Optimizing Centralized Photovoltaic Plant Deployment: A Geospatial Approach

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Abstract. *The growing reliance on fossil fuels underscores the urgent need to explore renewable energy sources to combat climate change. This article introduces a geospatial framework aimed at helping experts identify optimal locations for centralized solar power generation. The methodology has two distinct phases, incorporating multicriteria decision-making techniques, such as DEA and Fuzzy TOPSIS, along with GIS analysis that integrates geospatial data representations. A case study conducted in Brazil highlights the potential of 166 regions organized into 17 clusters, totaling 158 km² of suitable area for solar power plant installation. The regions are situated in Morro do Chapeú, Bahia, contributing to the overall stability and balance of the country's electrical grid.*

1. Introduction

Global dependence on fossil fuels, such as oil, natural gas, and coal, has led to substantial carbon dioxide (CO_2) emissions, contributing to climate change. Urgent international efforts, exemplified by UNFCCC COP26, aim to limit global temperature increases to 1.5°C and achieve net-zero emissions by mid-century [Lennan and Morgera 2022].

Brazil plays a significant role in renewable energy, primarily due to its robust hydroelectric infrastructure. The current energy matrix in Brazil is diversified, comprising hydroelectric power (51.9%), wind energy (12.7%), biomass (7.3%), small-scale hydroelectric projects (3.6%), photovoltaic (PV) solar energy (4.9%), natural gas (8.1%), fuel oil (2.0%), mineral coal (1.4%), and nuclear power (0.9%) sources, as reported by [ONS - National Operator of the Interconnected Power System 2023]. The prevalence of hydroelectric power plants creates an electrical grid imbalance, heavily dependent on rainfall near reservoirs. The research development by [Lima et al. 2020] underscores the importance of diversifying the energy mix by investing in renewable like wind and solar, while continuing to support hydro-power.

Electricity generation comprises two primary models: distributed generation and centralized generation. Centralized generation plays a critical role in efficiently transmitting electricity over long distances through high-voltage transmission lines. It falls under the purview of the Brazilian Electricity Grid Operator (ONS) and is regulated by the Brazilian National Electric Energy Agency (ANEEL).

Environmental data integration, which combines multicriteria decision techniques [Almasad et al. 2023] and Geographical Information System (GIS) analysis, enables the organization of regions with high solar potential into collaborative clusters for centralized electricity generation [Fortune 2017]. Similarly, [Alhammad et al. 2022] identified optimal locations for solar energy plants in Al-Qassim, Saudi Arabia, providing valuable guidance for comparable projects. In the context of Brazil, a country with significant solar potential, the application of such methodologies offers an opportunity to address this challenge and enhance energy security, as exemplified by [Lucena and de Holanda 2022].

This paper presents a geospatial methodology to identify optimal regions for centralized solar power plant deployment, utilizing multicriteria methods, including Data Envelopment Analysis (DEA), Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy TOPSIS), and Analytic Hierarchy Process (AHP) [Ali Sadat et al. 2021]. GIS techniques, such as Normalized Difference Vegetation Index (NDVI), slope and aspect assessments, and spatial data integration using Landsat 8 and Shuttle Radar Topography Mission (SRTM) images [USGS-EarthExplorer 2022], are applied. The methodology also considers total assessed area and proximity to high-voltage transmission lines. Selected micro-regions are clustered using Voronoi and Delaunay techniques. A case study in Brazil illustrates this methodology, providing insights for decision makers in the renewable energy sector and contributing to electrical grid optimization, considering potential impacts on energy efficiency and sustainability

2. Material and Methods

Initially, the methodology requires a set of environmental information, collected from Data Collection Platforms (DCPs), for example. This dataset can include atmospheric parameters such as temperature (°C), cloud cover (octas), wind speed (m/s), humidity, altitude (m) and solar irradiation on an inclined plane (kWh/m²/day). Additionally, leveraged remote sensing image data has to be used to terrain use and cover, and altimetry identification. Bands of Landsat images, for example, can be used to calculate the NDVI, a critical parameter for understanding land cover and land use, particularly in terms of vegetation health and solo occupation. SRTM elevation grids, for example, are sources of altimetry data available for free in the internet.

The proposed methodology has two distinct phases. In the first one, named Multicriteria Analysis, efficient solar energy regions are identified considering environmental data and infrastructure criteria. The second phase, named Integration of GIS and Remote Sensing, focuses on generating and exploring a thematic map that represent the suitability for PV module installations in centralized energy generation. Figure 1 illustrates the logical flow of the methodology, showcasing how these phases are closely linked.

