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

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Outline

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1. Problem Definition
   - Grid-connected Solar Farm Installation Site Selection
   - Significance of the Study
   - Objectives
   - Limitations
2. Methodology
   - Stage I -Feasible Solar Farm Site Location
   - Stage II -Solar Farm Installation Site Selection
3. Results and Discussion
   - Case Study: Occidental Mindoro
   - Identify Feasible Solar Farm Installation Sites
   - Select Solar Farm Installation Sites
4. Conclusion
5. Recommendation

Problem Definition

Grid-connected Solar Farm Installation Site Selection

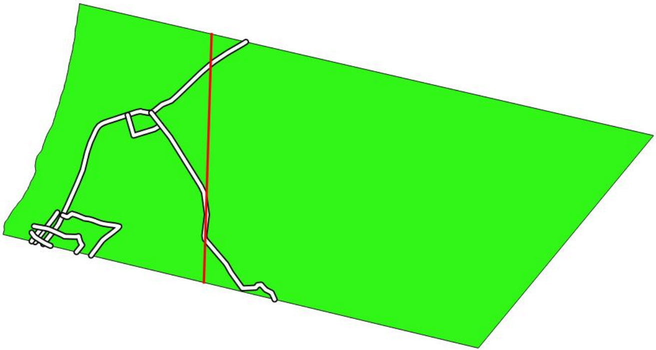
- Given an area of interest, locate solar farm installation sites for M number of solar farms with a given target total energy (Y) to be produced and estimated budget for the installation (TC) and 20-year maintenance (TMC) cost of the solar farms.

Example

Locate two solar farm installation sites (M=2) in Area B given a 100 MW (Y=100) target total energy, PHP 1 billion budget for installation (TC=1,000), and PHP 2 billion 20-year budget for maintenance (TMC=2,000).

Problem Definition

Grid-connected Solar Farm Installation Site Selection



A road and transmission system runs along Area B, which has a land area of 2,760 hectares.

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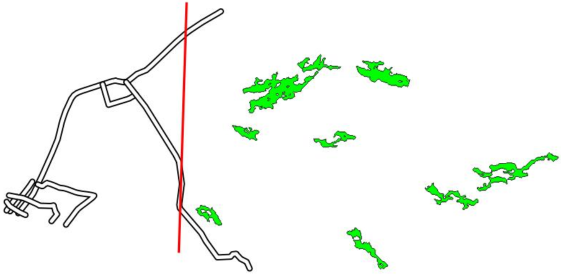

Feasible Solar Farm Installation sites with a total land area of 79 hectares.

Problem Definition

Grid-connected Solar Farm Installation Site Selection

ID	AREA (ha)	SOLAR IRRADIATION (W/m^2)	ENERGY (MW)	DISTANCE FROM NEAREST TRANSMISSION LINE (Km)	DISTANCE FROM NEAREST ROAD(Km)	DISTANCE FROM NEAREST BUILT-UP AREA (Km)	INSTALLATION COST (in Millions,PHP)	MAINTENANCE COST (in Millions,PHP)
1	12.8	6949.9	129.4	2.9	2.0	5.0	764.5	1962.4
2	22.3	7070.3	229.6	1.3	1.4	3.5	1333.2	3481.4
3	5.0	7028.6	50.9	1.9	1.5	4.2	297.5	772.2
4	3.6	7019.6	37.3	1.0	1.1	2.9	218.0	565.2
5	4.4	7084.3	45.4	2.0	2.0	3.8	262.8	687.7
6	8.7	7112.0	89.8	5.0	3.3	6.5	518.5	1361.8
7	4.3	7102.6	44.2	4.6	3.1	6.1	255.6	670.6
8	7.1	7086.8	73.6	3.8	2.4	5.2	426.5	1116.3
9	4.0	7037.3	41.1	5.1	3.0	2.0	239.5	622.5
10	6.5	6986.5	65.8	2.7	1.4	4.2	386.5	997.2

Data from Area B

Problem Definition

Grid-connected Solar Farm Installation Site Selection

Selected Solar Farm Installation sites.

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Significance of the Study

- Suggest a GIS-based methodology to select grid-connected solar farm installation sites.
- Help decision-makers to effectively choose solar farm installation sites. In the study, the province of Occidental Mindoro was used as the study site. Occidental Mindoro, located in an island, has experienced power shortages for the past 17 years.

Outline

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, with Occidental Mindoro as a case study site.

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This study specifically aimed to:

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

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3. use 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.

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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. Clear Sky GHI was used in the study since it is the only available data as of the date of writing this study.

