and Space Administration (NASA, n.d.), the Fengyun-4A, also referred to as FY-4A, is China's second-generation geostationary meteorological satellite. It was launched in December 2016 from the Xichang Satellite Launch Base (NASA, n.d.).

A digital surface model (DSM) was used to acquire a slope raster which was then used to generate the latitude raster. The slope and the latitude rasters, along with the adjusted SSI (SSI') data, were integrated to calculate solar irradiance received at the surface of a solar PV panel ($R_{surface}$) (Fig. 1).

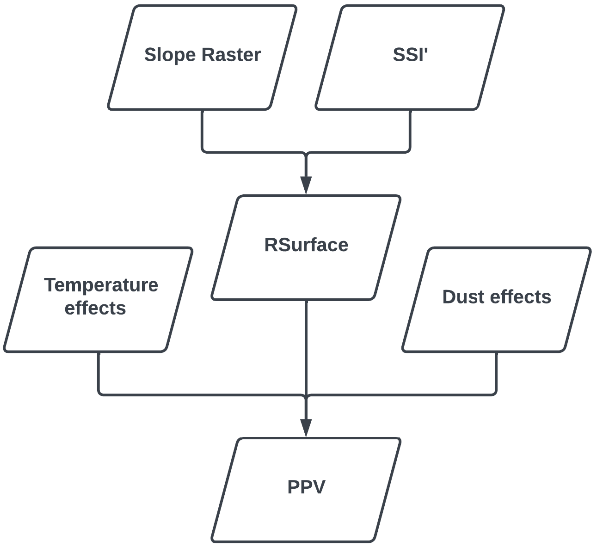
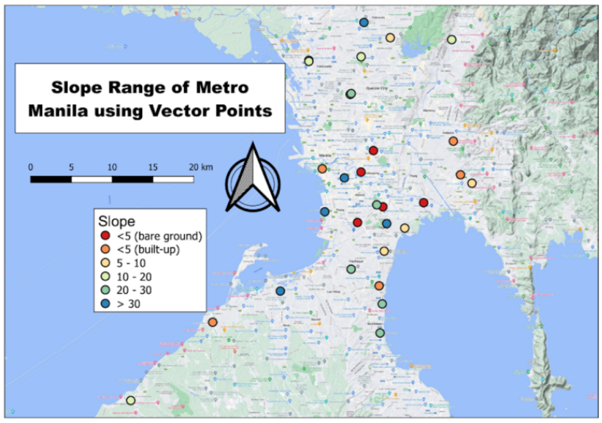


Figure 1. Flowchart of initial methodology to obtain potential PV values

To determine the maximum solar energy resource potential within the study area, theoretical solar energy obtained from SSI was CLOT-adjusted (Sotto et al., 2023). This computation factored in module tilt and the specific day of the year. The resulting $R_{surface}$ value was then used for potential PV output computation, with the adjustments for dust and temperature effects.

2.2 Determination of Slope Intervals and Points

Thirty (30) points of interest at five (5) per slope interval, were placed on each region and used to extract the solar PV power (PPV) potential values, as shown in Figs. 2a, 2b, and 2c. The average PPV for each point in each slope interval was computed and used to determine the optimal slope angle for solar PV installation.



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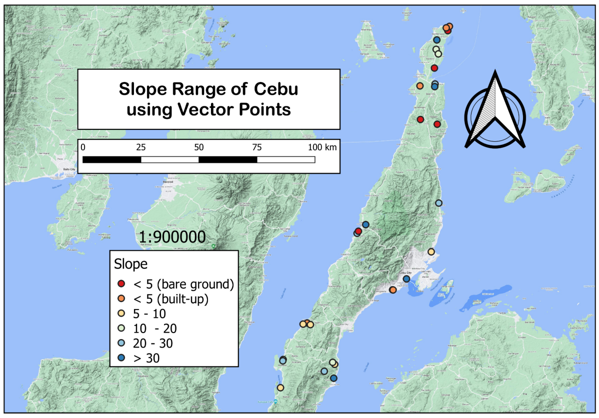