The Multicriteria Analysis of phase 1 uses specifically Data Envelopment Analysis (DEA) with an input-oriented approach [Lee et al. 2015],to identify regions modeled mathematically as Decision Making Units (DMUs) with the highest efficiency in harnessing solar energy. Following this, it was applied the Fuzzy TOPSIS method [Behzadian et al. 2012] to address data uncertainties and subjectivity, incorporating information about transmission lines and substations. This enabled energy experts to reassess DEA rankings, facilitating the selection of the best strategic macro-region that meets economic, environmental, and social criteria, a critical step in identifying promising solar

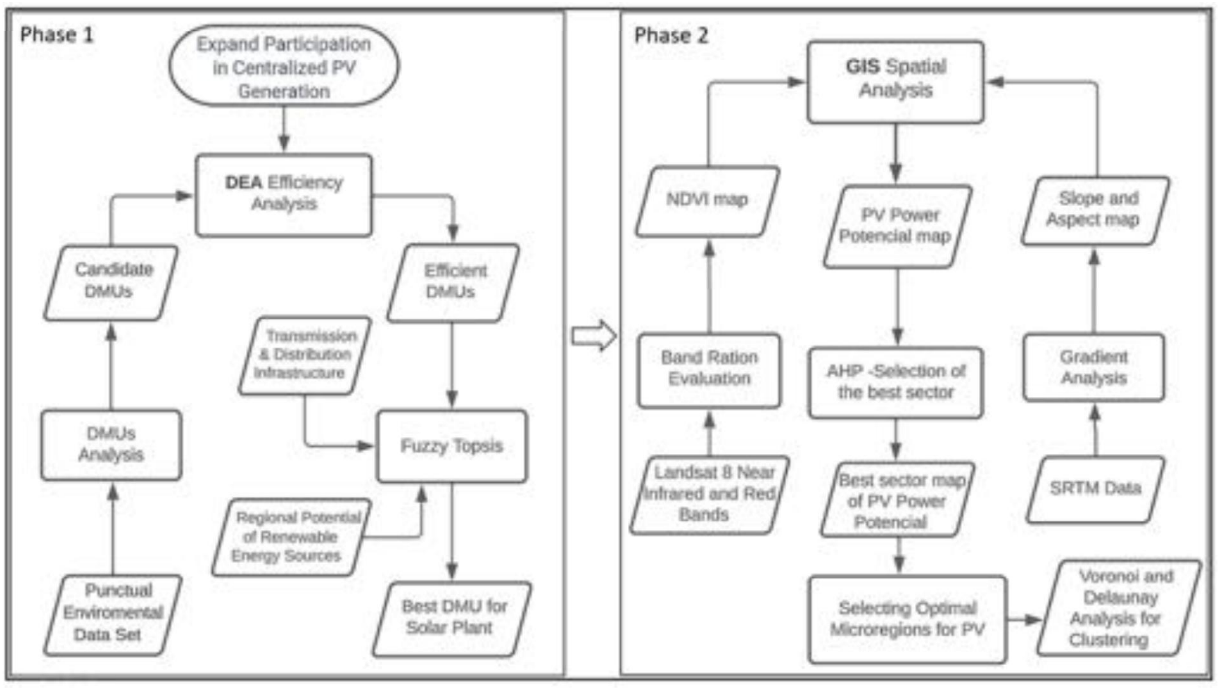

Figura 1. Methodological Framework for Assessing Solar PV Potential Regions.

energy generation areas.

In Phase 2, the focus shifted to the most efficient DMU identified on Phase 1. Here, it was employed GIS and remote sensing image analysis to create a thematic map highlighting classes of PV potentials. From the ratio of bands 3 and 4 of the LandSat image, a NDVI map was generated. The slope and aspect maps were assessed from the SRTM information using their local gradient vector analysis. Then, to generate the PV Power Potential map, the NDVI, the slope, and the aspect maps were algebraically integrated in a GIS environment by crossing their internal classes, that were user defined by ranges of values. Additionally, the AHP method [Noorollahi et al. 2022] was then used to designate an octant within a 100 km radius, centered on the Phase 1 region. Geometric computing techniques based on Voronoi and Delaunay analysis were then applied to identify clusters of regions with high PV solar energy potential.

3. Case Study

The Brazilian country was chosen, as a case study, to illustrate the application of the proposed methodology. The Brazilian territory extends 4,395 kilometers from north to south (between latitude 5°16'20"N and 33°44'32"S) and 4,319 kilometers from east to west (between longitude 34°47'30"W and 73°59'32"W). The selected area encompasses the entirety of Brazil's region, facilitating an in-depth analysis of solar energy potential across its varying climatic zones and geographical features.

4. Results and Discussion

This section reports details, along with results and discussion, of the methodology applied in Brazil.

