GIS-based Solar Facility Location using an Analytic Hierarchy Process and Weighted Goal Programming Approach

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***Abstract*—The goal of this study is to present a GIS-based method for selecting grid-connected solar farm installation sites using a combination of Analytic Hierarchy Process (AHP) and Weighted Goal Programming (WGP). The GIS was used to eliminate infeasible locations based on land type, land cover, protected areas, roads, aspect, and slope. AHP-WGP was used to select the installation locations of M number of solar farms, considering six criteria-total energy produced, distance from transmission lines, distance from roads, distance from built-up areas, installation cost, and maintenance cost. Weights of each criterion was computed using AHP. WGP was implemented to select the M solar farm installation sites that best satisfy the decision-makers' preferences.The performance of the AHP-WGP model was evaluated against the suitable locations found using the Technique for Order of Preference by Similarity to Ideal Solution (AHP-TOPSIS) method. Occidental Mindoro, Philippines was used as the study site. The feasible installation sites selected using AHP-WGP were located near roads and transmission lines while the installation sites selected using AHP-TOPSIS were less accessible and more costly.**

Keywords*—Geographic Information System, Analytic Herarchy Process, Weighted Goal Programming,Solar Farm Location-Allocation

I. INTRODUCTION

The amount of sunlight that reaches the earth's atmosphere, considering 60% transmittance through atmospheric clouds, is around 1.05×10^5 TW. Converting one percent of this solar energy to electrical energy at 10% efficiency can provide 105 TW, more than enough to supply the projected global energy needs for 2050 which is about 25-30 TW [1].

With an annual solar potential average of $5.1kWh/m^2/day$, the Philippines saw a couple of developments with off-grid photovoltaic systems due to a large number of isolated islands from the national power grid [2], [3]. However, despite the Philippines' vast solar potential and the Philippine government's initiative to accelerate the development of renewable resources through the Renewable Energy Law of 2008, there were only a few large central station PV projects that were developed.

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A. *Statement of the Problem*

The Philippines, as an archipelago, can benefit from PV systems used for electrification of national grid-isolated islands such as Mindoro [4]. Occidental Mindoro has been experiencing power shortages for the past 17 years. In 2015, Occidental Mindoro experienced six to 12-hour daily blackouts [5]. The power shortages experienced by the people of Mindoro not only affected their daily lives but also slowed down the economic growth of the province.

One possible solution to the power shortages in Occidental Mindoro is to install solar farms. This can take advantage of the solar resources in the province but choosing the installation site is no easy task due to various geographic, environmental and socioeconomic factors to be considered.

Given an area of interest, the goal is to locate installation sites for M number of solar farms with a given target total energy (Y) to be produced and estimated budget for the installation (TC) and 20-year maintenance (TMC) costs of the solar farms.

B. *Significance of the Study*

This study aimed to develop a GIS-based methodology that can be used to determine the solar farm installation sites in a specific area of interest. The study aimed to reduce the search space for the installation sites by applying GIS-based operations on thematic maps of the area of interest. Given the budget for the installation (TC) and maintenance (TMC), target total energy (Y) and preferred number of solar farms (M) to be installed in the area of interest, the solar farm installation sites were then selected among the feasible solar farm installation sites using a combined Analytic Hierarchy Process (AHP) and Weighted Goal Programming (WGP) approach. Using the AHP weights allowed the decision-makers' preferences to be considered in selecting the solar farm installation sites.

In this study, the methodology was applied in locating the solar farm installation sites in Occidental Mindoro. Determining the feasible location and allocation of solar farms in the province could help the decision-makers to effectively choose the solar farm installation sites, thus providing an alternative solution to the power shortages experienced by the province. This methodology could also be applied to any other areas of interest.

C. Objectives

The general objective of this study was to present a GIS-based AHP-WGP methodology used to solve grid-connected distributed solar farm location-allocation problem, using Occidental Mindoro as a case study site. This study specifically aimed to:

1) perform GIS-based operations on thematic maps to reduce the search space in determining the feasible solar farm installation sites;
2) develop and evaluate Analytic Hierarchy Process (AHP) and Weighted Goal Programming (WGP) model to determine the location of solar farms;
3) apply Analytic Hierarchy Process and Technique for Order Preference by Similarity to Ideal Solution (AHP-TOPSIS) to determine suitable installation sites;
4) compare the selected solar farm installation sites derived from AHP-TOPSIS and AHP-WGP approaches.

D. Limitations

The following assumptions and limitations were made in conducting this study:

1) The province of Occidental Mindoro, Philippines was used as the case study site.
2) In the application of GIS, Clear Sky Global Horizontal Irradiance (Clear Sky GHI) model was used to estimate the available solar resource in the study site. It estimates the terrestrial solar radiation under a cloudless sky[6]. Clear Sky GHI was used in the study since it is the only available data as of the date of writing this study.
3) The researchers selected flat and south-facing (aspect) installation sites since the case study site i.e. Occidental Mindoro, Philippines is located in the Northern Hemisphere. For areas of interest located in the Southern Hemisphere, select flat and north-facing installation sites.
4) In case of implementation of the solar facility installation, the Government will manage the location and allocation of solar farms. Also, since data on the land ownership in Occidental Mindoro was not available while conducting this study, only the geographic,environmental, and socioeconomic factors were considered.

II. Review of Related Literature

A. Location Science and Decision-Making Problems

Location decisions are decision-making problems that use spatial (geographical) information for solving the problem and are now a major part of Operations Research and Management Science (Location Science)[7]. Location science can be applied to a variety of areas such as public, private, business, and military facilities among others. There have been quite a number of developments since the inception of location science, most of which focused on single criterion location problems but during the past few decades multi-criteria location models were also introduced.

Farahani and Asgari[7] discussed a number of studies that focused on multiple criteria facility location problems. Bhattacharya[8] applied a fuzzy multi-criteria goal-programming model to locate a single facility on a plane. Plaras and Samaniego[9] applied different variants of Ant Colony Optimization (ACO) to solve for approximate solutions on the Minimum Metric p-Center facility location problem. Nijkamp and Spronk[10] used multiple objectives, instead of a single cost function, to solve an extended Weber problem. Ogryczak[11], [12] presented multi-objective lexicographic minmax and distribution approaches in solving location problems. Erkut and Tjandra[13] introduced a new multi-objective model to solve the location-allocation of waste treatment facilities. Tuzkaya[14] applied Analytic Network Process (ANP) to evaluate and select undesirable facility locations based on benefits, costs, opportunities, and risks. Aras and Koc[15] used multiple criteria to select a location for a wind observation station. Tzeng and Opricovic[16] used five aspects and 11 criteria for selecting a restaurant location in Taipei. Fernandez and Ruiz[17] made use of Analytic Hierarchical Process (AHP) to locate industrial parks. Chan and Chung[18] combined AHP and Genetic Algorithm (GA) to solve distribution network problems in supply chain management.Barda and Lencioni[19] used a combination of AHP and ELECTRE III to choose the best sites for thermal power plants.

