CHEMICAL ENGINEERING TRANSACTIONS
VOL. 106, 2023

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Peck Loo Kiew, Hon Huin Chin

ISBN 979-12-81206-05-2; **ISSN** 2283-9216

DOI: 10.3303/CET23106012

Application of Empirical Models to GIS-Based Suitability Analysis of Solar Siting on Limited Spatial Resolution

Dan William C. Martinez[a], Rommel Glenn S. Mendova[b,*], Gil G. Cruz[c], Nelson S. Andres[d]

[a]Department of Mechanical Engineering, College of Engineering and Architecture, Bataan Peninsula State University, Capitol Compound, Tenejero, Balanga, Bataan, Philippines 2100
[b]Department of Civil Engineering, Gokongwei College of Engineering, De La Salle University, 2339 Taft Ave, Malate, Manila, Metro Manila, Philippines 1004
[c]Research and Innovation Center for Climate Change and Sustainability, Bataan Peninsula State University, Capitol Compound, Tenejero, Balanga, Bataan, Philippines 2100
[d]Department of Electrical Engineering, College of Engineering and Architecture, Bataan Peninsula State University, Capitol Compound, Tenejero, Balanga, Bataan, Philippines 2100
rommel_mendova@dlsu.edu.ph

The escalating global demand for sustainable energy has spurred interest in solar energy as an eco-friendly solution. Determining suitable sites for solar installations requires evaluation of geographical, economic, and technological aspects. Geographic Information Systems (GIS) have emerged as powerful tools for evaluating spatial data in such analyses, enabling the integration of diverse geospatial information to support informed decision-making. Yet, prevailing research predominantly focuses on large-scale installations, largely due to data constraints concerning rooftop installations. This study seeks to address this gap by employing empirical formulas to estimate parameters relevant to characterizing and predicting solar energy output from rooftop installation sites. More specifically, this study aims to cite potential solar energy installation areas on the main campus of Bataan Peninsula State University. Using pre-processed Himawari-8 satellite data and Digital Surface Model, the total Potential PV Output of the University roof was calculated. It is estimated that using the most optimum tilt and orientation, the university receives 2,863.13 kWh/m^2.y. Considering a 20 % efficiency of solar PV Panels and 50 % loss from distribution to storage, the solar panels have a solar energy output potential of 286.31 kWh/m^2.y. With an average consumption of 27,980 kWh monthly, the university can achieve carbon neutrality on energy consumption by using less than 5 % of the total roof area. Therefore, a holistic action to achieve absolute carbon neutrality can be achieved.

1. Introduction

Renewable energy (RE) sources are one of the foremost targets in the Sustainable Energy Agenda of the Philippines. It is widely believed that RE is a vital part of the low-emission development strategy of a country, which is also crucial in addressing the challenges brought by climate change and energy security. Like other countries around the globe, the Philippines has acknowledged the impacts of dependence on fossils and exposure to its price fluctuations along with the balance among economic growth without neglect of public health, natural ecosystems, and the environment. The integration of renewable energy sources may be the key element for new energy policies as it reduces energy losses and brings stability to energy systems while minimizing environmental impacts.
In West Bengal, India, Ghose et al. (2020) analyzed the state on a Quantum Geographical Information System (Q-GIS) based model. Unsuitable areas were eliminated and an Analytical Hierarchy Process (AHP) for the Multi-Criteria Decision-Making (MDCM) was also employed to obtain a hierarchy of suitable regions for the construction of a solar photovoltaic (PV) plant. The study was able to site and map Raghunatpur and Belda as the most suitable areas for solar PV plants. The results obtained using Q-GIS became a directive for investors and policymakers who target the deployment of the model created for future decision–making in the energy