4.1. Phase 1: Multicriteria Analysis

In this initial phase, DEA and Fuzzy-TOPSIS were employed on the DCP data set to identify regions in Brazil with the potential for the installation of PV modules. The DCPs in

Brazil are managed by the National Institute of Meteorology (INMET) [INMET 2022]. This dataset spans from January 1, 2022, to December 31, 2022, and includes crucial atmospheric parameters such as temperature (°C), cloud cover (octas), wind speed (m/s), humidity, altitude (m) and solar irradiation on an inclined plane (kWh/m²/day). The combination of DEA and Fuzzy techniques allowed to rank the primary regions in Brazil that meet the criteria for centralized energy generation. As a result of this phase, the city of Morro do Chapéu, Bahia, was selected for presenting a DMU efficiency of H_k = 1 in Input-Oriented DEA and the highest proximity coefficient in Fuzzy-TOPSIS, CC_i = 0.5042, among all DMUs.

4.2. Phase 2: Integration of GIS and Remote Sensing

In this phase, Landsat and SRTM images were used to generate the IVDN, the slope and the aspect maps for the DMU region Morro do Chapéu. It acquired four Landsat 8 OLI/TIRS C1 Level-2 images dated October 15, 2020, and eight SRTM images available on September 23, 2014. The PV potential map for this region was obtained by crossing the following classes of IVDN, Slope and Aspect maps: Excellent (0.48 $\leq$ IVDN $\leq$ 0.69), Good (0.69 $<$ IVDN $\leq$ 0.71), and Regular (0.71 $<$ IVDN $\leq$ 0.72). The classes of angles, in degrees, of the slope map were: Excellent (0.0 ° $\leq$ Slope $\leq$ 14.0 °, Good (14.0 °$\leq$ Slope $\leq$ 25.0 °), Regular (25.0 ° $\leq$ Slope $\leq$ 35.0 °), Poor (35.0° $\leq$ Slope $\leq$ 50.0 °), and Prohibitive (50.0° $\leq$ Slope $\leq$ 90.0°)). The aspect, or solar exposure, angle classes were: Excellent ((0.0° $\leq$ Aspect $\leq$ 45.0°) or 315.0°) $\leq$ Aspect $\leq$ 360.0°)), Good ((80.0° $\leq$ Aspect $\leq$ 45.0°) or 280.0° $\leq$ Aspect $\leq$ 315.0°)), Regular ((80.0°) $\leq$ Aspect $\leq$ 100.0°) or 260.0°) $\leq$ Aspect $\leq$ 280.0°)) Poor ((120.0°) $\leq$ Aspect $\leq$ 100.0°) or 240.0°) $\leq$ Aspect $\leq$ 260.0°)), and Prohibitive in all other cases.

Furthermore, it was incorporated data related to energy infrastructure, including transmission lines and substations. These additional datasets supported experts in the energy field during the Fuzzy TOPSIS and AHP questionnaires. The data collection for this phase was completed in April 2022. So, following the generation of the Photovoltaic Potential Map, the AHP was applied to identify the octant of a circle, within 100 km radius centered in Morro do Chapéu DMU, where criteria for centralized energy generation by future photovoltaic modules were applied and which was in proximity to high-voltage transmission lines. The criteria considered for each octant included 1) High-Voltage Transmission Line Availability, 2) Proximity to Substations, 3) Solar Irradiation, 4) Region Suitability for PV, 5) Region Adequacy for PV, and 6) Region Restrictions for PV. The evaluated alternatives correspond to octants, based on the four cardinal directions (North, South, East, and West), namely: 1) NNE, 2) NEE, 3) ESE, 4) SES, 5) SSW, 6) SWW, 7) WNW, and 8) NWN. The use of the AHP method, involving paired comparisons by experts, ensures the selection of the most promising octant, in this case the WNW, for centralized energy generation. Figure 2 showcases the creation of the thematic map representing the solar utilization potential, within the Morro do Chapéu DMU.

Finally, Voronoi and Delaunay analysis were then applied to identify clusters of regions with high PV solar energy potential in the WNW sector as illustrated in Figure 3.

The results of this case study highlighted the potential of 166 regions organized into 17 clusters, totaling 158 km² of suitable area for solar power plant installation in Morro do Chapéu city, contributing to the overall stability and balance of the country's electrical grid.