B. Location Problems and Geographic Information Systems

Since location decisions or facility location problems make use of spatial data, Geo-
graphic Information System (GIS) was also utilized in a number of studies.

Higgs[20] combined GIS with multi-criteria analysis and evaluation to take into account the public decision making in waste management siting. Zhang, et al.[21] combined GIS and transportation cost model through a two-stage methodology to identify the optimal location for forest biomass to biofuel conversion facility. GIS and AHP were also used by Uyan[22] to determine suitable sites for solar farms in Kapinar region, Turkey. Environmental (i.e. distance from residential areas and land use) and economic (i.e.distance from roads, slope, distance from transmission lines) factors were considered in the study. Sanchez-Lozano, et al.[23] combined GIS with Multi-Criteria Decision Making (MCDM) methods to evaluate solar farm locations in South-eastern Spain. The weight of the MCDM factors (i.e. environmental, orographical, location, and climate) were determined by AHP while the assessment of alternatives were done through Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Heyns and van Vuuren[24] also proposed a multi-objective GIS-based facility location framework. This study was demonstrated in realistic, hypothetical bi-objective and tri-objective problem instances that showed that multi-objective approach returns better results compared to the single-objective approach.

C. Location Problems and Goal Programming

A number of studies also applied Goal Programming in order to solve facility location-allocation problems. Sinha and Sastry[25] proposed a goal programming model for facility location planning, specifically for a community storage facilities location-allocation, considering four major objectives such as necessary locations, maximum number of locations, capacity restrictions and transport cost/walking distance minimization. Kanoun, et al.[26] also used Goal Programming to select a site for fire and emergency service facilities in Sfax, Tunisia. Kanoun, et al. introduced a concept of satisfaction function to explicitly involve the decision-maker's preference in the decision-making process. Badri[27] also used Goal Programming with AHP to solve the facility location-allocation problem in an international setting. Memarian, et al.[28] combined GIS, AHP, and GP to solve for the optimal land use at the watershed scale. GIS and stochastic techniques were used in extracting water conservation and future land use scenarios. AHP was applied to determine the weights of each objective function used in the Weighted Goal Programming (WGP) model used to select the optimal land use scenario.

III. Theoretical Framework

A. Solar Photovoltaic Systems

Solar Photovoltaic (PV) Systems are composed of several interconnected components that converts solar energy to electrical energy. Its main components include PV modules, battery charging system, electrical energy conditioning subsystem, and auxiliary energy source (for hybrid PV systems)[29].

According to Kalogirou [1], solar PV Systems can be divided into two main categories: (1) stand-alone and (2) grid-connected PV systems. Stand-alone PV systems are typically used in areas that are inaccessible or off-the-grid areas. The energy produced in stand-alone Pvs is typically stored in batteries.

Electricity produced by grid-connected PV systems can be immediately used or can be sold to electric cooperatives. Grid-connected PV systems do not include batteries since power can be bought back from the grid once the system is unable to provide the required electricity (i.e. nighttime).

One of the most common application of PV technology is in constructing solar farms. Solar farms are large-scale PV systems typically designed to supply electricity into the grid. The electricity produced by solar farms is typically sold to local electricity providers. Choosing the location of a solar farm depends on a lot of factors such as geographical, environmental, and socioeconomic factors. Environmentally unsuitable sites are also determined in order to minimize the negative environmental impacts of constructing a solar farm. Unsuitable sites like highly populated areas, areas near roads, bodies of water, and protected areas are eliminated from the feasible installation sites [22].

B. Geographic Information System

Geographic Information Systems (GIS) is a special kind of information system used for capturing, storing, checking and displaying geographically referenced information. GIS helps in analyzing and understanding patterns and relationships in a way that is quickly understood and easily shared (i.e. through a map)[30], [31].

GIS is usually used, together with Multi-Criteria Decision Making (MCDM) methods, in urban planning and different site selection studies. GIS can be a powerful tool used to determine the suitable areas to be used.

There are two types of GIS representation: (1) raster data or (2) vector data. Raster data represents the map as a mesh or rectangular grids (pixels) with uniform sizes. Each pixel has information and geographic location assigned to it. Vector data, on the other hand, represents the geographic features with the same geometric figure as the feature [23].

C. Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) is a multi-criteria decision making (MCDM) tool used to deal with complex decision problems [23]. AHP breaks down the problem into a hierarchy of criteria and alternatives. AHP can be divided into three steps: (1) stating the objective, (2) defining the criteria, (3) and picking the alternatives[32]. The collected information is then arranged in a hierarchical tree as shown in Figure 1.

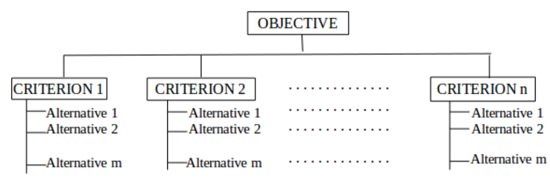


Fig. 1. AHP Information Hierarchy

A pairwise comparison of the criteria and alternatives is carried out based from the preferences of the decision-maker. Typically, an AHP scale from 1-9 is used by the decision-maker to compare two criteria or alternatives. A reciprocal matrix is constructed based from the pairwise comparison. To compute the weights for each criterion and alternative, the sum of each column of the reciprocal matrix is computed then each element of the matrix is divided by sum of its column to get the normalized relative weight. Then, the priority vector is then derived by getting the average of each row. This priority vector shows the relative weights among the things that were compared i.e. criteria and alternatives[33].

Given the relative weights of the criteria and alternatives, the decision-maker can also determine if the preferences were consistent. A Consistency Ratio (CR) is computed by getting the ratio between the Consistency Index (CI) and Random Consistency Index (RI). A Consistency Ratio that is greater than 10% means that the preferences were inconsistent so a revision is necessary. CI is computed by Equation 1.

$$CI = \frac{\lambda_{max} - n_s}{n_s - 1} \tag{1}$$

where λ_{max} is the Principal eigenvalue obtained from the summation of products between the eigenvector elements and sum of columns of the reciprocal matrix and n_s is the size of the comparison matrix.