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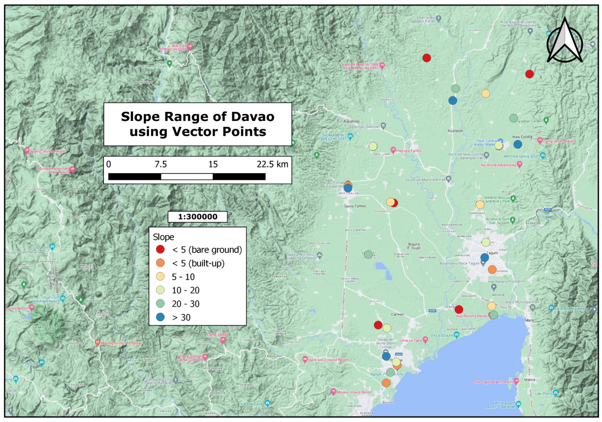

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Figure 2. Placement of vector points for slope analysis in **(a)** Metro Manila, **(b)** Cebu, and **(c)** Davao

Trial test runs were conducted with ten points of interest per slope interval. Each point was chosen based on a DSM raster layer of the city of interest. The different slope intervals were then categorized based on the slope interval assignment (<5° (ground), <5° (asbuilt), 5°-10°, 10°-20°, 20°-30°, >30°). Ten points were selected on the map for each slope interval.

Afterwards, the PPV values were computed and points were sampled in order to assign the PPV value per point. The points were then exported, and the PPV values per slope interval were calculated. Considering the computed PPV values, the difference between the average of the ten points and that of the five points was negligible. Consequently, it was determined that utilizing five points would suffice for the remainder of the research.

2.3 Estimation of Surface Solar Radiation

$R_{surface}$ was computed for each month of year 2020 using Eq. (1):

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

where: R’ = incident radiation
ϕ = latitude
d = day of the year
β = module tilt angle

The formula used in generating the $R_{surface}$ raster was adapted from the study of Principe and Takeuchi (2019) and Bauzon, M. D. A et al (2022).

2.4 Estimation of Effective Solar PV Potential

The effective monthly solar PV potential is estimated using Eq. (2) which is also adapted from the study of Principe and Takeuchi (2019) and Bauzon, M. D. A et al (2022):

$$P'_{PV} = A_{cell} \eta R(1 - \Delta\eta_t - \Delta\eta_d) \quad (2)$$

where: A_{cell} = total aggregated pixel area for the solar PV installation
η = conversion efficiency
$\Delta\eta_t$ = decrease η due to temperature
$\Delta\eta_d$ = decrease η due to dust
R = solar radiation data

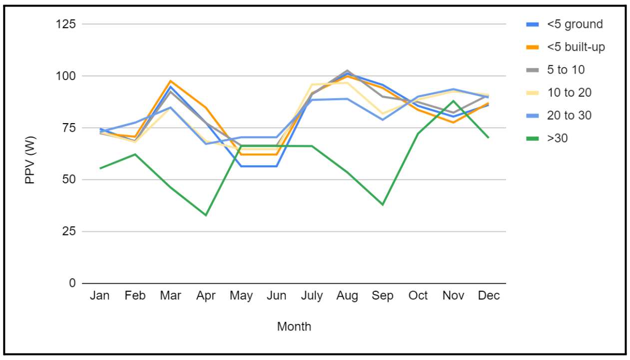
2.5 Estimated PPV and Slope Ranges

In the study, the focus was on comparing the means of PPV across multiple groups: at five different slope ranges in three different areas. Therefore, One-Way Analysis of Variance (ANOVA) was selected as the suitable statistical test for the analysis in comparing the estimated PPV across Metro Manila, Cebu, and Davao to assess whether there were statistically significant differences between the slope ranges. The null hypothesis states that there are no significant differences in PPV output among the various slope ranges within each area. A p-value lower than 0.05 indicates that there are statistically significant differences in PPV output across the slope ranges.

3. RESULTS AND DISCUSSIONS

3.1 Average computed PPV

Following the computation of PPV values, the average values per slope was taken and a line graph was constructed to further help in data visualization (Figs. 3a, 3b, and 3c). Table 1 presents a summary of the data extracted from the line graphs that have been created, while Fig. 4 shows the 2020 yearly average PPV from the data in bar graph form.



