Geospatial Modelling for the Optimal Location of Solar Panels for Agrivoltaic Systems - A Case Study in Olive Groves

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***Abstract*— Agrivoltaic systems represent an innovative strategy to improve sustainability in agriculture by integrating solar energy production with food cultivation. In the province of Jaén, Spain, where olive cultivation is key, the implementation of these systems could optimise land use and increase farmers' profitability. This study uses Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA), specifically the Analytic Hierarchy Process (AHP) method to identify the most suitable sites for the installation of agrivoltaics. The results indicate that 19% of the area studied (33,840 km²) is highly suitable for agrivoltaic systems, with solar radiation and terrain slope being the most influential factors. This paper contributes a reproducible GIS-MCDM methodology for agrivoltaic site selection using expert- weighted criteria and spatial layers. The novelty lies in applying these techniques specifically to olive groves in Jaén, integrating solar potential with crop viability to support land- use optimization.**

Keywords - Agrivoltaics; Geographic Information System; Agriculture; Geospatial analysis.

I. INTRODUCTION

The growing demand for energy and food intensifies competition for land use, making agrivoltaic systems a strategic solution for integrating agricultural production with solar energy generation. Photovoltaic energy has been expanding globally, and in Spain, after a period of stagnation, its capacity more than doubled between 2019 and 2021, driven by lower technology costs and high solar radiation levels [1] [2].

Agrivoltaic systems allow for dual land use, enabling both agricultural production and electricity generation, providing environmental and economic benefits, such as improved soil quality, reduced water consumption, and increased biodiversity [3]. Additionally, studies show that this system can increase farmers' income, especially in low- margin crops. However, poorly positioned solar panels may compromise the productivity of the solar plant.

To address this challenge, GIS and MCDA are widely used to select optimal locations for renewable energy projects [4]. AHP, in particular, is effective in weighting different criteria without complex calculations, ensuring more consistent decision-making [5].

Previous research has demonstrated the effectiveness of GIS and MCDA, specifically the AHP method, in the selection of ideal sites for solar power plants. Studies in Morocco [8], Turkey [9], and Indonesia [6] have shown that between 16% and 19% of the analyzed areas are highly suitable for photovoltaic installations. In addition to MCDA, methods such as Weighted Linear Combination (WLC), Fuzzy AHP, and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) have also been employed to evaluate multiple criteria [12].

This study focuses on Jaén province, Spain, the world's largest olive oil producer, where agrivoltaics is not yet widely implemented. The methodology combines GIS, MCDA, and 3D modeling to assess the impact of shading.

The results indicate that 19% of the study area is highly suitable for agrivoltaic projects, allowing clean energy generation without compromising agricultural productivity. This proposed approach can be replicated in other agricultural regions, promoting food and energy security in a sustainable way.

The remainder of this paper is structured as follows: Section 2 describes the study area and data collection process. Section 3 explains the MCDA methodology based on the Analytic Hierarchy Process (AHP). Section 4 presents the results of the spatial analysis, while Section 5 discusses the implications of the findings. Finally, Section 6 outlines conclusions and future research directions.

II. RELATED WORKS

Recent studies have applied Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) methods, particularly the Analytic Hierarchy Process (AHP), to identify optimal locations for photovoltaic (PV) energy projects. In Saudi Arabia [7][13], Morocco [8], Turkey [9], and Egypt [10], GIS-AHP frameworks have successfully classified between 16% and 19% of their territories as highly suitable for solar energy installations, primarily based on criteria such as solar radiation, slope, land use, and proximity to infrastructure. Additionally, alternative decision techniques such as Weighted Linear Combination (WLC), Fuzzy AHP [14], and TOPSIS [12] have been introduced to enhance evaluation accuracy.

However, although these approaches have been effective in optimizing site selection for energy purposes, they often overlook the agricultural context, particularly the preservation of existing crops and rural heritage. In Spain, olive groves cover more than 2.5 million hectares, representing not only a key agricultural product but also an important cultural and environmental asset. The rapid expansion of large-scale photovoltaic plants has raised concerns about the loss of olive cultivation areas, threatening food production, local economies, and traditional landscapes.

Addressing this gap, the present study proposes a GIS-MCDA framework specifically adapted for the development of agrivoltaic systems within existing olive groves, aiming to optimize land use by integrating solar energy production without displacing agricultural activities. By focusing on the specific conditions of Jaén province—the leading olive oil-producing region globally—this work contributes a reproducible methodology that balances renewable energy deployment with agricultural preservation and sustainability.