Paper Received: 30 May 2023; Revised: 08 September 2023; Accepted: 29 September 2023
Please cite this article as: Martinez D.W.C., Mendova R.G.S., Cruz G.G., Andres N.S., 2023, Application of Empirical Models to GIS-Based Suitability Analysis of Solar Siting on Limited Spatial Resolution, Chemical Engineering Transactions, 106, 67-72 DOI:10.3303/CET23106012

sector of the country. This research introduces the application of Analytic Hierarchy Process (AHP) to the process of solar energy siting. However, it is noteworthy that there exists potential for enhancement in the accuracy of parameter normalization. The current normalization approach employs a binary classification, which may not adequately address variations within the designated Boolean categories.
A study conducted by Hassan et al. (2021), provided a GIS-based model for multi-criteria suitability analysis of potential areas for PV plants with the use of a variety of spatial determinants. The model involved spatial indicators that reflect the criteria, namely irradiation, physical suitability of the site, cost–effectiveness, and availability of the land. The GIS-based model provided an example of the utilization of GIS as a Decision Support System (DSS) similar to the method used by Ghose et al., where GIS is also employed with MDCM, in the development of strategies for siting solar PV system farms and estimation of potential power sources that can be generated and utilized. Hassaan et al. (2021) pioneered a novel normalization approach that dispensed with categorization. Instead, they employed relational coefficients to align parameters—a technique termed "fuzzy membership," subsequently adopted in various MDCM investigations. The suggested model concluded that a total area of 2,515 km^2 located in the western and southern parts of Kuwait is suitable for solar energy generation, hence can accommodate the installation of a solar PV plant (Hassaan et al., 2021).
Studies in the application of analytical hierarchy process to policy and decision-making was already done in the Philippines (Rapal et al., 2017). In spite of this, the principal limitation inherent in the employed methodologies of these studies pertains to their limited replicability within smaller spatial scales. This constraint arises from the inherent restrictions associated with satellite-derived data, characterized by resolutions spanning several kilometers. Such data prove unsuitable for rooftop installation initiatives, which typically encompass spatial extents on the order of tens of meters. The objective of this study is to gather satellite data, to create a suitability map for potential renewable energy installation areas in Bataan Peninsula State University using a Geographical Information System (GIS)-based model. Then, analyze the effects of different parameters on site selection for solar photovoltaic cells and compute solar energy potential per unit area at the university. More specifically, to gather satellite data from Himawari Satellite (Sengupta, 2018), to normalize the collected data using fuzzy logic, to calculate the weights of selection criteria using AHP, and to map potential renewable energy installation areas in the university. This study will help with delineating suitable areas for limited spatial extents like rooftop installations, and the calculation of corresponding energy output potential.

2. Methods

GIS with an MDCM approach will be employed to prioritize areas based on their inclination for an installation of an efficient solar PV plant. The methodology can be divided into five distinct steps: developing suitability criteria, data preparation, developing suitability indices, delineation of most suitable sites, and solar PV potential output estimates of the selected sites.

2.1 Developing Suitability Criteria

When considering site suitability, spatial data can be categorized into two distinct groups: exclusion criteria and evaluation criteria. Exclusion criteria pertain to sites that are unsuitable for the installation of a solar PV plant. This study identifies several factors that fall under the exclusion criteria, namely shaded areas, old buildings undergoing renovation, and religious sites. The term "old buildings" encompasses structures with visibly deteriorating roofs due to rusting, as they would not be suitable for hosting solar PV systems. Buildings that are currently undergoing renovation and are scheduled for further work within the next five years are also excluded from data collection.
The evaluation criteria determine the suitability of roofs for solar PV installations. These criteria encompass various factors that contribute to optimal performance. Firstly, the installation areas must receive sufficient annual irradiance, ensuring an ample amount of sunlight throughout the year. Physical factors such as the tilt and orientation of the areas are essential considerations, as they directly impact sunlight absorption. Meteorological conditions also play a crucial role, as the ideal installation areas should exhibit favorable factors such as adequate average wind speed, which aids in reducing the cells' temperature. Areas with a higher sky-view or ambient occlusion are preferred, as they can capture more sunlight even on rainy or cloudy days. Lastly, given that the solar PV cells will be exposed to the elements, regular maintenance is imperative to ensure they consistently operate at peak performance.

2.2 Data Preparation and Empirical Formulas

The total received irradiation or global insolation (G) of the roofs refers to the total energy the roof receives annually. This is calculated by getting the sum of direct, diffused, and reflected radiation or Albedo (Hoyt, 1978) as shown in Eq(1).