The *Random Consistency Ratio* (RI) is derived from the table of RI values described in Table I [33]. These values were proposed by Thomas L. Saaty who developed AHP in the early 1970's[32].

TABLE I. RANDOM CONSISTENCY INDEX (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

D. Weighted Goal Programming (WGP)

Goal Programming (GP) provides a way to simultaneously strive toward multiple objectives by establishing a numerical goal and an objective function for each goal and then determining the solution that minimizes the sum of unwanted deviations of the objective functions from their respective goals [34]. It seeks goal "satisfaction" rather than "optimization" [28]. There are three types of goals that can be used to determine which among the deviational variables should be minimized according to the goal. Table II shows the different types of goals and unwanted deviational variables that should be minimized[35].

TABLE II. WGP UNWANTED DEVIATIONAL VARIABLES

Goal Type	Significance	Minimise
1	Achieve at most the target level	δ_t^+
2	Achieve at least the target level	δ_t^-
3	Achieve the target level exactly	$\delta_t^- + \delta_t^+$

One of the many variants of GP is the Weighted Goal Programming (WGP), a distance metric-based variant where each objective is assigned a different weight according to its importance and forms a single objective function which is the summation of the weighted deviational variables of each objective function [28]. WGP can be formulated using the following generalized form as shown by Equations 2 to 4.

$$Minimize \sum_{t=1}^{p} (w_t^+ \delta_t^+ + w_t^- \delta_t^-) \tag{2}$$

subject to:

$$Z_t(x) + \delta_t^- - \delta_t^+) = G_t fort = 1, 2, ..., p \tag{3}$$
$$x \in X$$

$$x, \delta_t^-, \delta_t^+ \geq 0 \tag{4}$$

where (w_t^+) and (w_t^-) are nonnegative and numerical weights for the positive (δ_t^+) and negative (δ_t^-) deviations of the t^{th} objective (Z_t), from the target value (G_t). The values of the decision variable vector x can be determined by minimizing the sum of the weighted deviations of all the p number of objectives. The set of all feasible alternatives is defined by X.

Since the objective functions have different units, nomalization of the objective function is an essential step in order to have uniform unit measurements for all the deviations [28]. The general form of the normalized objective function, using percentage normalization method, is shown by Equation 5.

$$Minimize \sum_{t=1}^{p} (\frac{\wp_t}{TL_t})(\delta_t^+ + \delta_t^-) \tag{5}$$

where $\wp_t$ is the weight of the t^{th} objective and TL_t is the target level of the t^{th} objective.

E. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) was introduced by Yoon and Hwang in 1981 [36]. The goal of this Multi-criteria Decision Analysis (MCDA) method is to select an alternative with the shortest distance to the positive ideal solution (maximum value) and farthest distance to the negative ideal solution (minimum value). Figure 2 shows the step by step procedure of the TOPSIS method [23].

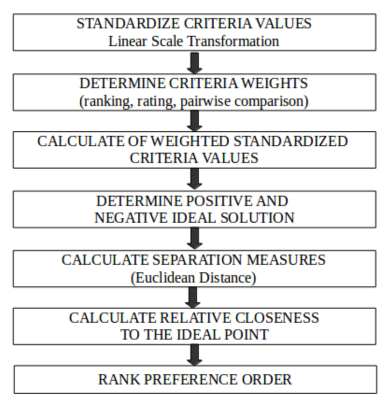


Fig. 2. TOPSIS Algorithm

IV. METHODOLOGY

A two-stage GIS-based methodology was proposed to identify the feasible solar farm installation sites. The two stages were identification of feasible solar farm installation sites using Geographic Information Systems (GIS) (stage I) and selection of the solar farm installation sites (stage II).

A. Stage I: Feasible Solar Farm Site Location

The goal of this set of procedures was to determine the feasible sites for solar farm installation given a set of thematic maps. The thematic maps used in this study were accessed from the Philippine GIS Data Clearinghouse [37], Phil-LiDAR Program and DREAM, and National Power Corporation. The following thematic maps of Occidental Mindoro were used in the study:

- Land Type Map
- Land Cover Map
- Protected Areas Map
- Aspect Map
- Slope Map
- Solar Irradiation Map
- Occidental Mindoro Barangay Map
- Road Map
- Built-Up Areas Map
- Occidental Mindoro Electric Cooperative Transmission Lines Map

The researchers implemented the GIS-based operations as a Script Tool in ArcGIS 10.3, a Geographic Information System software.

1) Identify Infeasible Locations based from Land Type and Land Cover: Land Type and Land Cover Maps were used to determine the infeasible locations for installation.Tables III and IV list the Land Type and Land Cover categories, respectively, considered for determining the feasible and infeasible locations for solar farm installation [38] [39].

TABLE III. LAND TYPE CATEGORIES

Feasible Locations	Infeasible Locations
Expansion Areas(4), Gently Sloping Lands (Irrigable & Paddy rice- irrigated)(2.1,1.2), Non-Agricultural (NAU), Pasture Lands(5.3), Potential Agro-Industrial Lands(4.2), Erodible Lands(5.2), Unclassified Lands	Alluvial Lands (Irrigable & Paddy rice-irrigated)(1.2, 2.1), Built-Up Area(BU), Fishponds/Saltbeds(5.4), River(RIVER)

TABLE IV. LAND COVER CATEGORIES

Feasible Locations	Infeasible Locations
Grassland(Eg), Cultivated Area mixed with brushland(Ec), Unclassified	Arable Land(Ic), Built-up Area(B), Closed(Fdc) and Open(Fdo), Canopy Forests, Coconut Plantation(Ipc), Coral Reef(C), Crop Land mixed with coconut plantation(Imc), Crop Land Mixed with other Plantations(Imo), Fishponds derived from mangrove (Ifm), Mangrove(Fm), Riverbeds(Nr), Siltation pattern (S)

The infeasible locations were selected from the Land Type and Land Cover maps, respectively. The resulting maps were combined into one map containing both the infeasible locations based from the Land Type and Land Cover maps. The goal of determining the infeasible locations for solar farm installation using Land Type and Land Cover Map was to avoid using medium to highly productive agricultural areas as installation sites.

2) Identify Infeasible Locations based From Protected Areas: The protected areas were also avoided while selecting the suitable solar farm installation sites. The map containing the infeasible locations based from the Land Type and Land Cover was combined with the Protected Areas map into a single map.

3) Identify Infeasible Locations based from Roads: Roads were also avoided while selecting the feasible solar farm installation sites. A 50-meter buffer on both sides of the road was set-up to keep the solar farm installation sites from occupying the road. The buffered roads map were combined with the previously identified infeasible installation sites.

