COMPARATIVE ANALYSIS OF CLOT-ADJUSTED AHI-8/9 AND FY-4A SOLAR RADIATION DATA FOR SOLAR PV POWER POTENTIAL ASSESSMENT IN THE PHILIPPINES

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ABSTRACT:

The theoretical solar photovoltaic (PV) power (PPV) potential in the Philippines has been estimated to range from 1.87 to 3.19 kWh/kWp daily and 681.80 to 1,162.58 kWh/kWp yearly using the shortwave radiation (SWR) product derived from the Advanced Himawari Imager-8 and 9 (AHI-8/9) satellite data. However, solar radiation measurements, especially for satellite-derived data, must be accurate when used to estimate the maximum solar energy available for solar PV power production. The objective of this study is to evaluate the satellite-derived measurements of AHI-8/9 SWR and Fengyun 4A surface solar irradiance (SSI) data products in the estimation of theoretical PPV output in the Philippines. Moreover, selected actual solar PV installation sites located across the Philippines, such as in the cities of Baguio, Cebu, and Tagum, are included in the analysis PV power production data. Both SWR and SSI products were adjusted using the cloud optical thickness (CLOT) product for cloud effects and consequently, obtain the maximum solar PV power potential. In this study, SWR and SSI products were analyzed to determine which factors may have contributed to the differences in the estimated values. The in-situ PV power production data was compared to the two satellite-based solar radiation data to assess the degree of correlation between the two. Diurnal trends for representative areas in Luzon, Visayas and Mindanao show that for all sites, the SWR data agrees with the actual PV production data better than the SSI data. Results show that the range of CLOT-adjusted solar irradiance values are higher when using SSI than SWR. It was also observed that CLOT reduces the solar radiation by an average of 19.36%, 16.08% and 10.54% during the cool dry season (December to January), rainy season (June to November) and hot dry season (March to May), respectively. In future studies, the adjusted solar radiation (R') data may be used instead of the raw AHI8 SWR or FY-4A SSI to estimate the theoretical maximum solar PV power potential (PPV). Geomorphological and meteorological factors can also be considered in the estimation of effective PPV.

1. INTRODUCTION

The theoretical or maximum possible solar PV power potential in the Philippines has been estimated to range from 1.87 to 3.19 kWh/kWp daily and 681.80 to 1,162.58 kWh/kWp yearly using the shortwave radiation (SWR) product derived from the Advanced Himawari Imager-8 and 9 (AHI-8/9) satellite data (Bauzon et al., 2022). However, accurate solar radiation measurements, especially for satellite-derived data, must be adjusted considering meteorological and geomorphological factors, and actual installable capacity to improve estimation of solar energy available for solar PV power production (J. Principe & Takeuchi, 2019).

Solar irradiance is measured at the Earth's mean distance from the Sun and at the top of the atmosphere on a plane parallel to the incident radiation (Earthdata, 2023). Solar irradiance, measured in W/m^2, is the amount of energy from the sun that strikes a given surface in a given amount of time and space. Irradiation, measured in W/m^2, is the sum of irradiance over a certain period of time or the total quantity of solar energy incident to a unit area over time (Al-Waeli et al., 2019; Stickler, 2016).

The amount of solar radiation that is attenuated by scattering and absorption is measured by the cloud optical thickness (CLOT). The amount of sunlight that is scattered and reflected increases with CLOT value (NASA, 2013) and affects radiation at non-water-absorbing wavelengths, while the effective particle radius affects radiation at water-absorbing near-infrared wavelengths (Kawamoto et al., 2001). Thus, remotely-sensed solar radiation products such as shortwave radiation (SWR) and solar surface irradiance (SSI) may still need to be adjusted for effects of cloud since the amount of reflected radiation is affected by CLOT (J. A. Principe, 2019; Sotto et al., 2023).

The maximum theoretical solar irradiance reaching the surface can be estimated by adjusting satellite-derived solar radiation data to account for cloudiness using a cloud optical property (Cotton et al., 2011; Mayer, 2009). According to Cotton et al. (2011), this theory is due to the fact that CLOT affects the intensity of reflected and transmitted radiation that reaches the earth's surface. Using CLOT to adjust solar radiation products, the maximum solar PV power (PPV) potential for each year will become similar to or within the same range regardless of the year. (Sotto et al., 2023).