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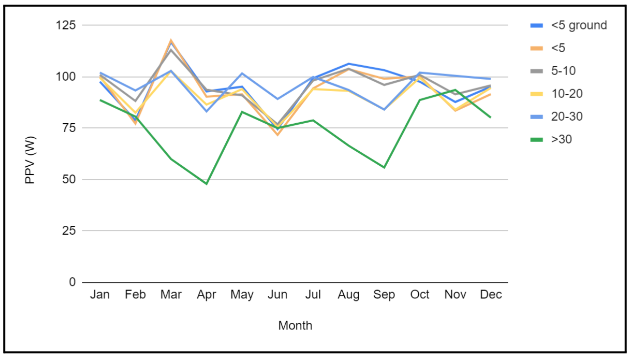

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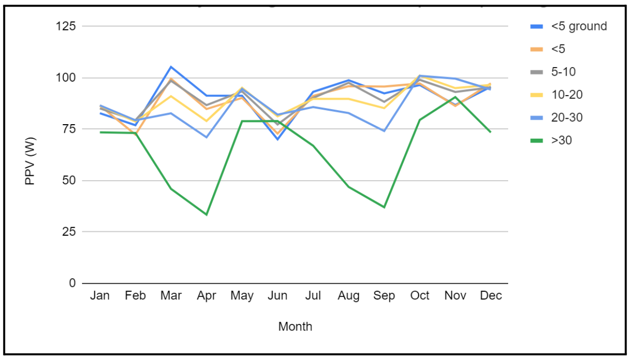

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Figure 3. Potential PV output trend from data points from each slope interval in **(a)** Metro Manila, **(b)** Cebu, and **(c)** Davao, 2020.

Slope Range	Metro Manila	Cebu	Davao
<5° Ground	80.79	95.50	90.13
<5° Built-up	82.08	93.47	89.21
5° to 10°	82.45	95.90	90.38
10° to 20°	80.98	90.93	89.13
20° to 30°	81.20	95.99	86.21
>30°	59.85	74.95	64.91

Table 1. Summary of 2020 Yearly Average PPV for each prominent urban area

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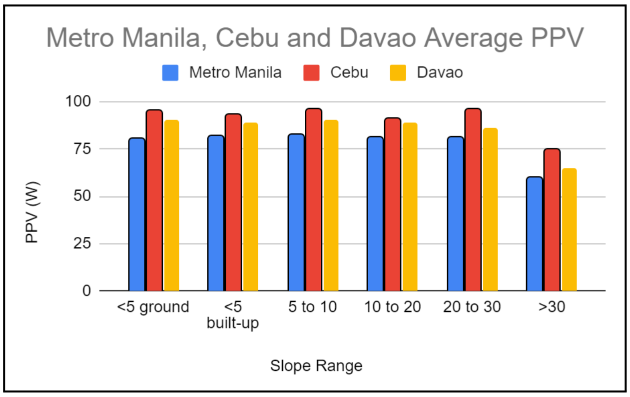
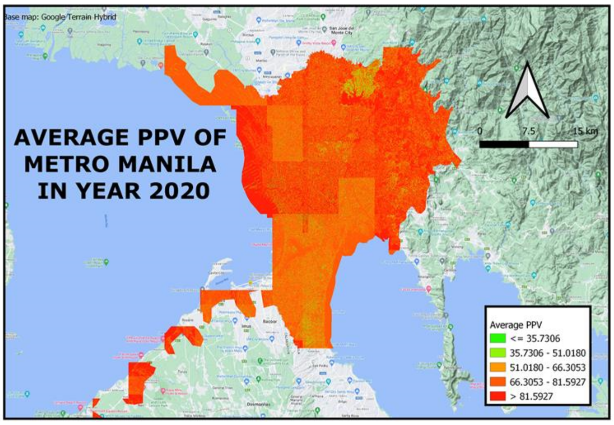


Figure 4. 2020 Yearly Average PPV for Metro Manila, Cebu and Davao

Results displayed in Figs. 9a, 9b and 9c show the average annual PPV map for the year 2020 in the regions of Metro Manila, Cebu, and Davao. In these figures, areas in the shades of red have higher PPV. Conversely, the yellow to green areas indicate lower values of PPV.