4) Identify Feasible Locations based from Aspect and Slope: In the study, it was assumed that the PV modules will be installed on fixed-tilt frames. The aspect or orientation values were derived from the Digital Elevation Model (DEM). The flat and south-facing values (south, southeast, and southwest) were extracted from the aspect map. Choosing flat and south-facing feasible installation sites was similar to adjusting the azimuth angle.

Slope(degree) was then computed for each flat or south-facing locations. All the locations with a slope greater than the geographic latitude were selected. Choosing the areas with slope greater than the local geographic latitude took advantage of the effects of latitude tilt on the amount of solar flux received by the PV modules.

5) Determine Feasible Locations: The infeasible locations were removed from the map of the 'Area of Interest' by erasing the corresponding locations based from the combined infeasible Land Type, Land Cover, Protected Areas and Buffered Roads maps. The resulting map was composed of the feasible solar farm installation sites based from land type, land cover, protected areas, and roads.

The generated 'feasible locations' map was used as a mask on the solar irradiation map of the 'Area of Interest' to produce the solar irradiation map of the feasible locations.

Using the Extract by Mask Tool in ArcGIS, the map of average solar irradiation of feasible locations was masked with the map of slopes of flat and south-facing locations. The resulting map contained the final average solar irradiation of flat and south-facing locations with slope greater than the geographical latitude.

The resulting map, which is a raster map, was converted to aggregate polygons. The area (in acres) for each polygon was computed. According to the National Renewable Energy Laboratory[40], the total-area capacity-weighted average in the United States is 8.9 acres/MWa. In the present study, contiguous land areas that were less than 8.9 acres were not considered. Then, the resulting map was used as a mask on the solar irradiation map to extract the solar irradiation values of the resulting feasible solar farm installation sites. For each feasible site, the mean solar irradiation for the area was computed. Also, using the Feature to Point Tool in ArcGIS, the center point of each feasible location was determined. Each point represented a feasible site. Then, using the mean solar irradiation map, the solar irradiation value for each specific point was extracted.

6) Determine the Nearest Distances of each Feasible Location from Roads, Transmission Lines, and Built-Up Areas: The distances from the nearest road, transmission line, and built-up area was computed for each feasible solar farm installation site. A Feasible installation sites map and an XLS file containing the area, mean solar irradiation, and distances from the nearest road, built-up area, and transmission line were generated by the script tool. The XLS file will be used as an input to the solver in Stage II.

B. Stage II: Solar Farm Installation Site Selection

After identifying the feasible solar farm installation sites, the solar farm locations were determined using Weighted Goal Programming (WGP). The Analytic Hierarchy Process (AHP) was also used to determine the weights of each goal.

1) Determine Weights of Goals Using Analytic Hierarchy Process: In this study, there were six factors considered in solving for the locations of the solar farms: (1) total energy produced, (2) distance from transmission lines, (3) distance from roads, (4) distance from built-up areas, (5) total installation cost and (6) total maintenance cost. Renewable energy experts were asked to complete a pairwise comparison of the six factors in a questionnaire provided to each of the respondents. A consolidated AHP weights were determined for each of the factors considered using the BPMSG AHP Priority Calculator developed by Goepel[41].Table V shows the AHP rating scale as used in the study [28].

TABLE V. ANALYTIC HIERARCHY PROCESS SCALE USED IN BPMSG AHP PRIORITY CALCULATOR

Level of Importance	Description	Explanation
1	Equal Importance	Two factors have equal contribution to the objective/goal
3	Moderate Importance	Slightly favor one factor over the other
5	Strong Importance	Strongly favor one factor over the other
7	Very Strong Importance	One factor is very strongly favored over the other and its dominance is demonstrated in practice
9	Extreme Importance	There is an evidence with the highest possible order of affirmation that favors one factor over the other
2,4,6,8		Values in between

2) WGP Weight Normalization: Since the goals/factors had different measurement units, it is required to implement a normalization technique to overcome the problem of incommensurability [35]. For the weighted goal programming weights, percentage normalization method was used to normalize the objective function. Percentage normalization converts each deviation into a percentage value away from the target value by dividing the weight by the target value.

3) Weighted Goal Programming Formulation: After determining the weight of each factor, the functional relationship of each factor was determined. The following set of equations show the functional relationship of each factor.

1) *Total energy produced*
The total energy produced by all the installed solar farms should be greater than an expected total target output Y as illustrated in Equation 7. The output energy of a solar farm, E_j, is given by

$$E_j = (A_j \mu_{PV} \bar{G}_j)\mu_{inv} \tag{6}$$

where:

A_j = total area of the installation site
$\bar{G}_j$ =Average yearly global irradiation at installation site j (W/m^2)
μ_{PV} = PV module efficiency
μ_{inv} = Inverter efficiency

$$\sum_{j=1}^{n} E_j x_j \geq Y \tag{7}$$

converting Equation 7 to goal constraint form,

$$\sum_{j=1}^{n} E_j x_j + \delta_1^- - \delta_1^+ = Y \tag{8}$$

where:
δ_1^-, δ_1^+ =positive and negative deviations of the first goal from the target value Y
$x_j = \begin{cases} 1, & \text{if site } j \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$
Since the goal for the total energy was to produce a total energy from all the installed solar farms that is greater than or equal to the target energy output Y, $\delta_1^-$was minimized.

2) *Distance from transmission lines*
Proximity to existing transmission lines can affect the cost and efficiency of the installed solar farm. Sites that are far from the existing transmission lines require longer interconnection cables and can suffer from transmission loss due to increase in resistance. The chosen installation sites should be at most 3000 meters away from the nearest existing transmission lines [22]. Equation 9 shows the functional relationship for the distance from transmission line.

$$\sum_{j=1}^{n} DT_j x_j \leq 3000M \tag{9}$$

converting Equation 9 to goal constraint form yields

$$\sum_{j=1}^{n} DT_j x_j + \delta_2^- - \delta_2^+ = 3000M \tag{10}$$

where:
δ_2^-, δ_2^+ =positive and negative deviations of the second goal from the target value $3000M$

DT_j = Distance of the j^{th} feasible location from the nearest transmission line
M = Number of solar farms to install
$x_j = \begin{cases} 1, & \text{if site } j \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$
Since the goal for the distance from transmission lines of each installed solar farms was to have a distance that is less than or equal to $M * 3000$ meters, δ_2^+ was minimized.

