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Environmental and Social Issues for Floating Photovoltaic Power Generation in an Artificial Lake

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A B S T R A C T

The growing urgency for sustainable energy solutions has significantly increased interest in floating photovoltaic (FPV) systems, especially on artificial lakes. This study investigates the environmental and social challenges associated with deploying FPV systems on Sobradinho Lake, aiming to optimize energy output while minimizing ecological impacts. Our primary objective is to evaluate potential areas for FPV installation using a robust methodology that integrates Geographic Information Systems (GIS) with the Fuzzy Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).The methodology involves applying GIS to layer various constraint factors, allowing us to identify suitable FPV system locations based on climatic, socio-environmental, and technical criteria. The results indicate that approximately 24.04% of Sobradinho Lake's total area is classified as having medium to high potential for FPV implementation. This finding highlights the viability of FPV systems as a renewable energy solution in regions with limited land resources.In conclusion, this study demonstrates that combining GIS and multi-criteria decision analysis can effectively inform the planning and deployment of FPV systems, ensuring environmental and social factors are thoroughly considered. This approach is adaptable for similar studies, promoting the adoption of renewable energy technologies while safeguarding ecological systems.

Keywords: floating photovoltaic system, photovoltaic plants GIS, MCDM, TOPSIS, AHP

Questões Ambientais e Sociais para Geração de Energia Fotovoltaica Flutuante em um Lago Artificial

R E S U M O

O aquecimento global e as mudanças climáticas impactam diretamente a produção agrícola, destacando a urgência de soluções sustentáveis para a climatização de instalações. Nesse contexto, a energia geotérmica superficial emerge como alternativa promissora, especialmente em regiões tropicais e subtropicais. Este estudo objetivou avaliar o potencial da energia geotérmica proveniente de um latossolo vermelho para climatização de instalações agrícolas, determinando os parâmetros ideais de projeto e eficiência energética em trocadores de calor horizontais. A pesquisa foi realizada no município de Dourados - MS, Brasil, em 2022, tendo sido calculada a taxa e coeficiente global de transferência de calor e a propagação térmica radial em torno de trocadores de PVC e cobre para determinação da profundidade e distancia radial ideal de instalação. Foram verificadas a profundidade ótima de instalação do trocador de calor (2,4 m) e a distância mínima entre tubos (0,5 m) para maximizar a eficiência. Constatou-se que o material do trocador (PVC ou cobre) não influenciou significativamente a taxa de transferência de calor, sendo o solo fator limitante. O diferencial de temperatura entre o fluido e o solo foi identificado como parâmetro de maior impacto. Com base nesse estudo, é indicada a construção de trocadores de PVC, pois apresentaram desempenho técnico semelhante ao cobre, porém com menor custo e maior facilidade de aquisição e manuseio. Os resultados dessa investigação fornecem subsídios técnicos relevantes para o dimensionamento otimizado de sistemas geotérmicos aplicados à climatização agrícola sustentável e econômica.

Palavras-chave: sistema fotovoltaico flutuante, plantas fotovoltaicas, SIG, MCDA, TOPSIS, AHP

Introduction

The current transformation in the electricity sector has increasingly encouraged the exploration of renewable sources of energy generation. The main objective is to reduce carbon emissions by modernizing the technologies used for generation, and the existing market, encouraging policies and research in the energy sector (Gorjian et al., 2021). According to the World Energy Outlook, released by the International Energy Agency (2019), in addition to reducing the current trend of these emissions, new sustainable infrastructure must be installed.

Solar energy is considered one of the most promising energy alternatives because it is renewable, clean, and abundant. Furthermore, it is free and available worldwide (Sharma et al., 2013). Among the existing photovoltaic arrangements, the floating photovoltaic system (FPV or floatovoltaic) is favorable, presenting higher efficiency than the systems set up on the ground and roofs due to the cooling effect of the water (Ranjbaran et al., 2019). In addition, floating systems can reduce reservoir evaporation and algae growth due to the shading effect on the water body (INMET, 2022).

The Brazilian semiarid region has a high rate of evaporation in its reservoirs because of high temperatures, solar irradiation wind speed, and low relative humidity. The high evaporation rate, added to the low rainfall in many areas, favors negative water balances (Macedo et al., 2021). Thus, the installation of a floating photovoltaic plant in a reservoir in these climatic conditions can reduce the factors that influence evaporation, in addition to increasing the efficiency of energy generation, complementing the hydroelectric system in periods of drought.