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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.
3. In case of implementation of the solar facility installation, the Government will manage the location and allocation of solar farms.

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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.
3. In case of implementation of the solar facility installation, the Government will manage the location and allocation of solar farms.Only the geographic,environmental, and socioeconomic factors were considered since data on the land ownership in Occidental Mindoro was not available while conducting this study.

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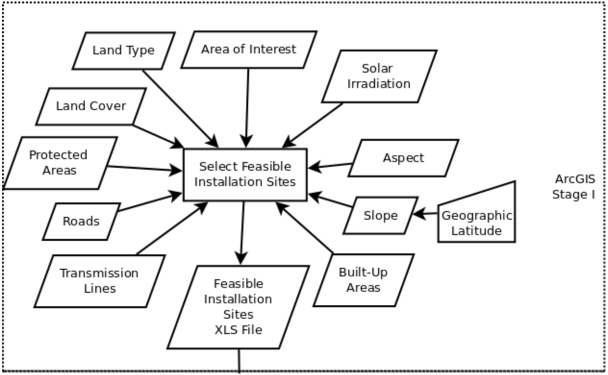


Identify feasible installation sites to reduce search space.

Land Type and Land Cover Categories

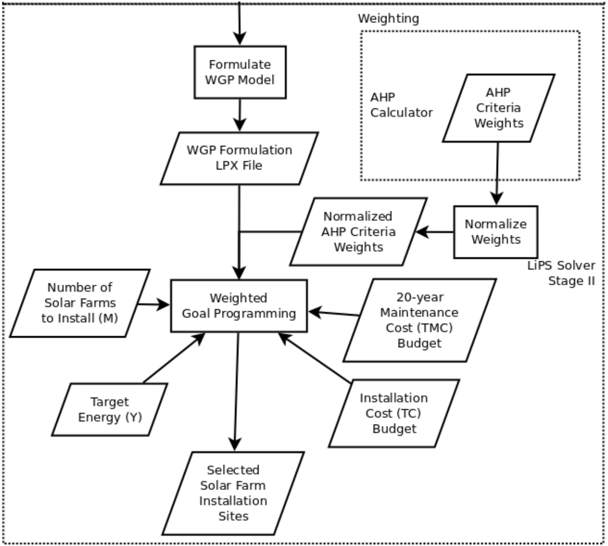
Feasible Locations	Infeasible Locations
Expansion Areas(4), Gently Sloping Lands (Irrigable & Paddy rice- irrigated)(2.1,1.2), Non-Agricultural (NAU), Pasture Lands(5.3), Potential Agro-Industrial Lands(4.2), Erodible Lands(5.2), Unclassified Lands	Alluvial Lands (Irrigable & Paddy rice-irrigated)(1.2,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

Land Type 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)

Land Cover Categories

Outline



Select M solar farm installation sites among the feasible installation sites.

Weighted Goal Programming

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

subject to:

$$Z_t(x) + \delta_t^- - \delta_t^+ = G_t \text{ for } t = 1, 2, ..., p \quad (2)$$

$$x \in X$$

$$x, \delta_t^-, \delta_t^+ \geq 0 \quad (3)$$

where (w_t^+) and (w_t^-) are nonnegative and numerical weights for the positive (δ_t^+) and negative (δ_t^-) deviations to the t^{th} objective (Z_t), from the target value (G_t).

Weighted Goal Programming:Unwanted Deviationsl Variables

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	$\delta_t^- + \delta_t^+$

Weighted Goal Programming Formulation

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

Subject to:

$\sum_{j=1}^{n} E_j x_j + \delta_1^- - \delta_1^+ = Y$ //Target Total Energy Goal Constraint Form

$\sum_{j=1}^{n} DT_j x_j + \delta_2^- - \delta_2^+ = 3000M$ //Distance from Trans Lines Goal Constraint Form

$\sum_{j=1}^{n} DR_j x_j + \delta_3^- - \delta_3^+ = 1000M$ //Distance from Roads Goal Constraint Form

$\sum_{j=1}^{n} DB_j x_j + \delta_4^- - \delta_4^+ = 500M$ //Distance from Built-Up Areas Goal Constraint Form

$\sum_{j=1}^{n} c_j x_j + \delta_5^- - \delta_5^+ = TC$ //Installation Cost Goal Constraint Form

$\sum_{j=1}^{n} mc_j x_j + \delta_6^- - \delta_6^+ = TMC$ //20-year Maintenance Cost Goal Constraint Form