The objective of this study is to estimate the maximum solar PV power potential by evaluating the satellite-derived measurements of SWR and SSI data products from AHI-8/9 and FY-4A, respectively, in the estimation of theoretical solar PV power output in the Philippines. Comparing SWR, SSI,

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and PV production data provides an analysis on which factors possibly affect the differences in their observed values in low-latitude areas including the Philippines. The results of this study can contribute to the improvement of key parameters (e.g., solar radiation, meteorological parameters) involved in the calculation of solar PV power potential.

2. METHODOLOGY

In this study, remotely-sensed solar radiation values were analyzed to determine how cloud optical thickness (CLOT) has contributed to the differences of actual and adjusted SWR and SSI values. The in-situ PV power production data was compared to the remotely-sensed solar radiation data (SWR and SSI) to assess the degree of correlation between the two.

2.1 Himawari Shortwave Radiation (SWR)

The JAXA Himawari is one of the most modern satellites that is currently in use. It is the eighth Himawari satellite that the Japan Meteorological Agency (JMA) has launched and is currently in operation. Himawari -8 and 9 were launched in October 2015 and November 2016, respectively (EORC & JAXA, 2022). The satellite images from sensors onboard Himawari satellites are mostly used for weather analysis, predictions, and other applications that need highly temporal data and observations taken in close to real-time. The satellite's primary instrument is the 16-channel Advanced Himawari Image (AHI), which can take visible and infrared images of most of Asia and the Pacific. AHI-8/9 has a spatial resolution of 5 kilometers and a temporal resolution of 10 minutes for Level 2 products. (Bessho et al., 2016; EORC & JAXA, 2022)

This study uses Shortwave Radiation (SWR) from Photosynthetically Available Radiation Data and Cloud Optical Thickness (CLOT) from Cloud Property data products of Advanced Himawari Imager (AHI) 8 and 9. The SWR product was derived using the method of Frouin & Murakami (2007) in the photosynthetically available radiation (PAR) for ADEOS-II Global Imager Data. .

2.2 Fengyun-4A Surface Solar Irradiance (SSI)

The FY4A surface solar irradiance (SSI) Level 2 product from China Meteorological Administration (CMA) National Satellite Meteorological Center (NSMC) is available at 15-minute temporal resolution and 4-kilometer spatial resolution (NSMC, 2023). Surface solar irradiance is defined as the solar radiation flux density incident on the surface in watts per square meter. FY-4A SSI is the total solar radiation energy received by the area, combining direct and diffuse solar radiation (Jia et al., 2021; NSMC, 2023).

2.3 Data Preprocessing

AHI-8 SWR and CLOT products were downloaded from JAXA Himawari Monitor (https://www.eorc.jaxa.jp/ptree/). SWR and CLOT were available in NETCDF file format and at 10-minute temporal resolution and 5-kilometer spatial resolution. FY-4A SSI was downloaded directly from the NSMC Online Portal (https://satellite.nsmc.org.cn/) in HDF format. SSI raster files were converted to NETCDF file format and resampled from 4 km to 5 km spatial resolution for consistency with AHI products.

This study used SWR (in W/m^2), SSI (in W/m^2), and CLOT (dimensionless) data acquired during the period January 01, 2020 to December 31, 2021.

2.4 Cloud Optical Thickness and Correction Factor for Solar Radiation

Downward global horizontal irradiance (GHI) values from SWR and SSI were adjusted using cloud optical thickness (CLOT), a cloud optical property, to obtain the maximum solar energy resource potential of the study area (J. A. Principe, 2019; Sotto et al., 2023). Fig. 1 shows the flowchart used to obtain the correction factor for solar radiation (CFSR) using CLOT.