Some studies on this topic have been developed and some deserve special attention.Ma et al. (2021) highlights floating photovoltaic systems (FPV) as a promising clean energy solution with 1000 GW global potential, offering land savings and improved efficiency. The study reviews FPV construction trends, site selection criteria, and ecological interactions, serving as a reference for design and regulations. Piana et al. (2021) examines FPV's growing use on water bodies, emphasizing the need for local sustainability assessments. The article provides a screening checklist to identify suitable sites, focusing on artificial mountain lakes used by hydroelectric plants and acknowledging both their synergistic potential and implementation challenges. Sulaeman et al. (2021) proposes integrating FPV in existing dam reservoirs, demonstrating how this investment improves system reliability, minimizes load shedding, and adds flexibility to hydroelectric management without building new dams. Nobre et al. (2023) addresses FPV's global expansion despite limited understanding of ecological impacts. While FPVs reduce light penetration, wind speed, and water temperature, cascading effects on biological processes remain unknown. These modifications could alter ecosystem dynamics and greenhouse gas balance, highlighting the need for context-specific impact monitoring. Madeško et al. (2024) explores FPV integration with hydroelectric plants using artificial reservoirs like Lake Buško, potentially generating 302 GWh annually and increasing hydroelectric production by 91% while maintaining recreational and ecological functions. Finally, Benjamins et al. (2024) predicts significant FPV expansion in aquatic environments, noting potential impacts on hydrodynamics, water-atmosphere exchange, and aquatic communities. Despite FPVs' importance for decarbonization, stakeholder collaboration is essential to understand impacts, develop monitoring methods, and ensure sustainable industry expansion.

During the solar energy planning process, it is essential to establish the factors or criteria that affect the availability of this resource (Thari et al., 2015). These criteria used in site selection for new plants can be environmental, climatic (solar radiation, temperature), social (economic or recreational use of the water body), and related to location (distance to the substation).

Thus, all aspects must be considered, due to the complexity of the process, in which complete information is needed on a wide range of criteria and their implications to decide on the available areas (Lee et al., 2014). Therefore, Multi-Criteria Decision Analysis (MCDA) approaches are the most appropriate means to provide the necessary information for the decision. Examples of methods for this multi-criteria decision are the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Fuzzy-TOPSIS (an adaptation of TOPSIS); both stand out for their simplicity of use and the ability to evaluate an unlimited number of alternatives and criteria simultaneously (Makwakwa et al., 2024).

Given this, Geographic Information Systems (GIS) are tools capable of analyzing spatial information and have been widely used in the energy scenario, whether for resource assessment or even in infrastructure planning. From the use of GIS, it is possible to manipulate data in digital models (raster and vector) and offer a collection of procedures, techniques, and algorithms to structure data to instantiate decision problems that deal with design, in addition to evaluating and prioritizing alternatives of decision (Madanchian & Taherdoost, 2023).

Decision-making techniques can be quite diverse, such as the MCDA method based on the Analytic Hierarchy Process (AHP) for selecting wind farm installation strategies (Janke, 2010), multicriteria decision models (MCDA) for solar and wind farms using GIS (Charabi and Gastli,, 2011), location of solar farms using GIS and fuzzy logic (Maleki et al., 2017) and multicriteria evaluation of photovoltaic technologies using TOPSIS and AHP methods (Martins et al., 2007).

This study aims to assess the feasibility and identify ideal locations for floating photovoltaic solar systems in Lake Sobradinho, Bahia State, Northeastern Brazil, through multi-criteria analysis and geoprocessing techniques using Geographic Information Systems (GIS) and fuzzy AHP-TOPSIS methodologies; specifically, it evaluates climatic, socio-environmental, and technical factors including solar radiation, temperature, and proximity to substations, incorporates restriction layers related to fishing, tourism, and fish farming while addressing distance constraints from substations, and examines the environmental and social implications of implementing floating photovoltaic systems to ensure proposed solutions are sustainable and beneficial for local communities, thereby contributing to carbon emission reduction, renewable energy promotion, and sustainable infrastructure development in Brazil.

This work will use the fuzzy AHP-TOPSIS method (Fuzzy-TOPSIS method associated with AHP) combined with GIS to classify the possible locations for floating photovoltaic plants in Sobradinho Lake, located in the reservoir of the Sobradinho Hydroelectric Power Plant - Bahia, in ordered categories of merit according to evaluation criteria.

In this analysis, environmental, social, and technical-environmental aspects will be considered, including solar radiation, temperature, and distance to the substation. The objective of this study is, therefore, to provide a methodology to identify sites with potential for floating photovoltaic generation in lakes and, in this way, to contribute to the progress of floating plants in the Brazilian power generation scenario.

Study the location of photovoltaic solar plants using GIS to find the ideal solution (Fuzzy AHP-TOPSIS)

Criteria for the selection of sites for the implementation of floating photovoltaic solar plants

The criteria considered in the installation of photovoltaic plants can be diverse, Macedo et al. (2021) cites some important criteria for the implementation of a conventional photovoltaic plant such as accessibility, orientation and slope, ground cover, location and inclination of the panels and land use. This range of criteria makes solar energy planning increasingly complex. The criteria can be grouped into four categories: climatic (solar radiation and temperature), socioeconomic, technical-economic (location), and environmental.