$\sum_{j=1}^{n} x_j = M$ //Number of Solar Farms Constraint

and

$\sum_{j=1}^{n} E_j x_j >= Y$ //Target Energy Constraint

$x_j \in 0, 1$ //Integer Constraint

δ_t^- **and** $\delta_t^+ >= 0$ for $t = 1, 2, \ldots, 6$ //Positivity Constraint

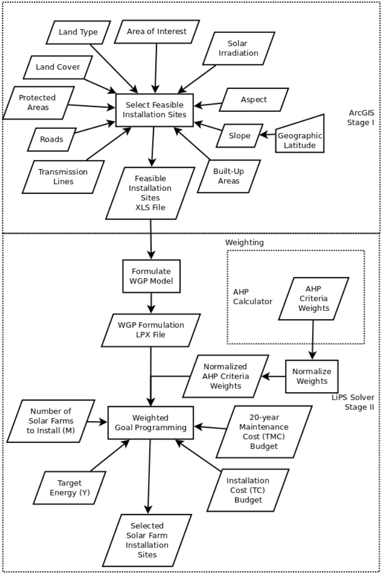
where:

$x_j = \begin{cases} 1, & \text{if site } j \text{ is selected} \\ 0, & \text{otherwise} \end{cases}$ //Feasible Installation Location

$E_j = (A_j \mu_{PV} \bar{G}_j)\mu_{inv}$ //Solar Farm Output Energy estimate

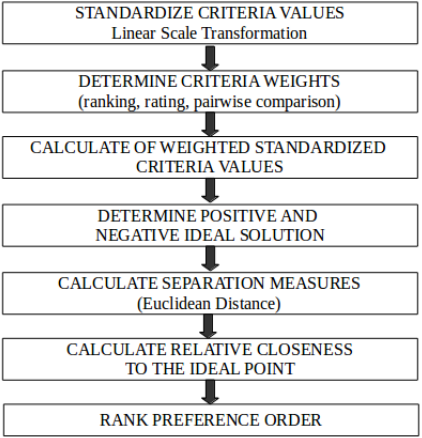
Definition of variables

E_j	//Output energy of a solar farm
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
M	//Number of solar farms to install
Y	//Total target output energy of the solar farms
TC	//Budget for installation
TMC	//Budget for maintenance (20-years)
DT_j	//Distance of the j^{th} feasible location from the nearest //transmission line
DR_j	//Distance of the j^{th} feasible location from the nearest //road
DB_j	//Distance of the j^{th} feasible location from the nearest //built-up area
c_j	//installation cost of the j^{th} feasible location
mc_j	//20-year maintenance cost of the j^{th} feasible location
δ_t^- for $t = 1, 2, \ldots, 6$	//negative deviation of the t^{th} goal from the target value
δ_t^+ for $t = 1, 2, \ldots, 6$	//positive deviation of the t^{th} goal from the target value



GIS-based AHP-WGP methodology for selecting *M* solar farm sites

Analytic Hierarchy Process-Technique for Order of Preference by Similarity to Ideal Solution (AHP-TOPSIS)



AHP-TOPSIS

Outline

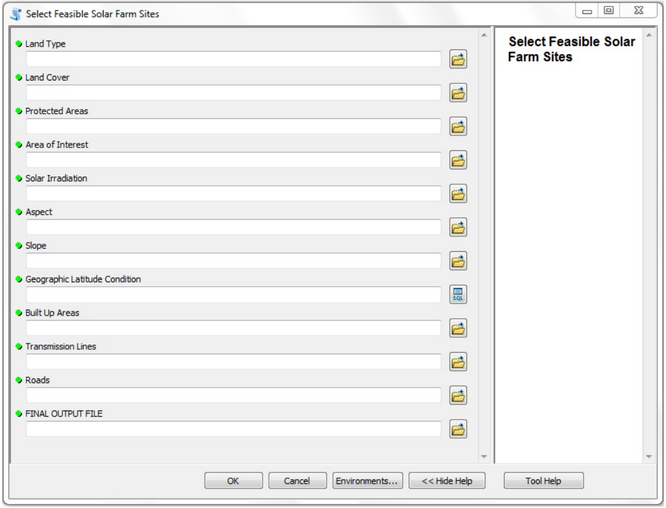
Case Study:Occidental Mindoro

Definition

Locate installation sites for three (M=3) grid-connected solar farms in the province of Occidental Mindoro, given a 500 MW target total energy (Y=500) to be produced and estimated PHP 10 B budget for the installation (TC=10,000) and PHP 20 B 20-year budget for maintenance (TMC=20,000) of the solar farms.