$$G = G_{DIRECT} + G_{DIFFUSED} + G_{ALBEDO} \quad (1)$$

Direct Radiation is the radiation received by the solar photovoltaic cells directly from the sun. Eq(2) shows the translation of Direct Normal Irradiation, DNI, to Direct Radiation which is described as a function of the angle of incidence. It is approximately (Al Garni et al., 2019; Guo et al., 2017; Levin, 1924):

$$G_{DIRECT} = DNI \cos(\theta) \quad (2)$$

where θ is the angle of incidence between the direct beam of sunlight to the normal of the solar panel.
Diffused Radiation received by solar cells is radiation that was a result of atmospheric refraction. There are a number of diffused radiation models that can be used to determine the diffused radiation (Yadav et al., 2020). Eq(3) shows the Hay and Davies Model (Hay and Davies, 1980) which is used to calculate the Diffused Radiation.

$$G_{DIFFUSED} = DHI \left[A_i R_b + (1-A_i) \frac{1-\cos\cos\beta}{2}\right] \quad (3)$$

Where DHI is the Diffused Horizontal Irradiance; R_b is the view factor for beam radiation and is calculated as the ratio of angle of incidence and the solar zenith angle; and A_i is the Anisotropy Index and is a function of Direct Normal Irradiance, DNI and the Extra-terrestrial Radiation, E_a (E_a = 1360.8 ± 0.5 W/m^2).
Reflected Radiation refers to the radiation that is reflected by the surrounding environment. Eq(4) shows the Reflected Radiation or Albedo as a function of the Global Horizontal Irradiation, GHI; surface albedo, α; and sky-view factor, SVF (Hoyt, 1978).

$$G_{ALBEDO} = GHI\,\alpha\,[1-SVF] \quad (4)$$

The natural slope and aspect of the roofs in the university were derived from a digital elevation model and serve as tilt and orientation for the calculations. However, flat roofs have inherent tilt and orientation. The optimum tilt and orientation for the study area were developed to model how the total received radiation changes as slopes and orientation differ. For slanted roofs, tilt and orientation were calculated and rasterized using the digital surface model (DSM) from UP-LiPAD Project. The DSM was processed in QGIS to extract its slope and aspect using Zevenbergen and Thorne's algorithm (Zevenbergen and Thorne, 1987) where the slope is the derivative of the height with respect to the slope.

2.3 Criteria Standardization

Standardization is one of the most important steps in suitability analysis. The gathered maps have varying ranges, units, and values. To be able to understand the interaction between the differing units and values, it must be converted into a common unit and range. Fuzzy logic is used to standardize the criteria in this study. Fuzzy theory suggests that there is an infinite number of values that data can be categorized from 1 to 0. Suggesting that 1 means that the value belongs in the set and 0 means that it does not. The fuzzification method is used in every criterion. The methods are assigned based on the current understanding of the values under a specific criterion. As shown in Table 1, the solar PV tilt has a Gaussian membership due to the relationships of different tilt values to the global insolation. On the other hand, the total received irradiance only has linear ascending membership since there is only a linear relationship between the received radiation and the suitability of sites.

Table 1: Membership functions and fuzzification parameters

Criteria	Fuzzy Membership	Function Type	Unit	a	b
Global Insolation (Noorollahi et al., 2022)	Linear	Ascending	Wh/sqm.y	Min	Max
Tilt (Ruiz et al., 2020)	Gaussian	-	degrees	13	45
Orientation (Hassaan et al., 2021)	Gaussian	-	degrees	0, 360	180
Wind Speed (Noorollahi et al., 2022)	Linear	Ascending	m/s	0	6
Sky-View	Gaussian	-	unitless	1	0.5
Distance from existing maintenance facilities (Ruiz et al., 2020)	Linear	Descending	meters	0	100

In this study, 10 academia and industry experts are asked to fill out the pairwise comparison matrix of primary and secondary indicators. The pairwise comparison ranged from 1-9 based on the relative importance of the parameters. The results were then processed in Excel to extract the corresponding weights of the criteria. Table

2 shows the result of the AHP. In each comparison, the insistency ratio is kept less than or equal to 0.1 for it to be acceptable. Otherwise, the criterion is deemed inappropriate.