Solar radiation is a very important criterion to be evaluated since the amount of radiation received will define the amount of solar energy that can be converted into electrical energy. If the site under analysis has all the criteria at optimal levels, but the solar radiation is not satisfactory, this area will not be a good place to install a photovoltaic plant (Thari et al., 2015). According to the US National Renewable Energy Laboratory (NREL), solar radiation can be classified into four categories: moderate (less than 4 kWh/m2/day), good (4-5 kWh/m2 /day), very good (5-6 kWh/m2/day) and excellent (> 6 kWh/m2/day) (Martins, 2007). The annual average of total daily global solar irradiation that arrives in Brazil is adequate for the generation of electric energy (Doile et al., 2021). Despite the diverse climatic characteristics found in Brazil, the country has uniform global radiation, varying between 4.25 and 6.5 kWh/m2/day (Skoplaki and Palyvos, 2009).

Temperature is another factor that conditions the normal operation of solar panels and the production of solar energy. Studies suggest that areas with average temperatures below 10 °C and above 20 °C are excluded (Pinto et al., 2016). The c-Si photovoltaic modules lose energy with a temperature increase above the standard test conditions (25°C) at the rate of 0.5% and 0.6% /°C, therefore it is not recommended to exceed the critical limit of 25°C. On the other hand, the greater the amount of relative humidity in an area, the greater the absorption of shortwave solar radiation by surface moisture, which decreases the total amount of incident solar irradiance usable by the solar panel (Pinto et al., 2016), (Wilma et al., 2013).

Many reservoirs, as is the case of the object of study of this work - Lake Sobradinho, are used for recreational uses, tourism activities, and navigation, in addition to contributing to the income of many families in the local community with fishing activities and fish farming. Therefore, some areas must be excluded in the process of identifying potential locations for the installation of floating photovoltaic solar plants, such as areas of fishing routes, fish hatcheries present in the lake, and tourist routes, such as, for example, the one used by the Vapor do Vinho.

The distance between the solar plant and the substations is another fundamental criterion when planning the installation of a photovoltaic plant. Because the construction costs of new transmission lines are generally very high and depend on the voltage level of the line and its length, the solar plant must be positioned as close as possible to transmission lines with load capacity. After 50 km of cabling length, the reactive power value becomes significant, due to the capacitive effect of the submarine cables, requiring this reactive power to be compensated at both ends of the cable (Bontempo et al., 2021).

Another important analysis is from the environmental aspect, as the use of this technology has the potential to cause negative environmental impacts, such as implications for the local aquatic flora and fauna, risk of water contamination by the use of chemicals during maintenance (Gorjian et al., 2021), possibility of change in evaporation rates in the watershed (Mathijssen et al., 2020) and risk of change in water quality due to leaching of heavy metals found in some materials of the system (Decree nº 9,957, 2006). However, as the entire length of the lake is included in the Environmental Protection Area of Sobradinho Lake by State Decree No. 9,957 (2006), and also taking into account CONAMA Resolution No. 302 of March 20, 2002, which establishes parameters, definitions, and limits of Permanent Preservation Areas for artificial reservoirs and the usage regime of surrounding areas (Rios & Duarte, 2002), no activity considered effective or potentially degrading can be implemented without prior consent from the environmental policy body of the State of Bahia, INEMA (Institute for the Environment and Water Resources). Therefore, the entire length of the lake is subject to the same environmental criteria.

Geographic Information System (GIS) for spatial analysis

The manipulation of information associated with a geospatial reference, or geographic coordinates is possible from a Geographic Information System (GIS). GIS can contribute to the capture, storage, verification, manipulation, and analysis of data related to positions on the earth's surface (Sánchez-Lozano et al., 2013). In addition, these systems make it possible to organize geographic data, making it easier to read the map and select the data needed for a specific project (Gherboudj and Ghedira, 2016).

There are two types of GIS data models, raster or vector. Raster models are represented by a mesh and each element is called a pixel, which contains information about the geographic location of the features. Vector model models store geographic objects as vectors, maintaining geometric properties and take the form of points, lines and polygons (Gherboudj and Ghedira, 2016).

The use of GIS can facilitate the selection of locations with high potential for solar energy production. With the help of this tool, geographic data (criteria maps) can be combined to obtain useful information for decision-making considering spatial distribution, identifying suitable locations for installing photovoltaic plants, more specifically for our study, floating photovoltaic plants.