III. MATERIALS AND METHODS

A. Study Area

The study area consists of 22 towns in Jaén, Andalusia, Spain, covering 2,700 km², a region with high solar radiation (2,625 kWh/m² annually) and extensive olive cultivation (550,000 ha). Jaén is the world's largest olive oil producer and has 219 MW of installed solar capacity, enough to power 100,000 homes. The region's long sunshine hours and available land make it highly suitable for agrivoltaic systems, allowing farmers to integrate solar energy with agriculture, improving land productivity and income while promoting sustainable energy generation.

B. Definition criteria

Identifying the factors used to evaluate site suitability is essential for optimizing solar power plant performance and cost efficiency. Common factors include Global Horizontal Irradiance (GHI), slope, and land cover, though variations exist depending on the study area and expert knowledge.

The criteria are divided into two types:

- Evaluation Criteria – Factors that influence site suitability.
- Constraints – Factors that exclude unsuitable areas.

The constraints were selected based on previous research on optimal PV plant siting [4][9][10][11]. These include permanent water bodies, restricted zones (airports, military sites), protected areas (e.g., Natura 2000, cultural heritage sites), and urban centers. These restricted areas and their buffer zones were identified following the Guide for Environmental Impact Studies for Photovoltaic Projects. In this study, the evaluation criteria were grouped into three categories: Climatology, Orography, and Location (Figure 1). The selection was based on previous studies and expert evaluations in PhotoVoltaic (PV) energy.

- Selected Criteria:

C1 - Slope (%): Steep slopes complicate solar panel installation and reduce sunlight exposure. Research indicates that areas with slopes less than 5° are ideal for maximizing PV system efficiency [13] [14].

C2 - Aspects (Orientation): The orientation of the land influences solar energy capture. In the Northern Hemisphere, south-facing panels receive the most sunlight, whereas in the Southern Hemisphere, north-facing ones are optimal. Non-optimal orientations may require adjustments to improve efficiency [15].

C3 - Global Horizontal Irradiance (GHI) (kWh/m²): Solar radiation is the most critical factor in PV site selection. High GHI values ensure continuous and effective energy generation.

C4 - Average Temperature (°C): High temperatures negatively impact photovoltaic cell performance. Efficiency drops when temperatures exceed 25°C, making it essential to consider temperature variations when selecting sites.

- Distance-Based Criteria:

C5 - Distance to Roads (m): Sites close to roads ensure easy transportation, installation, and maintenance of solar panels. Proximity minimizes infrastructure costs and environmental impacts [15].

C6 - Distance to Transmission Lines (m): PV plants should be near power lines to reduce energy losses and avoid the high costs of new transmission infrastructure. Efficient connection to the grid ensures profitability [15].

C7 - Distance to Residential Areas (m): Closeness to urban centers affects land availability, costs, and energy distribution. While proximity reduces grid connection expenses, buffer zones are necessary to minimize social and environmental impacts.

These criteria were validated by PV energy experts and integrated into GIS and MCDA to determine the most suitable locations for agrivoltaic systems. The evaluation criteria, such as climate, topography, and location, were prioritized according to expert judgment and literature of 100,000 homes. The region's long sunshine hours and available land make it highly suitable for agrivoltaic systems, allowing farmers to integrate solar energy with agriculture, improving land productivity and income while promoting sustainable energy generation.

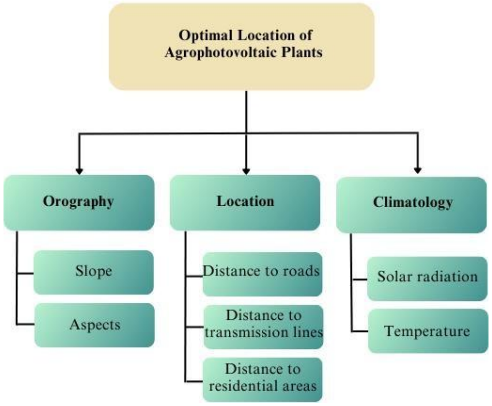

Figure 1. Criteria for optimal location of agrivoltaic plants.

C. Obtaining Thematic Layers

After defining the criteria, thematic layers were created through geoprocessing in Quantum Geographic Information System (QGIS) to analyze the suitability of sites for agrivoltaic plants. This involved combining GIS and MCDA techniques to assess the installation sites for solar panels. The process began with the collection of data, followed by spatial analysis using tools like surface, geometric, and distance operations.