3) *Distance from roads*
The distance of the solar farm installation site from the existing road network gives an idea about the accessibility of the installation site. It gives an idea on the cost of transporting and installing the materials

and equipments used to construct the solar farm. It also affects the cost of maintaining the solar farm. Installation sites that are far from the existing road network has a higher installation and maintenance cost while installation sites that are too close to the road network is also not a good idea. In this study, sites that are too close to the existing road network, distance is less than or equal to 50 m, were eliminated at Stage I so the target goal considered in Stage II was to make sure that solar farms are not too far from the existing road network. The target distance from the nearest road was set to be less than or equal to $M * 1000$ meters, as illustrated by Equation 11 [22].

$$\sum_{j=1}^{n} DR_j x_j \leq 1000M \tag{11}$$

converting Equation 11 to goal constraint form yields

$$\sum_{j=1}^{n} DR_j x_j + \delta_3^- - \delta_3^+ = 1000M \tag{12}$$

where:
$\delta_3^-, \delta_3^+ =$ positive and negative deviations of the third goal from the target value 1000M
DR_j =Distance of the j^{th} feasible location from the nearest road
$M =$ Number of solar farms to install
$x_j = \begin{cases} 1, & \text{if site } j \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$
Since the goal for the distance from roads of each installed solar farms was to have a distance that is less than or equal to $M * 1000$ meters, δ_3^+ was minimized.

4) *Distance from built-up areas* According to Uyan [22], solar farms should not be constructed within 500 meters from rural and urban residential areas since the solar farms can cause negative environmental impact on the urban growth and population. Equation 13 shows that functional relationship for the distance of solar farm installation sites to the nearest built-up area.

$$\sum_{j=1}^{n} DB_j x_j \geq 500M \tag{13}$$

converting Equation 13 to goal constraint form yields

$$\sum_{j=1}^{n} DB_j x_j + \delta_4^- - \delta_4^+ = 500M \tag{14}$$

where:
$\delta_4^-, \delta_4^+ =$ positive and negative deviations of the fourth goal from the target value 500M
$DB_j =$ Distance of the j^{th} feasible location from the nearest built-up area
$M =$ Number of solar farms to install
$x_j = \begin{cases} 1, & \text{if site } j \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$
Since the goal for the distance from built-up areas of each installed solar farms was to have a distance that is greater than or equal to $M * 500$ meters, δ_4^- was minimized.

5) *Total installation cost*
The total installation cost for all the installed solar farms should not exceed the allocated budget, TC as illustrated in Equation 15. Total installation cost, c_j, factors in the cost of buying or leasing the installation site, cost of the materials and equipments used in the installation, and the transportation cost of the equipments.

$$\sum_{j=1}^{n} c_j x_j \leq TC \tag{15}$$

converting Equation 15 to goal constraint form yields

$$\sum_{j=1}^{n} c_j x_j + \delta_5^- - \delta_5^+ = TC \tag{16}$$

where:
$\delta_5^-, \delta_5^+ =$ positive and negative deviations of the fifth goal from the target value TC
$c_j =$ installation cost in the j^{th} feasible location
$x_j = \begin{cases} 1, & \text{if site } j \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$
Since the goal for the total installation cost for all the installed solar farms was to stay within the specified budget TC, δ_5^+ was minimized.

6) *Total Maintenance cost*
The 20-year total maintenance cost for all the installed solar farms should be within the allocated budget, TMC, as illustrated in Equation 17. Total maintenance cost, mc_j, factors in the 20-year maintenance cost of equipments(i.e. PV modules, inverters, and cables) and its transportation cost.

$$\sum_{j=1}^{n} mc_j x_j \leq TMC \tag{17}$$

converting Equation 17 to goal constraint form yields

$$\sum_{j=1}^{n} mc_j x_j + \delta_6^- - \delta_6^+ = TMC \tag{18}$$

where:
δ_6^-, δ_6^+ =positive and negative deviations of the sixth goal from the target value TMC
mc_j =20-year maintenance cost in the j^{th} feasible location
$x_j = \begin{cases} 1, & \text{if site } j \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$
Since the goal for the total maintenance cost for all the installed solar farms was to stay within the specified budget TMC, δ_6^+ was minimized.

Using Weighted Goal Programming in determining the locations of the solar farm installation sites, the overall objective is to find the values of x_j so as to minimize

$$Z = \left(\frac{w_1}{Y}\right)\delta_1^- + \left(\frac{w_2}{3000M}\right)\delta_2^+ + \left(\frac{w_3}{1000M}\right)\delta_3^+ + \left(\frac{w_4}{500M}\right)\delta_4^- + \left(\frac{w_5}{TC}\right)\delta_5^+ + \left(\frac{w_6}{TMC}\right)\delta_6^+ \quad (19)$$

subject to:

$$\sum_{j=1}^{n} E_j x_j + \delta_1^- - \delta_1^+ = Y$$

$$\sum_{j=1}^{n} DT_j x_j + \delta_2^- - \delta_2^+ = 3000M$$

$$\sum_{j=1}^{n} DR_j x_j + \delta_3^- - \delta_3^+ = 1000M$$

$$\sum_{j=1}^{n} DB_j x_j + \delta_4^- - \delta_4^+ = 500M$$

$$\sum_{j=1}^{n} c_j x_j + \delta_5^- - \delta_5^+ = TC$$

$$\sum_{j=1}^{n} mc_j x_j + \delta_6^- - \delta_6^+ = TMC$$

$$\sum_{j=1}^{n} x_j = M \quad (20)$$

and

$$\sum_{j=1}^{n} E_j x_j >= Y$$

$$x_j \in 0, 1$$

$$\delta_t^-, \delta_t^+ >= 0 \text{ for } t = 1, 2, ..., 6 \quad (21)$$

The objective function given by Equation 19 was used to minimize the sum of the unwanted deviations that were present in Equations 8, 10, 12, 14, 16, and 18 which represent the functional relationships of the factors considered in choosing the solar farm installation sites. Equations 20 indicated that the total number of candidate locations in the final solution should be equal to the value of M, set as the total number of solar farms to allocate. The value for each feasible location was restricted to a binary value 0 or 1. Equation 7 was used as a constraint to make sure that the total energy produced from the selected solar farm installation sites were strictly greater than or equal to the target energy output, Y. Equation 21 made sure that the positive and negative deviation values were non-negative. A parser was written in MATLAB to generate an LPX file containing the Weighted Goal Programming Formulation.The LPX file was run on the Linear Program Solver (LiPS) developed by Melnik[42]. Figure 3 outlines the two stages of the GIS-based methodology proposed in the study.