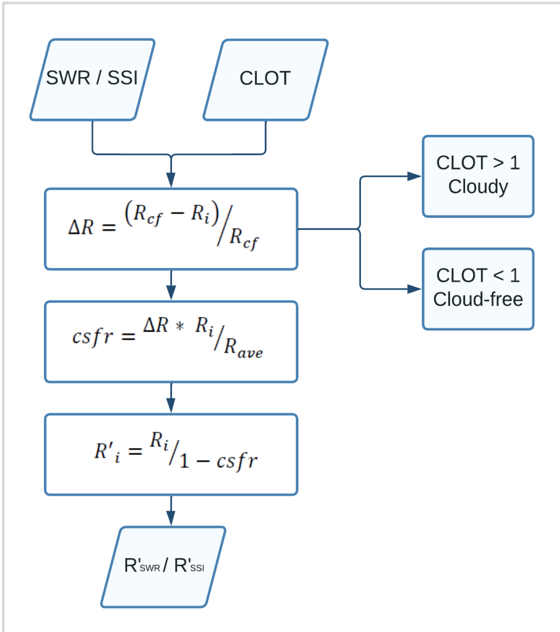

Figure 1. CLOT-derived correction factor for solar radiation (CFSR) using AHI-8/9 SWR and FY-4A SSI.

To characterize the cloudiness of a certain pixel, CLOT data from the AHI-8/9 CLP product was used. A CLOT value of less than 1.0 indicates a clear sky or cloud-free (cf) while a CLOT value greater than or equal to 1.0 indicates a cloudy sky.

ΔR is defined as the difference between the retrieved solar radiation with the nearest cloud free day. For CLOT > 1.0, CFSR was computed by looking for the nearest cloud-free day and looking for its corresponding solar radiation value to compute for ΔR using Eq. (1):

$$\Delta R = \frac{R_{cf} - R_i}{R_{cf}} \quad (1)$$

where R_{cf} is the mean daily cloud-free solar radiation and R_i is the mean daily observed solar radiation affected by clouds. For CLOT ≤ 1.0, CFSR is equal to zero and the value of the radiation will be the same as the initial.

The correction factor for solar radiation, applied per day of observation, is computed using Eq. (2):

$$CFSR = \frac{\Delta R \ x \ R_i}{R_{ave}} \quad (2)$$

where R_{ave} is the mean monthly radiation.

Lastly, Eq. (3) is used to compute the mean adjusted solar radiation using the initial radiation data and CFSR for each day.

$$R' = \frac{R_i}{1 - CFSR} \quad (3)$$

Eq. (3) was used to compute for the adjusted SWR (R'_{SWR}) and adjusted SSI (R'_{SSI}) as shown below:

$$R'_{SWR} = \frac{R_{i,SWR}}{1 - CFSR} \quad (4)$$

$$R'_{SSI} = \frac{R_{i,SSI}}{1 - CFSR} \quad (5)$$

Computation of R'_{SWR} and R'_{SSI} using Python is discussed in the next section.

2.5 Estimation of R' using Python

Data processing to produce cloud-free irradiance data was automated using Python (Fig. 2). Its main tasks were the cloud cover analysis and the computation of correction factor for solar radiation (CFSR). The script makes use of the Numpy library for numerical operations and the GDAL library for geospatial data processing.