A filtering step was performed on the Cadastral Parcels layer, focusing on olive grove farms identified by SIGPAC land use codes: OV (Olive groves), VO (Olive grove–Vineyard), OF (Olive grove–Fruit trees), FL (Shell fruit trees–Olive grove), and OC (Olive grove–Citrus). These categories correspond to different types of agricultural land where olive cultivation is predominant, either alone or in combination with other crops. Only parcels larger than 1,000 m² were selected, as smaller plots are not suitable for photovoltaic installations.

For each evaluation criterion, relevant data layers were generated:

- Criterion C1 - Slope (%): Calculated using Digital Elevation Model (DEM) with the QGIS Slope tool to identify flatter areas.
- Criterion C2 - Aspects: Orientation of the terrain calculated using DEM and the QGIS Aspect tool, with south-facing areas considered ideal for solar panels.
- Criterion C3 - Global Horizontal Irradiation (kWh/m²): Solar irradiance data from the Global Solar Atlas [16], downloaded as raster layers and clipped to the study area. Data was transformed using QGIS to align with the study's spatial resolution and suitability classification.
- Criterion C4 - Average Temperature (°C): Temperature data from the Global Solar Atlas, also clipped to the study area.
- Criterion C5, C6, C7 - Distance to Roads, Transmission Lines, and Residential Areas (m): Distances calculated using QGIS Euclidean distance tool for proximity analysis.

Once all layers were created, they were standardized on a common scale. Each layer was reclassified into 10 classes (1 = most suitable, 10 = least suitable), with special restrictions applied for Aspect (south-facing = 1) and Slope (slopes greater than 5° = 1). This reclassification allowed for integration into a unified suitability map for agrivoltaic plant siting. The processing results can be seen in the maps presented in Figure 2.

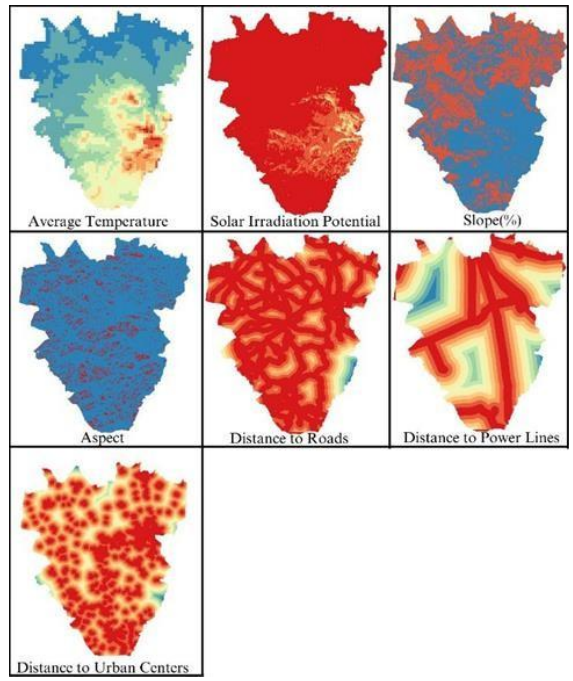

Figure 2. Maps of the geoprocessed and classified criteria.

Figure 2 presents the raster layers classified for each evaluation criterion. The slope and aspect maps reveal that south-facing land with gentle slopes-ideal for solar panel efficiency-are concentrated in the southern and southwestern regions of the study area. The solar radiation layer indicates higher irradiance values in these same areas, reinforcing their suitability. In addition, proximity-based criteria, such as distance to roads and power lines, highlight the advantage of the central and western municipalities in terms of access to infrastructure.

IV. MCDA Using an AHP Approach

This study employs the Analytic Hierarchy Process (AHP) within a Geographic Information System (GIS)- based Multi-Criteria Decision Analysis (MCDA) framework to identify optimal sites for agrivoltaic systems in Jaén, Spain. The AHP method is particularly suitable for renewable energy applications due to its ability to incorporate multiple qualitative and quantitative factors through structured expert judgment.

The AHP process follows structured steps, as shown in Figure 3 (decision-making flowchart). The process begins with problem definition, followed by hierarchical structuring of criteria and sub-criteria, and then constructing the Pairwise

Comparison Matrix (PCM). Experts evaluate the importance of each criterion using pairwise comparisons, and the results are normalized before computing the overall weight. A critical step is checking the Consistency Ratio (CR), which should be less than or equal to 10% to ensure the reliability of the decision matrix. If CR exceeds this threshold, adjustments are required before proceeding with the GIS mapping.