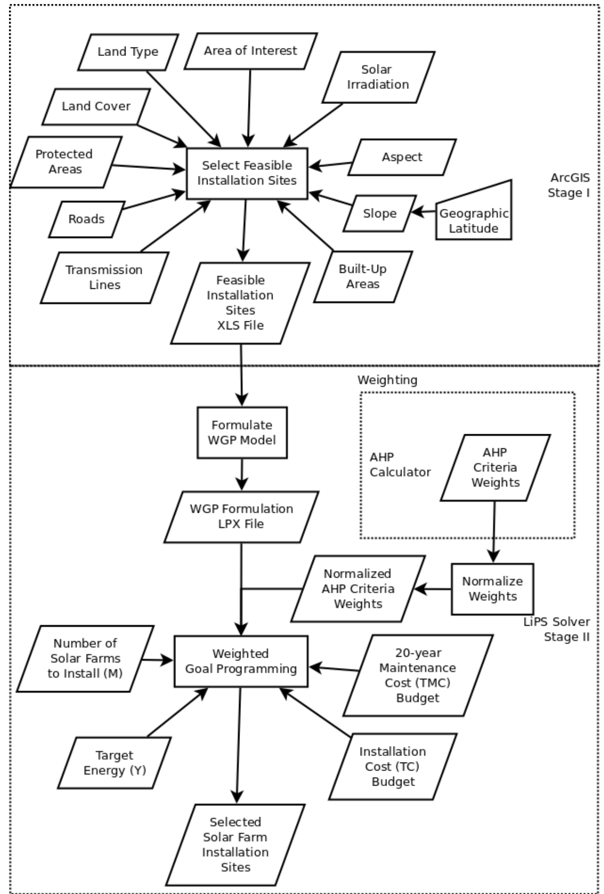


Fig. 3. GIS-based AHP-WGP Methodology

C. Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS, a commonly used MCDA technique in creating site suitability maps, was implemented to compare with the results derived from the AHP-WGP approach proposed in the study. A matrix containing the criteria values for each alternative (feasible solar farm installation sites) was created. For each criterion, maximum value was determined. Since the criteria values were measured using different scales (units), Maximum Score Linear Scale Transformation was used to standardize the criteria values. The relative closeness to the ideal point of the feasible installation sites were sorted in descending order and was used to rank the alternatives to determine which among the alternatives should be selected as solar farm installation sites. For M number of solar farms to be installed, ranks 1 to M alternatives were selected as installation sites.The AHP-TOPSIS methodology was implemented in MATLAB and outputs a CSV file containing a list of the M selected solar farm installation sites.

V. Results and Discussion

A. Stage I: Feasible Solar Farm Site Location

The study presented a two-stage GIS-based methodology for determining the solar farm installation sites. The proposed methodology was used to determine the solar farm installation sites in the province of Occidental Mindoro, Philippines. Figure 4 shows the input window of the 'Select Feasible Solar Farm Sites' ArcGIS Script Tool used to automate the identification of the feasible solar farm sites.

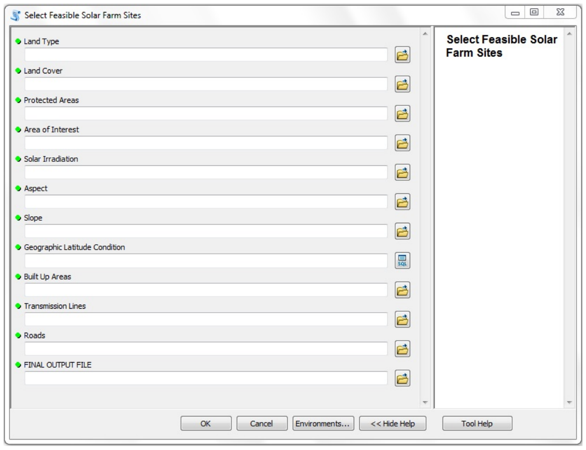


Fig. 4. Input window of the 'Select Feasible Solar Farm Sites' ArcGIS Script Tool

Using the 'Select Feasible Solar Farm Sites' ArcGIS Script Tool, the search space was reduced from a total provincial land area of 586,571 hectares to 68,006 hectares of feasible solar farm installation sites [43]. A total of 1592 feasible installation sites were identified using the ArcGIS Script Tool. Figure 5 shows the feasible locations determined at stage I using the 'Select Feasible Solar Farm Sites' ArcGIS Script Tool. The feasible locations were determined based on land type, land cover, protected areas, built-up areas, roads, solar irradiation, aspect, and slope of the area of interest.

B. Stage II: Solar Farm Installation Site Selection

1) Analytic Hierarchy Process (AHP) Weights: After the feasible solar farm site locations were identified from stage I, the optimal solar farm site locations were selected. A pairwise comparison questionnaire on the six solar siting criteria considered in the study was prepared. The respondents consisted of an engineer with a doctorate degree on Energy Engineering, an engineer with a doctorate degree on Industrial Engineering who also published several papers on optimal solar farm location and an Energy and Power Consultant with 17 years of experience. AHP was performed using the Business Performance Management Analytic Hierarchy Process (BPMSG AHP) Calculator. The consolidated AHP weights were determined based from the questionnaire responses. The AHP calculator was run with a linear 1-9 AHP scale and 0.1 threshold for acceptance of inconsistency (α). Table VI shows the consolidated AHP weights of the solar siting factors considered in the study.

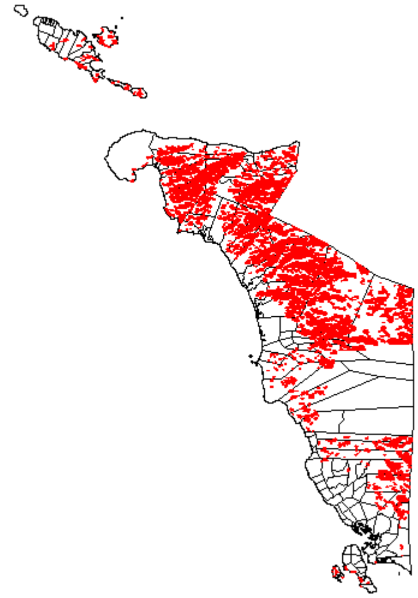


Fig. 5. Identified Feasible Solar Farm installation sites in Occidental Mindoro

TABLE VI. Consolidated AHP weights of Solar Siting factors

Criterion	AHP Weight	Rank
Total energy produced (w_1)	43.93	1
Distance from Transmission Lines (w_2)	19.77	2
Distance from Roads (w_3)	9.61	5
Distance from Built-Up Areas (w_4)	9.90	4
Total Installation Cost (w_5)	11.34	3
Total Maintenance Cost (w_6)	5.45	6

2) Data Collection and Setup: To compute for the estimated output energy of each site, the PV and inverter maximum efficiency were set to 15% and 97%, respectively. The PV efficiency was based on a 250-watt YGE 60 cell series 2 at Standard Test Conditions (STC). Inverter efficiency was based on Equinox 250 kW with California Energy Commission (CEC) efficiency. Operation & Maintenance cost per megawatt (MW) in a period of 20 years was set to PHP 15,162,000 [44](Ocampo, 2015). An average installation cost per acre of PHP 24,171,425.32/acre was estimated based on the available installation costs of existing solar farms in the Philippines as shown in Appendix B. Distances from the nearest road, transmission lines and built-up areas for each location were determined from the XLS file generated at stage I.