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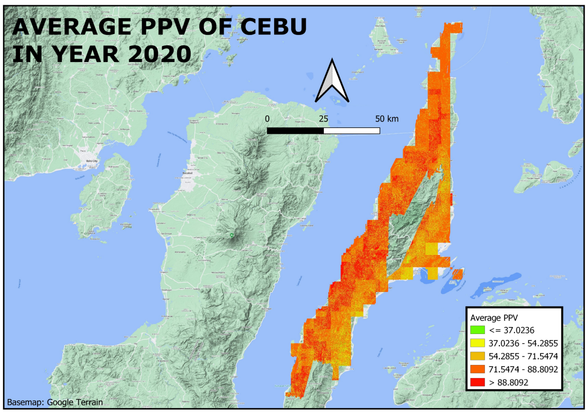

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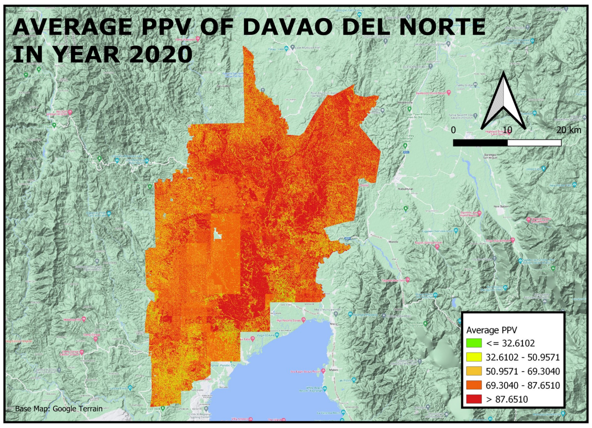

(c)

Figure 5. 2020 Yearly Average PPV Map of (a) Metro Manila, (b) Cebu, and (c) Davao.

3.2 Most Optimal Slope Range

As shown in Figs. 6, 7, and 8, the monthly average PPV within each slope range was used to obtain the yearly averages for the three distinct regions.

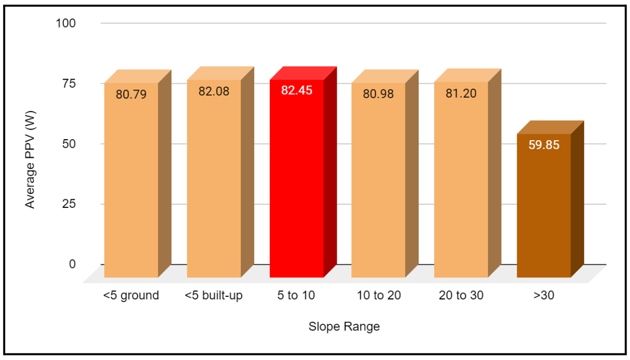

Figure 6. Metro Manila *PPV* across different slopes in 2020.

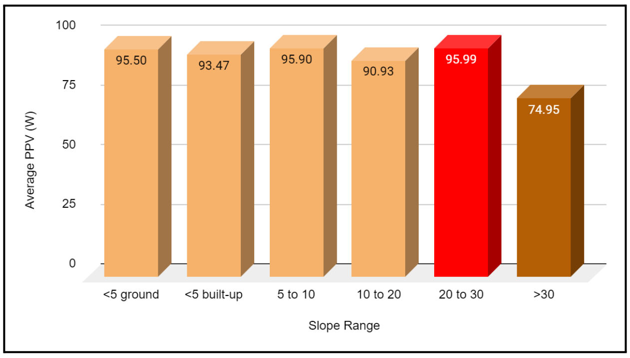

Figure 7. Cebu PPV *PPV* across different slopes in 2020.

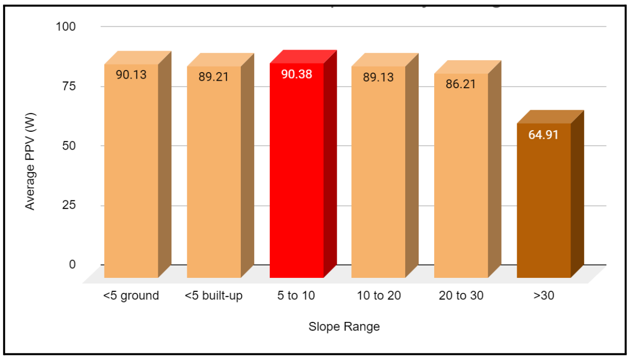

Figure 8. Davao *PPV* across different slopes in 2020.