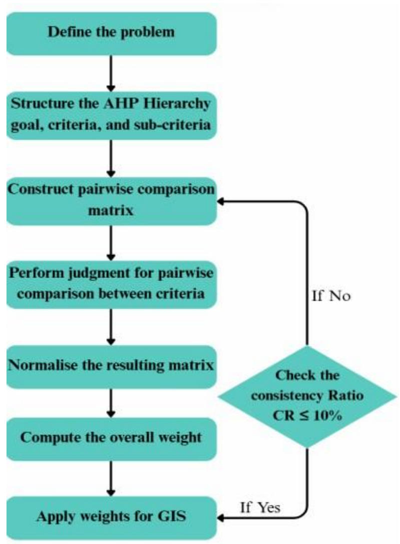

Figure 3. Steps for applying the AHP multi-criteria decision method.

AHP relies on expert pairwise comparisons, using a numerical scale from 1 (equal importance) to 9 (extreme importance). Table I presents the scale used to assess the relative importance of each criterion.

TABLE I. JUDGEMENT OF THE PAIRWISE COMPARISONS

N	Importance
Ci is equally as important as Cj	1
Ci is slightly more important than Cj	3
Ci is strongly more important than Cj	5
Ci is very strongly more important than Cj	7
Ci is extremely more important than Cj	9
Intermediate values	2, 4, 6, 8

After defining the importance levels, a PCM is constructed using a numerical grade scale (using Table I). Each criterion is compared with the others based on expert judgment. The reciprocal property is applied: if one criterion is considered much more important than another (e.g., C1 is 6 times more important than C6), the inverse value (1/6) is assigned to the opposite comparison (C6 compared to C1).

TABLE II. PAIRWISE COMPARISON MATRIX (PCM)

Criteria	C1	C2	C3	C4	C5	C6	C7
C1	1	2	3	4	7	6	5
C2	1/2	1	2	3	6	5	4
C3	1/3	1/2	1	2	5	4	3
C4	1/4	1/3	1/2	1	4	3	2
C5	1/7	1/6	1/5	1/4	1	1/2	1/3
C6	1/6	1/5	1/4	1/3	2	1	1/2
C7	1/5	1/4	1/3	1/2	3	2	1

Each entry a_{ij} in the pairwise comparison matrix was normalized by dividing it by the sum of its respective column, as shown in Equation (1):

$$s_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{1}$$

This transformation ensures that all criteria are expressed in relative terms, making them directly comparable. To determine the criterion weight vector (W_j), Equation (2) was applied. The relative weight of each criterion was obtained by averaging the normalized values across each row, where n is the number of elements in the row:

$$W_j = \frac{\sum_{j=1}^{n} s_{jk}}{n-1} \tag{2}$$

Then, the CI was divided by the Random Consistency Index (RI), a reference value that varies depending on the number of criteria (3):

$$CR = \frac{CI}{RI} \tag{3}$$

The resulting weights are presented in Table III, with slope (C1) and aspect (C2) emerging as the most influential criteria for site selection.

TABLE III. FINAL RESULT OF THE AHP APPLICATION

Criterion	Valor	Percentage
C1	0.354	35.44%
C2	0.240	24.00%
C3	0.159	15.85%
C4	0.104	10.36%
C5	0.031	3.11%
C6	0.045	4.49%
C7	0.068	6.75%

To ensure the reliability of expert judgments, a Consistency Ratio (CR) was calculated. First, the Consistency Index (CI) is determined by comparing the maximum eigenvalue of the matrix with the number of criteria.

$$CI = \frac{\lambda max - n}{m} \tag{4}$$

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Then, the CI is divided by a Random Consistency Index (RI), a reference value that depends on the number of criteria in the matrix. The RI values used for reference are presented in Table IV.

TABLE IV. RANDOM CONSISTENCY INDEX (RI) VALUES

N	1	2	3	4	5	6	7
RI	0	0	0.58	0.90	1.12	1.24	1.32

A CR ⩽ 10% indicates acceptable consistency, ensuring that expert evaluations are logically consistent. In this study, the calculated CR was 0.03, confirming that the matrix is reliable.

Once the normalized weights were established, a final suitability map was created using a weighted linear combination method (Figure 4). Each criterion was represented as a raster layer previously standardized on a 1–10 suitability scale, and each layer was multiplied by its corresponding weight. The weighted layers were then summed to produce a composite suitability score for each cell in the study area.