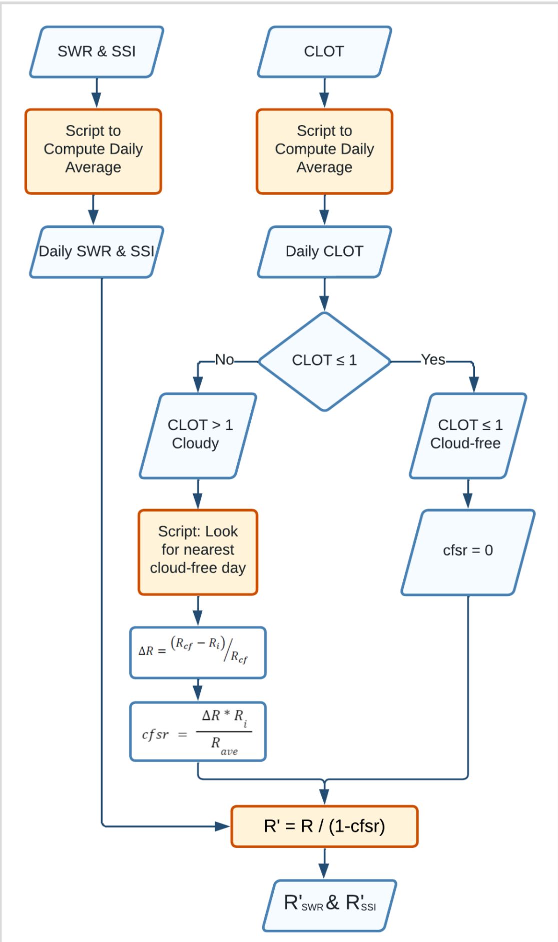

Figure 2. Estimation of R' using Python.

The Python script begins by examining the SWR and CLOT raster images and converting each raster image into a 2D array to compare the values of the corresponding pixel with the same coordinates.

For each pixel, the program identifies if it will fall under cloudy or cloud-free conditions. If the program identifies it as a cloudy day (CLOT > 1), the script will find the nearest point in time either in the previous days or days ahead, until it identifies the nearest cloud-free day at that given location. The SWR value at the nearest cloud-free day is used to compute the CFSR. In cloud-free conditions (CLOT ≤ 1), the program will not apply any adjustments to the original radiation data and CFSR will be set to zero. The resulting CFSR array is used to create new raster files. CFSR was computed for daily, monthly, and seasonal adjustments of the SWR product. This study used daily CFSR for the adjustment as it was observed that the daily correction factor reflects the conditions better when compared to monthly or seasonal CFSR. The daily correction factor for solar radiation was used to obtain adjusted SWR (R'_{SWR}) raster.

To compute for the adjusted SSI (R'_{SSI}), the methodology as shown in Fig. 2 was also applied to the SSI product using the same CLOT product from JAXA Himawari due to absence of such cloud property data from CMA.

3. RESULTS AND DISCUSSION

This study assessed the theoretical solar PV power resource potential of the entire Philippines. As shown in Fig. 3, daily correction factors were used instead of monthly and seasonal adjustments. The finer temporal resolution produces more accurate solar radiation adjustments as the correction computed for a specific day is applied on the same day instead of using an averaged monthly or seasonal correction factor.

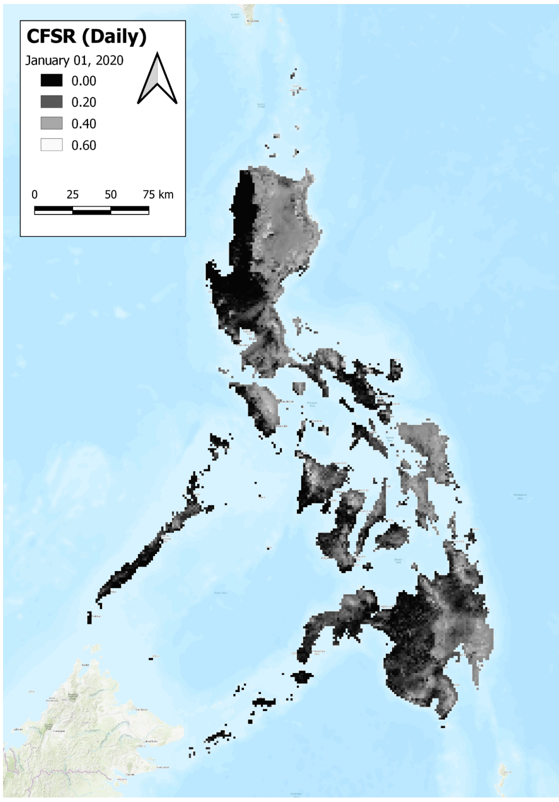

Figure 3. Sample output of daily CFSR raster file using the Python Script for January 1, 2020.

Point data with hourly temporal resolution from solar PV installations in Baguio City, Cebu City, and Tagum were used in the comparative analysis of satellite-based measurements with onsite measurement of PPV.