Table 2: Primary and Secondary Criteria Weights

Primary Criteria	Value	Secondary Criteria	Value
Global Insolation	0.534	Global Insolation	1
Physical	0.168	Tilt	0.568
		Orientation	0.432
Meteorological	0.327	Wind	0.225
		Ambient Occlusion	0.775
Maintenance	0.029	Maintenance	1

2.4 Site Delineation

Weighted linear combination, WLC, method is used to overlay the primary and secondary evaluation criteria. Each cell on the standardized secondary layer is multiplied by its corresponding weight. The summation of the secondary layers creates the primary layer which is also multiplied to its corresponding weight and summed up to get the suitability map. Eq(5) shows the WLC equation used in merging evaluation criteria where S is the final suitability value, x_i is the cell value of the criteria, W_i is the weight of the criteria and n is the total number of criteria.

$$S=\sum_{i=1}^{n} x_i W_i \tag{5}$$

2.5 Output estimate

The theoretical potential is the amount of solar radiation received by the solar cells in a period. Technical potential, on the other hand, refers to the potential energy production using current solar energy conversion technologies (Pojadas and Abundo, 2022). The efficiency of these conversion technologies depends on a variety of factors. Most literature assumes that the conversion is mainly affected by cell efficiency, temperature efficiency, efficiency loss due to placement, and other factors in the installation such as soiling and efficiency of the electrical components. For this study, efficiency loss due was already calculated in the global insolation index. As shown in Eq(6), the potential output estimate will be determined where PVout is the estimated output potential, G is the global insolation index, A is the area, AF is the Area Factor, and η_T is the total system efficiency. Area Factor Refers to the total area that can be utilized for a photovoltaic array in consideration of shading. In this calculation, the area factor is assumed to be 0.7 (Noorollahi et al., 2022).

$$PV_{out} = G * Area * AF * \eta_T \tag{6}$$

Table 3 shows the values of efficiency used in calculating the solar potential estimate. The total system efficiency is calculated as

$$\eta_T = \eta_c * \eta_{temp} * \eta_i \tag{7}$$

Table 3: Primary and Secondary Criteria Weights

	Cell Efficiency (Pandey et al., 2016), η_c	Temperature Efficiency, η_{temp}	Installation Efficiency, η_i	Total Efficiency, η_T
Si (crystalline)	0.229	0.90	0.80	0.164
CIGS (Cd free)	0.175	0.90	0.80	0.126

3. Results

Fuzzy Layers have been prepared using the Raster Calculator in QGIS. This is calculated using the fuzzy membership transform parameters as shown in Table 1. After the parameters were standardized. The primary indices were determined. This contains the indices from Global Insolation, Physical Factors, Meteorological Factors, and Maintenance Factors.

Notable findings from this investigation include the following observations: Firstly, among sites with arbitrary tilt, it was determined that a 13-degree inclination would yield the most optimal results. Secondly, roof slants facing North were identified as strategically advantageous locations for positioning solar PV arrays. The university was

found to encompass 12 % of good locations in terms of suitability, with 27 % classified as moderately suitable, and the remaining 61 % deemed unsuitable for installation. The theoretical potential for solar installation varied among the different site categories, with good locations estimated to reach 1,902 MWh/sqm.y, moderate suitability locations at 1,850 MWh/m^2.y, and unsuitable locations at 1,308 MWh/sqm.y.
Additionally, the study explored the technical potential specifically for Crystalline Silicon solar cells, revealing energy outputs of 1,181 GWh.y, 2,643 GWh.y, and 1,964 GWh.y for suitable, moderate, and unsuitable locations, respectively. As for CIGS solar cells, the technical potential was estimated at 907 GWh.y, 2,030 GWh.y, and 1,509 GWh.y for the corresponding site categories.

3.1 Initial Suitability Map

The initial suitability map (Figure 1) was calculated by Weight Linear Combination of the global insolation, physical factors, meteorological factors, and maintenance factors with 0.534, 0.168, 0.327, and 0.029, respectively.