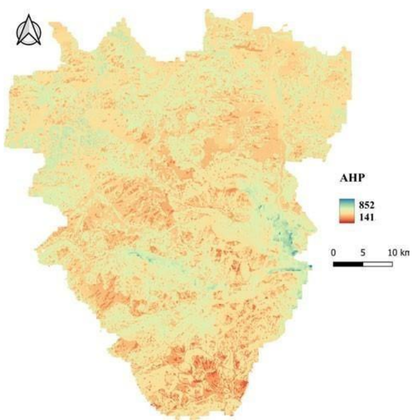

Figure 4. AHP Map.

In this step, spatial constraints previously defined — such as steep slopes or protected zones — were applied to mask out unsuitable areas. The result is a continuous raster map highlighting the most favorable locations for agrivoltaic development. To refine the results, areas deemed unsuitable for agrivoltaics—such as protected zones, urban regions, and bodies of water—were excluded from the final map.

The analysis revealed that 19% of the studied area is highly suitable for agrivoltaic projects, effectively balancing solar energy generation with agricultural productivity.

In sumary, using the MCDA-AHP technique, weighted values were assigned, and QGIS was used for spatial analysis. The results indicate that 33,840 km² of the study area are highly suitable, with a suitability level exceeding 80%. To simplify interpretation, the results were classified using the Land Suitability Index (LSI), as shown in Table V.

TABLE V. LAND SUITABILITY INDEX (LSI)

Suitability Level	Suitability Percentage	Area (km²)
Most Suitable	> 80%	33,840
Highly Suitable	70% – 80%	899,710
Moderately Suitable	60% – 70%	1,416,590
Marginally Suitable	50% – 60%	257,810
Least Suitable	< 50%	2,320

After classification, restricted areas (e.g., protected lands, urban zones, and bodies of water) were excluded using the QGIS clipping tool (Figure 5).

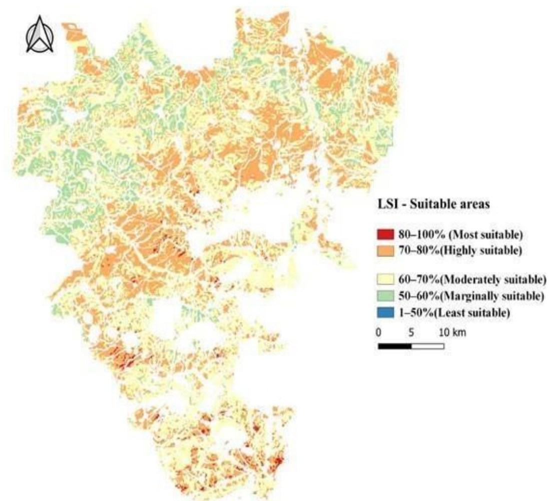

Figure 5. LSI with Restrictions excluded.

The most highly suitable areas are mainly in the south and west, benefiting from lower temperatures, high solar radiation, and accessibility to roads and power infrastructure. In contrast, northwestern areas are less suitable due to lower irradiation and infrastructure density. This solar site suitability analysis provides a data-driven approach to support decision-makers in selecting optimal agrivoltaic locations in Andalusia, whether for small or large-scale PV systems.

IV. CONCLUSION AND FUTURE WORKS

This study proposed a spatial framework based on GIS and Multi-Criteria Decision Analysis (MCDA) to identify optimal locations for agrivoltaic installations in olive-growing areas of Jaén province, Spain. By combining environmental, topographic, and infrastructure-related criteria using the Analytic Hierarchy Process (AHP), the study generated a spatial suitability map indicating that 33,840 km² — mainly in the south and west — are highly suitable for agrivoltaic systems, with an overall suitability level above 80%.

These results demonstrate that the integration of GIS and AHP methodologies enables informed land-use decision-making, promoting both energy transition and agricultural productivity. The spatial framework developed is replicable and adaptable to other contexts, making it a valuable tool for planners and policymakers.

However, this study is not without limitations. Agronomic variables such as crop yield under shading or irrigation needs were not included, and they could significantly influence the final suitability of the sites. Additionally, the results rely on static environmental datasets and expert-derived weights, which may vary over time or across regions.