The diurnal trends of SWR, SSI, and actual PV production data in selected sites across the Philippines are shown in Figs. 4a, 4b and 4c. The sites were selected on the basis of actual PV production data availability and also to represent areas in the Luzon, Visayas, and Mindanao regions of the country. The diurnal trends show that for all sites, the SWR data follows the general trend of the actual PV production data better than the SSI data. In Baguio City, it can be observed that the SWR data follows the trend of the PV production data even if their values have different magnitudes. Also, it can be observed that there is a certain lag and lead of the SSI data trend compared to the SWR and PV production data trends. In Cebu City, it can also be observed that the SWR data follows the trend of the PV production data, and their magnitude of values fall within the similar range. In the Tagum site, the diurnal trends of the datasets seem different with each other, though it can be noticed that they all have a similar curve. However, the PV production data has a lag in its trend while the SWR and SSI have different magnitudes.

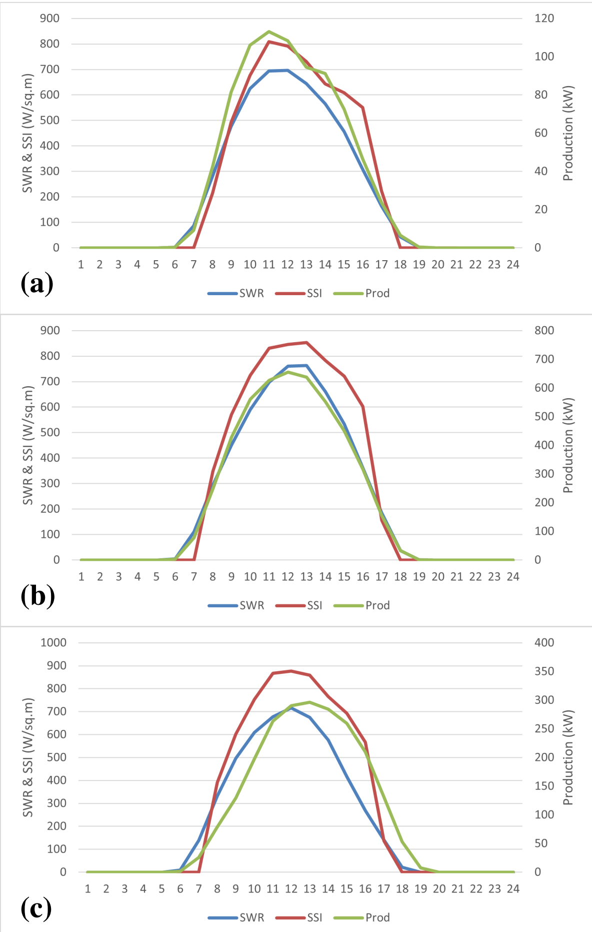

Figure 4. Diurnal trend of SWR, SSI, and PV production data in **(a)** Baguio City, **(b)** Cebu City, and **(c)** Tagum 2021.

Mean monthly SWR, SSI, R'_{SWR}, and R'_{SSI} for 2020 and 2021 are shown in Figs 5 and 6. Minimum solar radiation values can be observed during December across all variables while maximum solar radiation values were tabulated during the months March and April.

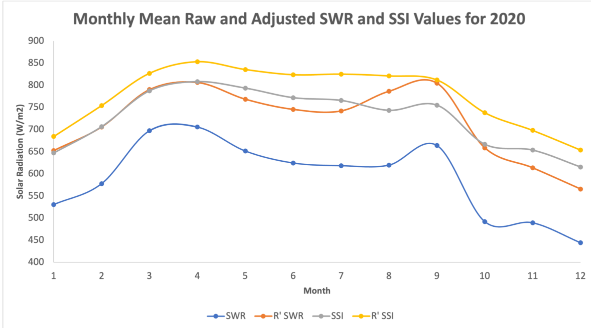

Figure 5. Mean raw and adjusted SWR and SSI values for 2020.