3) AHP-WGP Approach: The AHP-WGP approach used the same AHP weight for each respective criterion in the weight normalization of each goal. Percentage normalization was used to compute the normalized weight of each goal. The expected total output ($Y = 500$) was set to 500 MW. The total installation cost ($TC = 10,000$) was set to ten billion pesos (PHP 10 B). The total maintenance cost ($TMC = 20,000$) for 20 years was set to 20 billion pesos (PHP 20 B). After running the Linear Programming Solver, the feasible installation locations corresponding to variables (x_j) with values equal to 1 in the LiPS output file were selected as the installation locations for the M solar farms. Figure 6 shows the selected locations for three (3) solar farms to be constructed ($M = 3$). Table VII shows the details of the selected locations.Table VIII shows the deviation to the goal target value of the selected installation sites.

TABLE VII. SELECTED FEASIBLE LOCATIONS USING THE AHP-WGP APPROACH

CODE	c_i+	AVERAGE SLOPE (deg)	AVERAGE ELEVATION (Km)	AREA (ha)	DISTANCE FROM NEAREST ROAD(Km)	DISTANCE FROM NEAREST BUILT-UP AREA (Km)	DISTANCE FROM NEAREST TRANSMISSION LINE (Km)	ENERGY PRODUCED (MW)	INSTALLATION COST (in Millions,PHP)	MAINTENANCE COST (in Millions,PHP)
712	0.7	25.9	0.8	2,254.1	16.0	22.2	19.8	23,266.0	134,632.0	352,761.0
441	0.6	25.6	0.6	1,734.3	15.3	19.7	14.5	17,655.0	103,588.0	267,683.0
670	0.6	26.3	0.9	1,497.9	19.8	26.5	21.6	15,473.0	89,466.0	234,596.0

TABLE VIII. SUMMARY OF DEVIATION VALUES TO EACH GOAL OF THE SELECTED INSTALLATION SITES USING WGP FOR $M = 3$

Goal	Target	Fact	Difference	Normalized Weight
Total energy produced (MW)	$\geq$ 500	546.1800	46.1800	0.0192
Distance from Transmission Lines (m)	$\leq$ 9,000	2,546.3700	6,453.6300	0.0011
Distance from Roads (m)	$\leq$ 3,000	1,410.9700	1,589.0300	0.0066
Distance from Built-Up Areas (m)	$\geq$ 1,500	7340.2300	5,840.2300	0.0293
Total Installation Cost (in Millions, PHP)	$\leq$ 10,000	3,182.9500	6,817.0500	0.0011
Total Maintenance Cost (for 20 years)(in Millions, PHP)	$\leq$ 20,000	8,281.1200	11,718.8800	0.0003

C. AHP-TOPSIS Approach

After the AHP weights for each solar siting factor were determined, a combined Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) approach was used to determine the locations for the M solar farms to be installed. The TOPSIS method for spatial decision problems was implemented in MATLAB. The AHP-TOPSIS approach used the maximum score linear scale transformation for the standardization of the criteria values. The standardized criteria value ranges from 0 to 1. The AHP weights for the six criteria was used as the criteria weights in the TOPSIS method. The relative closeness to the ideal point (c_{i+}) for each feasible location was computed and ranked.

The maximum value obtained (best possible installation site) was 0.7371 which corresponds to location 712. The minimum value obtained (worst possible installation site) was 0.0067 which corresponds to location 1279. Figure 6 shows the selected locations for three ($M = 3$) solar farms to be constructed. The top three feasible locations, with respect to the value of c_{i+}, was selected as the installation site of the three solar farms. Table IX shows the details of the top three feasible installation sites that were selected.

TABLE IX. SELECTED FEASIBLE LOCATIONS USING THE AHP-TOPSIS APPROACH

CODE	c_i+	AVERAGE SLOPE (deg)	AVERAGE ELEVATION (Km)	AREA (ha)	DISTANCE FROM NEAREST ROAD(Km)	DISTANCE FROM NEAREST BUILT-UP AREA (Km)	DISTANCE FROM NEAREST TRANSMISSION LINE (Km)	ENERGY PRODUCED (MW)	INSTALLATION COST (in Millions,PHP)	MAINTENANCE COST (in Millions,PHP)
712	0.7	25.9	0.8	2,254.1	16.0	22.2	19.8	23,266.0	134,632.0	352,761.0
441	0.6	25.6	0.6	1,734.3	15.3	19.7	14.5	17,655.0	103,588.0	267,683.0
670	0.6	26.3	0.9	1,497.9	19.8	26.5	21.6	15,473.0	89,466.0	234,596.0

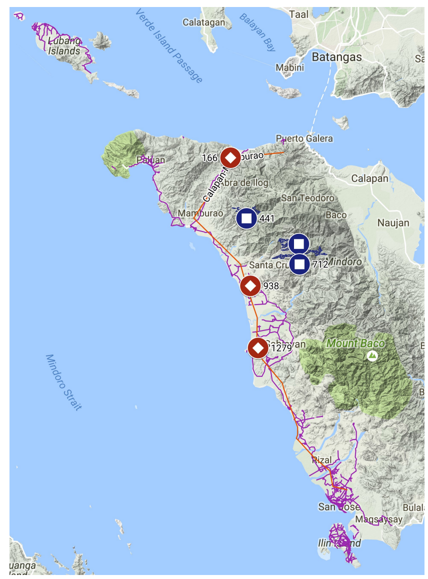


Fig. 6. Selected installation sites of three (M=3) solar farms based on AHP-TOPSIS and AHP-WGP approaches.

Sites selected using AHP-TOPSIS are marked by blue pins while sites selected using AHP-WGP are marked by red pins. Red lines represent the transmission line while the roads are in purple.