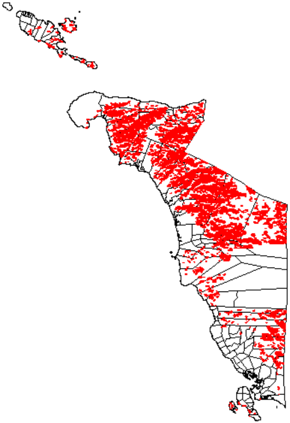
Outline

ArcGIS Script Tool



'Select Feasible Solar Farm Sites' ArcGIS Script Tool

Identified Feasible Solar Farm Installation Sites



Feasible Solar Farm Installation Sites in Occidental Mindoro.

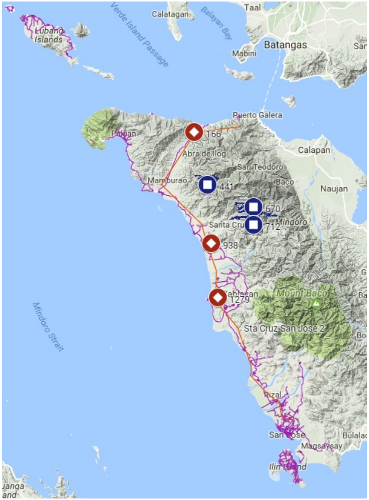
Outline

Analytic Hierarchy Process (AHP) Weights

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

Consolidated Criteria Weights

Selected Solar Farm Installation Sites



Selected Solar Farm Installation Sites in Occidental Mindoro for M=3 using AHP-TOPSIS (blue) and AHP-WGP (red)

AHP-TOPSIS

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

Selected Feasible Locations using the AHP-TOPSIS Approach

AHP-WGP

CODE	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)
166	17.6	0.1	16.1	0.8	0.9	0.7	165.0	964.0	2,505.0
938	20.9	0.1	33.1	0.3	4.5	1.3	340.0	1,979.0	5,154.0
1279	17.0	0.1	4.0	0.3	2.0	0.5	41.0	240.0	623.0

Selected Feasible Locations using the AHP-WGP Approach

Target deviation Values

Goal	Target	Fact	Difference	Normalized Weight
Total energy produced (MW)	$\geq$ 500	546.2	46.2	0.0192
Distance from Transmission Lines (m)	$\leq$ 9,000	2,546.4	6,453.6	0.0011
Distance from Roads (m)	$\leq$ 3,000	1,411.0	1,589.0	0.0066
Distance from Built-Up Areas (m)	$\geq$ 1,500	7,340.2	5,840.2	0.0293
Total Installation Cost (in Millions, PHP)	$\leq$ 10,000	3,183.0	6,817.0	0.0011
Total Maintenance Cost (for 20 years)(in Millions, PHP)	$\leq$ 20,000	8,281.1	11,718.9	0.0003

Summary of deviation values to each goal of the selected installation sites using WGP for $M = 3$

Criterion	Target	Fact	Difference	Weight
Total energy produced (MW)	$\geq$ 500	56,394.0	55,894.0	0.4393
Distance from Transmission Lines (m)	$\leq$ 9,000	55,900.0	46,900.0	0.1977
Distance from Roads (m)	$\leq$ 3,000	51,100.0	48,100.0	0.0961
Distance from Built-Up Areas (m)	$\geq$ 1,500	68,400.0	66,900.0	0.0990
Total Installation Cost (in Millions, PHP)	$\leq$ 10,000	327,686.0	317,686.0	0.1134
Total Maintenance Cost (for 20 years)(in Millions, PHP)	$\leq$ 20,000	855,040.0	835,040.00	0.0545

Summary of deviation values to each criterion of the selected installation sites using TOPSIS for $M = 3$

Conclusion

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- AHP-WGP also allowed decision-makers to include target energy, installation and maintenance budget constraints unlike AHP-TOPSIS.

Recommendations

- Use **real-sky model** instead of for the solar irradiation map to obtain a more realistic estimate of the energy that can be produced in the feasible installation site.

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- Use **real-sky model** instead of for the solar irradiation map to obtain a more realistic estimate of the energy that can be produced in the feasible installation site.
- Use **Land ownership** as a factor in selecting the solar farm installation sites.
- Consider a larger study site.

Summary

- The ArcGIS Script Tool (Stage I) was used to narrow down the search space.
- Weighted Goal Programming (Stage II) was used to select M installation sites given total energy(Y), installation ((TC)) and maintenance (TMC) budget constraints.
- The installation sites selected using the AHP-TOPSIS can produce high amounts of energy but were less accessible than the sites selected using the AHP-WGP approach