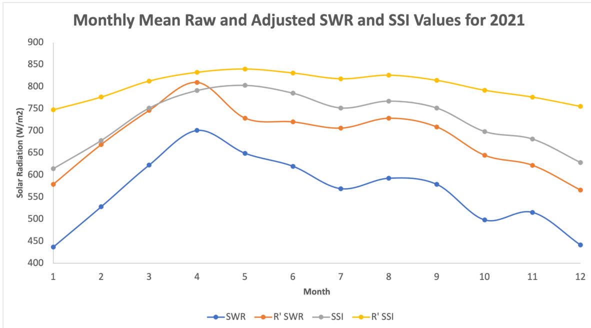

Figure 6. Mean raw and adjusted SWR and SSI Values for 2021.

Mean seasonal solar radiation for 2020 and 2021 are tabulated in Table 1. Results show that the maximum SWR and SSI were recorded during the hot dry season (March, April, and May) while the minimum SWR and SSI were observed during the cool dry season (December, January, and February). The rainy season (June, July, August, September, October, and November) has moderately high SWR and SSI values that spikes in the month of September and falls rapidly after.

	SWR	R'_{SWR}	SSI	R'_{SSI}
Cool Dry	493.11	622.88	648.20	728.66
Hot Dry	671.13	774.95	789.08	833.40
Rainy	573.46	706.77	732.59	797.89

Table 1. Mean Seasonal Solar Radiation Values

Figs. 7a and 7b show the range of solar PV power output values using SWR and SSI in the Philippines as 2021 annual maps. The maps show that the range of CLOT-adjusted solar irradiance values are higher when using FY-4A SSI than the AHI-8/9 SWR product. Areas in yellow and red indicate low and high SWR/SSI, respectively. In both CLOT-adjusted SWR and SSI maps, the highest values occur in the Mindanao region of the country.

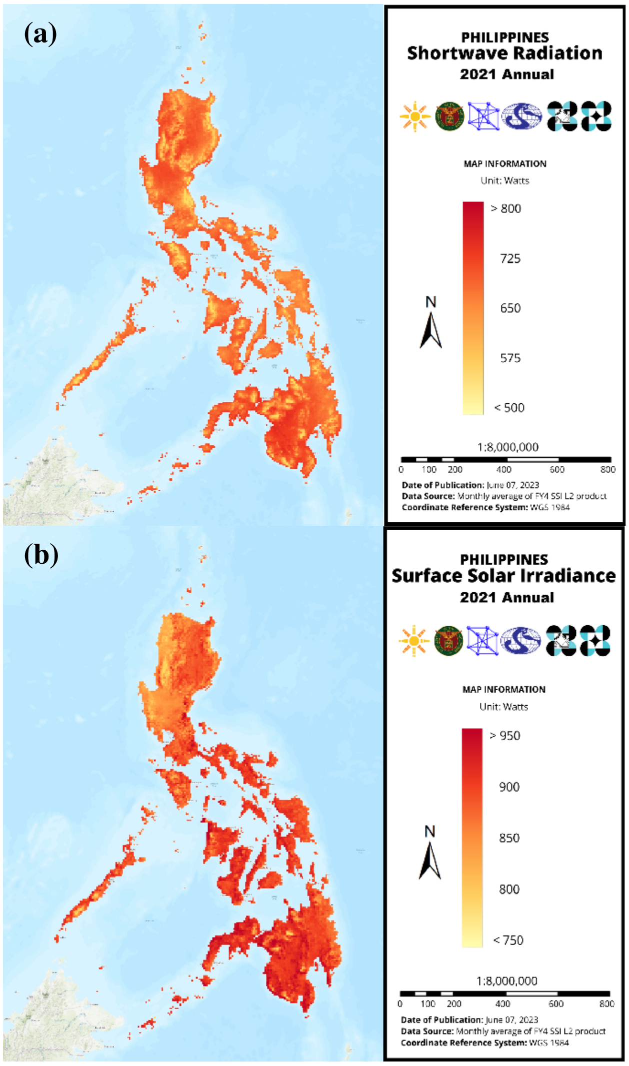

Figure 7. Theoretical solar PV power potential in the Philippines in 2021 using CLOT-adjusted **(a)** SWR and **(b)** SSI.