In Metro Manila and Davao, the most favorable photovoltaic output was observed within the 5° to 10° slope range with values of 82.45 and 90.38, respectively. Conversely, Cebu exhibited its highest optimal photovoltaic output of 95.99 in the 20° to 30° slope range, although the 5° to 10° range yielded a value of 95.90, which is still a sufficiently high result for meaningful comparison across regions. Notably, all three areas consistently showed that the slope range of >30° was the least optimal, generating the lowest *PPV* output. This variation underscores the diverse optimal slope ranges across different areas in the Philippines, which could be attributed to variations in local climate patterns, solar radiation, or geographical features.

3.3 Validation

Using the 2020 average photovoltaic output (PPV) data from Metro Manila, Cebu, and Davao, one-way ANOVA analyses were conducted to examine PPV variations across different slope ranges. As shown in Table 2, in Metro Manila, the ANOVA revealed a significant difference in average PPV among slope ranges with an F-statistic of 5.61 and an extremely small p-value of 0.0002 suggesting that there are significant differences in the slopes of PPV readings among different areas within Metro Manila. Similarly, Cebu produced an F-statistic of 6.97159 and a small p-value of 0.000028 indicates significant differences in the slopes of PPV readings among different areas within Cebu, as shown in Table 3. Finally, Davao produced an F-statistic of 9.77 and very small p-value of 0.00000051 which also indicates significant differences in the slopes of PPV readings among different areas within Davao, as shown in Table 4.

High values of F-statistic, together with the extremely small p-values of 0.0002, 0.0000005 and 0.00003 that are less than the typical significance level of 0.05, suggests that there are significant differences in the slopes of PPV readings among different areas within Metro Manila, Cebu and Davao, hence strong evidence for rejecting the null hypothesis. In other words, there are specific areas within the three regions where *PPV* readings significantly vary at different slopes, and these differences are unlikely to be random. These results underscore the importance of selecting appropriate slope ranges for efficient solar energy utilization in each region.

4. CONCLUSIONS

Using the SSI product from Fengyun-4A, $R_{surface}$ values for each slope interval were estimated and consequently, the solar PV power potential (PPV). Results show that the highest estimated *PPV* in Metro Manila and Davao were produced from solar PV panels tilted at 5° to 10° with an average *PPV* value of 82.9 W. Meanwhile, in Cebu, the highest estimated *PPV* was at the 20° to 30° tilt angle range with an average *PPV* value of 95.99 W. The lowest *PPV* was consistent in all the study areas, which was observed at tilt > 30° and at an average *PPV* value of 65.02 W. This implies that to obtain the maximum PPV output, the solar PV panels must be tilted at specific angles depending on location. Location dictates the optimum tilt angle to maximize PPV as this affects how much sunlight an area receives.

For future studies, it is recommended that the number of sites per slope interval be increased. Although the differences are minimal, having more data points per study area may generate more accurate average values of solar *PPV* potential. Lastly, *PPV* values can be used as input to a more accurate forecasting of power outputs from potential solar PV installations.

Source	DF	Adj SS	Adj MS	**F-Value**	**P-Value**
Slope	5	4712.00	942.4	**5.61**	**0.00023**
Error	66	11089.6 5	168.023	N/A	N/A
Total	5	15801.65		N/A	N/A

Table 2. Summary of results of Analysis of covariance for PPV in Metro Manila area.

Source	DF	Adj SS	Adj MS	**F-Value**	**P-Value**
Slope	5	3993.15	798.63	**6.97**	**0.000028**
Error	66	7560.62	114.56	N/A	N/A
Total	5	11553.7 7		N/A	N/A

Table 3. Summary of analysis of covariance for PPV in Cebu PPV area.

Source	DF	Adj SS	Adj MS	**F-Value**	**P-Value**
Slope	5	5939.02	1187.8	**9.77**	**0.000000 51**
Error	66	8025.90	121.61	N/A	N/A
Total	5	13964.92		N/A	N/A

Table 4. Summary of analysis of covariance for PPV in Davao area.

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