Future work should consider the integration of dynamic agronomic models, real-time data, and alternative decision-making techniques such as the Fuzzy AHP algorithm. In addition, developing an intuitive and user-friendly interface would enhance accessibility and enable stakeholders to interact with spatial data and suitability maps more effectively, thereby supporting informed decision-making and encouraging broader public engagement. Finally, expanding this methodology to other agricultural regions of Spain or the Mediterranean could provide a more generalized understanding of sustainable dual land use.

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REFERENCES

[1] I. Mauleón, "Optimising the spatial allocation of photovoltaic investments: Application to the Spanish case", *Energy Conversion and Management*, vol. 291, pp. 117292, 2023.

[2] M. Šúri, T. A. Huld, E. D. Dunlop, and H. A. Ossenbrink, "Potential of solar electricity generation in the European Union member states and candidate countries", *Solar Energy*, vol. 81, no. 10, pp. 1295–1305, 2007.

[3] H. Marrou, L. Guilioni, L. Dufour, C. Dupraz, and J. Wery, "Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels?", *Agricultural and Forest Meteorology*, vol. 177, pp. 117–132, 2013.

[4] L. Albraheem and L. Alabdulkarim, "Geospatial analysis of solar energy in Riyadh using a GIS-AHP-based technique", *ISPRS International Journal of Geo-Information*, vol. 10, no. 5, pp. 291, 2021.

[5] K. Ioannou, G. Tsantopoulos, and G. Arabatzis, "A decision support system methodology for selecting wind farm installation locations using AHP and TOPSIS: Case study in Eastern Macedonia and Thrace region, Greece", *Energy Policy*, vol. 132, pp. 232–246, 2019.

[6] H. S. Ruiz, A. Sunarso, K. Ibrahim-Bathis, S. A. Murti, and I. Budiarto, "GIS-AHP Multi Criteria Decision Analysis for the optimal location of solar energy plants at Indonesia", *Energy Reports*, vol. 6, pp. 3249–3263, 2020.

[7] H. Z. Al Garni and A. Awasthi, "Solar PV power plant site selection using a GIS-AHP based approach with application in Saudi Arabia", *Applied Energy*, vol. 206, pp. 1225–1240, 2017.

[8] A. A. Merrouni, F. E. Elalaoui, A. Mezrhab, A. Mezrhab, and A. Ghennioui, "Large scale PV sites selection by combining GIS and Analytical Hierarchy Process. Case study: Eastern Morocco", *Renewable Energy*, vol. 119, pp. 863–873, 2018.

[9] H. E. Colak, T. Memisoglu, and Y. Gercek, "Optimal site selection for solar photovoltaic (PV) power plants using GIS and AHP: A case study of Malatya Province, Turkey", *Renewable Energy*, vol. 149, pp. 565–576, 2020.

[10] J. R. Doorga, S. D. V. Rughooputh, and R. Boojhawon, "Multi-criteria GIS-based modelling technique for identifying potential solar farm sites: A case study in Mauritius", *Renewable Energy*, vol. 133, pp. 1201–1219, 2019.

[11] S. Zambrano-Asanza, J. Quiros-Tortos, and J. F. Franco, "Optimal site selection for photovoltaic power plants using a GIS-based multi-criteria decision making and spatial overlay with electric load", *Renewable and Sustainable Energy Reviews*, vol. 143, pp. 110853, 2021.

[12] J. M. Sánchez-Lozano, M. S. García-Cascales, and M. T. Lamata, "Evaluation of suitable locations for the installation of solar thermoelectric power plants", *Computers & Industrial Engineering*, vol. 87, pp. 343–355, 2015.

[13] I. Guaita-Pradas, I. Marques-Perez, A. Gallego, and B. Segura, "Analyzing territory for the sustainable development of solar photovoltaic power using GIS databases", *Environmental Monitoring and Assessment*, vol. 191, no. 12, pp. 764, 2019.

[14] S. Wang, L. Zhang, D. Fu, X. Lu, T. Wu, and Q. Tong, "Selecting photovoltaic generation sites in Tibet using remote sensing and geographic analysis", *Solar Energy*, vol. 133, pp. 85–93, 2016.

[15] G. Rediske, J. C. Mairesse Siluk, N. G. Gastaldo, P. D. Rigo, and C. B. Rosa, "Determinant factors in site selection for photovoltaic projects: A systematic review", *International Journal of Energy Research*, vol. 43, no. 5, pp. 1689–1701, 2019.

[16] The World Bank, ESMAP, "Global Solar Atlas", *The World Bank Group*, Washington, DC, 2020. [Online]. Available: https://globalsolaratlas.info.