Further analysis of the solar radiation product adjustment using CLOT derived correction factor was done to validate the results of the study. Comparative analysis was done for SWR vs R'_{SWR} (adjusted SWR product) and SSI vs R'_{SSI} (adjusted SSI product). The differences of the original (SWR, SSI) and CLOT adjusted solar radiation (R'_{SWR}, R'_{SSI}) values for each pixel were compared and zonal statistical analysis was done to obtain the mean, minimum and maximum values. As shown in Fig. 8, adjustment using CLOT increases the SWR and SSI values by an average of 124.26 W/m^2 with a minimum of 40.31 W/m^2 in Ilocos Sur and a maximum of 201.56 W/m^2 in Aklan. The significant increase in solar radiation values were mostly observed in mountainous areas or areas with high elevation. Areas least affected by CLOT adjustments were Ilocos Region, Central Luzon and Central Mindanao.

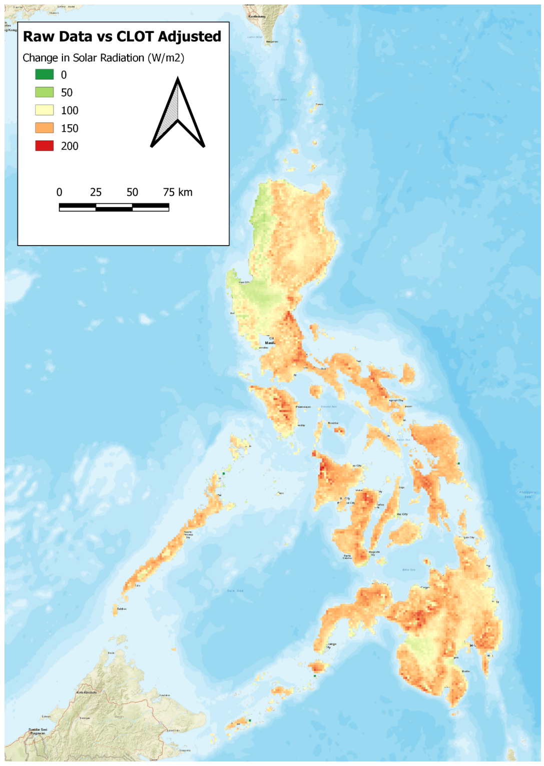

Figure 8. Non-CLOT adjusted vs CLOT Adjusted data Map of average SWR and SSI data in W/m^2.

4. CONCLUSION

In estimating solar PV power output, clouds act as a critical parameter due to their higher spatial and temporal variability compared to any other atmospheric factor. Prevalence of cloud cover on raster images can significantly decrease the forecasted PPV output compared to the actual output. CLOT adjustments may help in generating a single PPV potential map applicable for any period of assessment.

Comparing the mean seasonal SWR vs R'_{SWR}, the shortwave radiation value has increased by 26.32% in the cool dry season, 15.47% in the hot dry season, and 23.25% in the rainy season. Meanwhile, the SSI values have increased by 12.41%, 5.62%, and 8.91% for the cool dry, hot dry and rainy seasons, respectively, when adjusted with CLOT. It can be observed that cloud optical thickness highly affects solar irradiation during the cool dry season, followed by the rainy season and hot dry season.

In future studies, the adjusted solar radiation (R') data may be used instead of raw SWR or SSI to estimate the theoretical maximum solar PV power potential (PPV). Geomorphological and meteorological factors such as dust, precipitation, and high temperature may also be used to calculate theoretical and effective PPV more accurately.

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REFERENCES

Al-Waeli, A. H. A., Kazem, H. A., Chaichan, M. T., & Sopian, K., 2019. *Photovoltaic/Thermal (PV/T) Systems: Principles, Design, and Applications*. Springer International Publishing. https://doi.org/10.1007/978-3-030-27824-3

Bauzon, Ma. D. A., Sotto, M., Santos, J. A., & Principe, J. (2022). Spatial Analysis on Solar PV Potential Hotspots using Himawari-8 SWR data and Locations of Existing Solar PV Projects: Case of the Philippines. *30th IIS Forum Earth Observation, Disaster Monitoring and Risk Assessment from Space.* University of Tokyo, Japan.