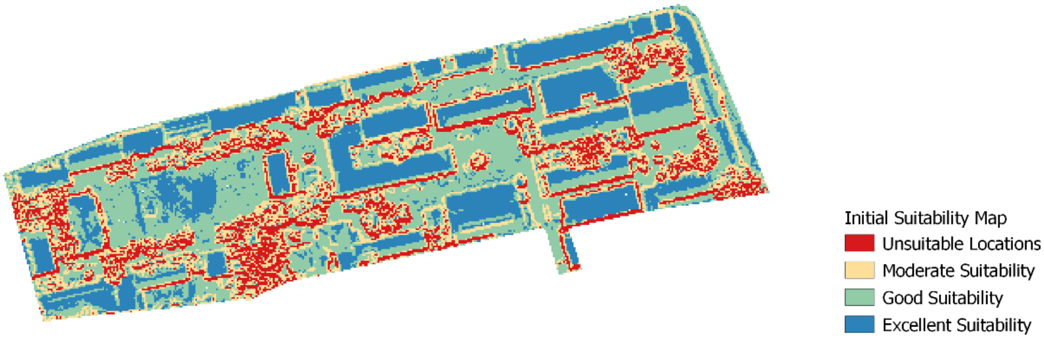

Figure 1: Layered Initial Suitability Map

3.2 Final Suitability Map

The final suitability map was mapped using the raster calculator in QGIS. This exclusion map was multiplied by the initial suitability map to remove the areas under the exclusion criteria. As shown in Figure 2, the final suitability map has a discrete legend. Unsuitable sites are those that fall under 0.6 in the total score, while cells above 0.6 and below 0.8 were deemed moderate suitability, and those that score greater than 0.8 was delineated as good suitability. Excluded Areas have a 0-raster value.

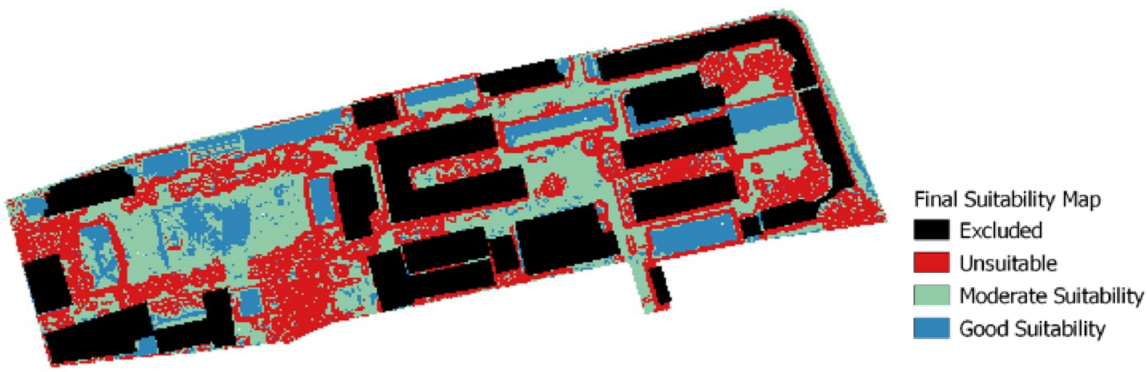

Figure 2: Final Suitability Map

Considering the distribution, a third of the total area of the university was excluded from the siting criteria. Most of these areas have either old structural components or it is still in construction. This would leave only 12 % of the university categorized as good suitability. Most of these areas have a North facing tilt where it would receive the highest global insolation which was the primary determining factor in this analysis.

3.3 Theoretical and Potential Output Estimate

Table 4 shows the summary of potential output estimates calculated using Eq(6) and (7). The average received irradiation of areas with unsuitability, moderate suitability, and good suitability are 1.31, 1.85, and 1.90

GWh/sqm,y, respectively. A CIGS solar cell covering the whole area of good suitability is expected to produce at least 900 GWh per year which would amount to more than double the average annual consumption of the campus pre-pandemic which is less than 350 GWh. This means that less than 5 % of solar cell coverage of the total area of the university if placed strategically, can push the campus into total energy self-sufficiency.

Table 4: Insolation received per year by each suitability condition

Condition	Insolation MWh/sqm.y	Total Area (ha)	PVout (Si) TWh.y	PVout (CIGS) TWh.y
Excluded	-	1.50	-	-
Unsuitable	1.308	1.31	1.964	1.509
Moderate	1.850	1.24	2.643	2.030
Good	1.902	0.54	1.181	0.907

4. Conclusions

In this study, an assessment was conducted to determine the optimal tilt and orientation of solar photovoltaic (PV) cells, as well as suitable installation areas and the potential energy output at the Bataan Peninsula State University-Main Campus. A combination of AHP Multi-criteria analysis, Fuzzy Logic, and Weighted Linear Combination techniques was applied within a GIS application. The aim was to identify the most favorable site for installing solar PV cells on the university grounds. The study further estimated the theoretical and technical solar PV output for various site categories. These findings provide valuable insights for decision-makers in implementing solar PV systems effectively at the Bataan Peninsula State University-Main Campus, maximizing energy generation and optimizing sustainability efforts.

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