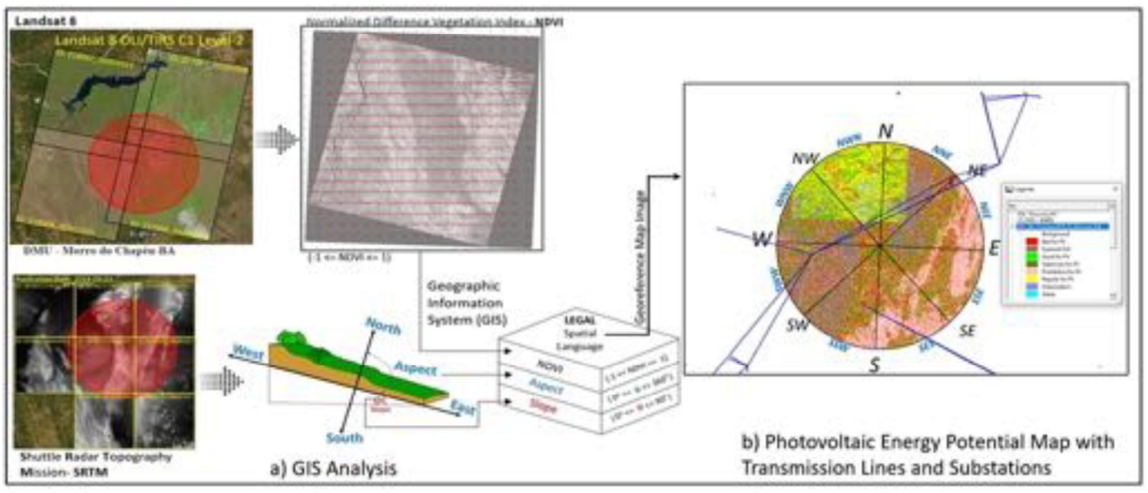

Figura 2. Photovoltaic Power Potential Mapping (PPPM).

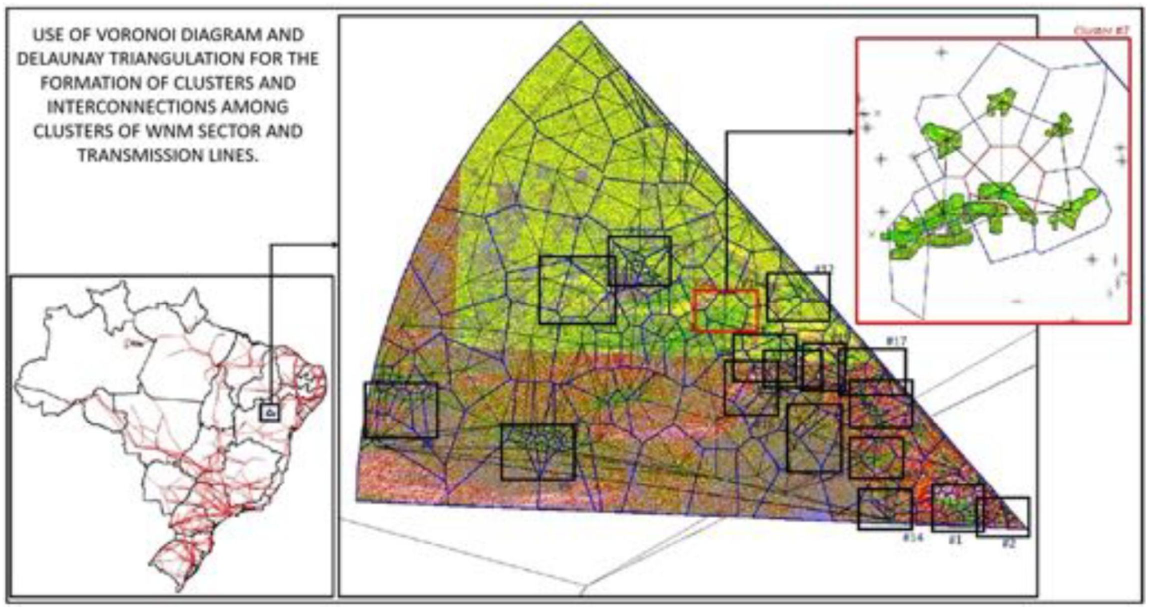

Figura 3. Clustering of the WNW Sector on a PV Energy Suitability Map.

5. Final Remarks

In conclusion, our geospatial framework successfully identifies optimal locations for centralized solar power generation, addressing energy transition challenges. By integrating Multicriteria, GIS, and Remote Sensing Data Analysis, we present a methodology for selecting suitable areas for solar power plant installations in a case study. These findings align with broader goals of sustainable and cleaner energy sources. The methodology empowers decision makers to advance sustainability and energy efficiency.

This research underscores the effectiveness of geospatial methodologies in renewable energy efforts. Further validation of cluster feasibility through simulations is essential. Meticulous site selection is crucial for advancing solar energy utilization. Future research should prioritize detailed simulations with PVsyst software for cluster regions, exploring innovative solar technologies for residential and industrial transformation.

Our integration of the Voronoi diagram into thematic GIS images related to PV energy generation significantly contributes to reducing Brazil's energy matrix imbalance, historically reliant on hydroelectric power. By promoting centralized generation, our approach enhances grid stability, ensuring a reliable energy supply.

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