Bessho, K., Date, K., Hayashi, M., Ikeda, A., Imai, T., Inoue, H., Kumagai, Y., Miyakawa, T., Murata, H., Ohno, T., Okuyama, A., Oyama, R., Sasaki, Y., Shimazu, Y., Shimoji, K., Sumida, Y., Suzuki, M., Taniguchi, H., Tsuchiyama, H., Yoshida, R., 2016. *An Introduction to Himawari-8/9: Japan's New-Generation Geostationary Meteorological Satellites. Journal of the Meteorological Society of Japan.* Ser. II, 94(2), 151–183. https://doi.org/10.2151/jmsj.2016-009

Cotton, W., Bryan, G., & van den Heever, S., 2011. Chapter 5. Radiative Transfer in a Cloudy Atmosphere and Its Parameterization. *International Geophysics*, 99, 143–175. https://doi.org/10.1016/S0074-6142(10)09911-0

Earthdata, 2023. *Solar Irradiance*. www.earthdata.nasa.gov/topics/atmosphere/atmospheric-radiation/solar-irradiance.

EORC & JAXA, 2022. Himawari Geophysical Parameter Data through the JAXA's P-Tree System. *Earth Observation Research Center (EORC) Japan Aerospace Exploration Agency (JAXA).* https://www.eorc.jaxa.jp/ptree/documents/README_HimawariGeo_en.txt.

Frouin, R., & Murakami, H. 2007. Estimating photosynthetically available radiation at the ocean surface from ADEOS-II global imager data. *Journal of Oceanography*, 63(3), 493–503. https://doi.org/10.1007/s10872-007-0044-3

Jia, D., Hua, J., Wang, L., Guo, Y., Guo, H., Wu, P., Liu, M., & Yang, L. 2021. Estimations of Global Horizontal Irradiance and Direct Normal Irradiance by Using Fengyun-4A Satellite Data in Northern China. *Remote Sensing*, 13(4), Article 4. https://doi.org/10.3390/rs13040790

Kawamoto, K., Nakajima, T., and Nakajima, T. Y., 2001. A Global Determination of Cloud Microphysics with AVHRR Remote Sensing. *Journal of Climate*, 14(9), 2054-2068. doi.org/10.1175/1520-0442

Mayer, B., 2009. Radiative transfer in the cloudy atmosphere. *EPJ Web of Conferences,* 1, 75–99. https://doi.org/10.1140/epjconf/e2009-00912-1

NASA, 2013. Hyperwall: Monthly Cloud Optical Thickness (Terra/MODIS). svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=30385.

NSMC, 2023. FengYun-4A Product Catalogue. *National Satellite Meteorological Center, China Meteorological Administration.* https://fy4.nsmc.org.cn/data/en/code/FY4A.html.

Principe, J. A., 2019. Assessment of solar PV power potential over Asia Pacific region with remote sensing and GIS. Department of Civil Engineering, Graduate School of Engineering, The University of Tokyo, Tokyo, Japan.

Principe, J., & Takeuchi, W. 2019. Assessment of solar PV power potential over Asia Pacific region with remote sensing considering meteorological factors. *Journal of Renewable and Sustainable Energy*, 11(1), 013502. https://doi.org/10.1063/1.5059335

Sotto, M., Bauzon, M., Cañete, J., & Principe, J., 2023. AHI-8 SWR Adjustment using CLOT-derived Correction Factor for Solar PV Power Potential Assessment in the Philippines. *31st IIS Forum Earth Observation, Disaster Monitoring and Risk Assessment from Space.* University of Tokyo, Japan.

Stickler, G., 2016. Educational Brief: Solar Radiation and the Earth System. web.archive.org/web/20160425164312/http://education.gsfc.nasa.gov/experimental/July61999siteupdate/inv99Project.Site/Pages/science-briefs/ed-stickler/ed-irradiance.html.