D. Comparison: AHP-WGP and AHP-TOPSIS

The locations selected using the AHP-TOPSIS approach were locations with the largest land areas. The land area of the installation site is directly proportional to the energy produced from the location so the larger the land area of the feasible installation site indicates a higher energy produced from the site.Since the distance from roads, transmission lines, and built-up areas were of relatively lower significance than the total energy, the large-area installation locations located on mountainous areas were still selected. The average slope of the selected installation sites ranges from 25.6 to 26.3

degrees while the average elevation of the selected installation sites range from 0.6 to 0.9 kilometers above sea level. The selected installation sites were also relatively less accessible with a range of 15.3 to 19.8 kilometer distance from the nearest roads, 19.7 to 26.5 kilometer distance from the nearest built-up areas, and 14.5 to 21.6 kilometer distance from the nearest transmission lines. The inaccessibility of the selected installation sites makes installation and maintenance more expensive.

On the other hand, the locations selected using AHP-WGP approach were relatively smaller in land area but were located nearer to roads and transmission lines. This means that the selected locations were more accessible for delivering the components to the site with a range of 0.3 to 0.8 kilometer distance from the nearest roads, 0.9 to 4.5 kilometer distance from the nearest built-up areas, and 0.5 to 1.3 kilometer distance from the nearest transmission lines. The average slope of the selected installation sites ranges from 17.0 to 20.9 degrees while the average elevation of the selected installation sites 0.1 kilometers above sea level. The more accessible the location is, the less expensive the operation and maintenance and installation costs are. Using AHP-WGP, the decision-makers' preferences were considered. The total energy that can be produced from the site, 546 MW, did not go under the decision-makers' preference of 500 MW. Each of the selected locations did not exceed the 1 km- preferred distance from the nearest roads and the 3 km-preferred distance from the nearest transmission lines. The selected locations also did not violate the 0.5 km built-up area buffer. The selected locations were also 6.8 billion pesos cheaper than the 10 billion-peso budget allotted for the installation of the solar farms. The selected locations were also 11.7 billion pesos cheaper than the projected 20 billion-peso budget allotted for the 20-year Operation and Maintenance cost of the solar farms.

VI. Summary and Conclusion

This study proposed a two-stage methodology for selecting grid-connected solar farm installation sites given the number of solar farms to be installed (M), target total energy (Y), installation (TC) and 20-year maintenance (TMC) budget. The first stage applied GIS-based processes to thematic maps of the area of interest to determine feasible solar farm installation sites. An ArcGIS Script Tool was developed to automate the processes. The second stage used a combined Analytic Hierarchy Process and Weighted Goal Programming approach to select the solar farm installation sites from the feasible installation sites identified at Stage I. The consolidated AHP weights, derived from questionnaires given to three renewable energy experts, was used as weights in the WGP formulation. The goals in the WGP formulation included six criteria– total energy, distance from transmission lines, distance from roads, distance from built-up areas, total installation cost, and total (20-year) maintenance cost.

The province of Occidental Mindoro was used as the study site. The AHP-WGP model was used to identify three ($M = 3$) solar farm installation sites in the province. A combined AHP and TOPSIS, commonly used in creating site suitability maps, was also used on the same set of data in order to compare its results with the installation sites selected using the AHP-WGP approach.

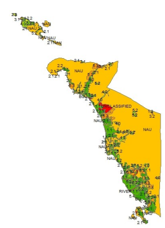
Running the model showed that the ArcGIS Script Tool helped in narrowing down the search space. The selected installation sites using AHP-WGP were located near roads and transmission lines while the installation sites selected using AHP-TOPSIS were less accessible and more costly. AHP-WGP also allowed decision-makers to include target energy, installation and maintenance budget constraints unlike AHP-TOPSIS.

Future studies can use a real-sky model,instead of the clear-sky model, for the solar irradiation map to obtain a more realistic estimate of the energy that can be produced from the feasible installation site. Land ownership can also be considered as a factor in selecting the installation sites. Future studies can also consider other larger location scope such as a nationwide solar farm installation site selection.

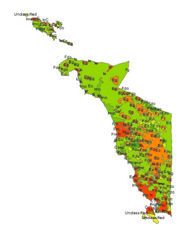
Acknowledgment

The authors would like to thank National Power Corporation, Occidental Mindoro Electric Cooperative Inc., DREAM, Phil-LiDAR Program, Marcial T. Ocampo, and Juan Miguel Sánchez-Lozano for the inputs used in the study.

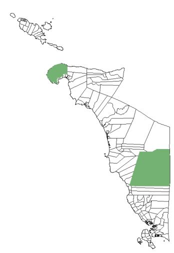
Appendix A
Thematic Maps used in the Study



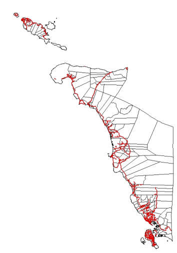
Land Type



Land Cover



Protected Areas



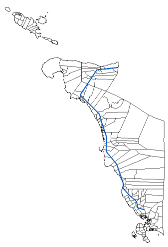
Roads

Aspect

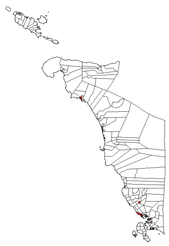
Slope

Area of Interest

Solar Irradiation



Transmission Lines



Built-Up Areas

Digital Elevation Model

APPENDIX B
INSTALLATION COST OF OPERATIONAL SOLAR FARMS IN THE PHILIPPINES AS OF AUGUST 2016

STATION	CA-PACITY (MW)	COMMUNITY	STATUS	SIZE (ACRES)	YEAR	INSTAL-LATION COST (in PHP)
CEPALCO Photovoltaic Plant	1.00	Cagayan de Oro, Misamis Oriental	Operational	4.82	2004	281.00 M
SaCaSol I	45.00	San Carlos City, Negros Occidental	Operational	49.42	2014	1.90 B
Kirahon Solar Farm	12.50	Misamis Oriental	Operational	37.07	2015	1.10 B
Calatagan Solar Farm	63.30	Calatagan, Lian, Balayan Batangas	Operational	395.37	2016	5.70 B
Mabalacat Solar Philippines	22.30	Clark, Pampanga	Operational	61.78	2016	40.00 M
MonteSol	18.00	Basic, Negros Oriental	Operational	55.35	2016	1.30 B
IslaSol I & II	32.00,48.00	La Carlota and Manapla Negros Occidental	Completed	268.18	2016	139.59 M
SacaSun	59.00	San Carlos City, Negros Occidental	Completed	185.33	2016	4.90 B

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