Furthermore, with these information systems, it is possible to separate the data into several layers of themes and store them independently so that this information can be analyzed simply and quickly. This process also allows existing information through object typology to be related, to generate other information that could not be obtained otherwise (Thari et al., 2015).

It is possible to find works that used GIS as a tool to select locations for installing photovoltaic modules. For example, the use of maps combining terrain data, roof slope, and other environmental variables to build maps within a GIS environment and calculate the photovoltaic potential of rooftops in Hong Kong (Mahtta et al., 2014), the inclusion of devastated areas to calculate the potential using a filtering approach in a GIS environment in the United Arab Emirates (Uyan, 2014) and through the combination of Geographic Information Systems and multi-criteria analysis to obtain suitable locations for the development of large-scale solar photovoltaic projects in Peru (Sánchez-Lozano et al., 2013) and in Spain (Gherboudj and Ghedira, 2016).

Geographic Information System (GIS) for spatial analysis

Multiple-Criteria Decision Analysis (MCDA) corresponds to a set of systematic procedures to analyze complex decision problems where there are situations of doubt or conflict of information. One of these multi-criteria decision-making methods is the Analytic Hierarchy Process (AHP) and it can be used to analyze and support decisions that have multiple and even competing objectives (Şengül et al., 2014). According to Macedo et al. (2021), decisions on energy-related issues deal with attributes that are difficult to define and components that may involve quantitative and qualitative factors. Therefore, the method can contribute to decision-making processes to resolve the imprecision, ambiguity, and subjectivity of human judgment.

A study carried out in Turkey developed a multi-criteria decision support framework to classify renewable energy supply systems using the Fuzzy-TOPSIS method, which is a combination of fuzzy logic with the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) multi-criteria decision support method (Liu et al., 2014) used the fuzzy AHP method to propose the creation of a general sustainability index to evaluate renewable sources.

The AHP-TOPSIS fuzzy model consists of the union of two multicriteria decision support methods and was proposed by Trindade (Martins, 2017) for problems of multidimensional measurement of the innovative capacity of small and medium-sized companies. The model has two phases: fuzzy AHP and fuzzy TOPSIS. In the first step, the fuzzy AHP, the criteria, and sub-criteria are defined, the calculation of the fuzzy paired comparison matrices is performed, the consistency analysis of the fuzzy paired comparison matrices is performed and the weights of the criteria and sub-criteria of fuzzy AHP are obtained. In the second step, fuzzy TOPSIS, the evaluation matrices of the alternatives are built, as well as the definition of the positive and negative ideal solution (PIS and NIS) and the ranking definition based on the descending order of the values obtained by each alternative (Sengupta et al, 2018).

Material and methods

This work uses the methodology developed by Macedo et al. (2021), who used the method to identify potential locations for the installation of photovoltaic solar systems in the state of Pernambuco, in the Northeast region of Brazil. In this study, the methodology will be applied to identify sites with the potential for floating photovoltaic generation in Sobradinho Lake, which can be replicated in other water bodies.

The methodology has five steps, as shown in the flowchart in Figure 1. The first step is where the study area is defined. In Step 2, the criteria for the suitability of a floating photovoltaic plant are defined through expert analysis and bibliographic analysis. These factors included site characteristics, territorial restrictions, and exclusionary areas. In Step 3, the variables to be included in the GIS model are identified and data are collected. In Step 4, MDCA techniques are applied to the input data set so that the criteria and sub-criteria are weighted. Finally, in Step 5, the production and analysis of the map with the potential locations for the installation of photovoltaic systems takes place.

Step 1 - Study Area

Sobradinho Lake is the reservoir of the Sobradinho Hydroelectric Power Plant, located in the São Francisco River basin, involving areas of the municipalities of Casa Nova, Remanso, Pilão Arcado, Sento Sé, and Sobradinho, in the state of Bahia, Brazil. The reservoir measures approximately 320 km in length, has a water surface of 4,214 km², and a storage capacity of 34.1 billion cubic meters at its nominal height of 392.50 m (Resolution nº 302, 2002). The study area can be seen in Figure 2.

In the case of a larger CNT base radius, the heat flow of the system has to be larger. The heat flow of the (50.50)@(45,45) CNT with the largest.

Step 2 - Criteria definition

In this step, ArcGIS 10.3 (ESRI) and QGis (OSGeo 4W) software were used. For climate criteria, solar radiation maps were obtained from The National Solar Radiation Data (NSRDB) (Sengupta et al, 2018) and temperatures were obtained from the Global Climate and Weather Data (WorldClim).

For social criteria, fishing routes were obtained using GPS, tourist routes were obtained from the Transport Information and Maps Bank of the Executive Secretariat of the Ministry of Infrastructure (Faria and Morais, 2019) and fish farming areas were collected from data from the São Francisco and Parnaíba Valley Development Company, Codevasf (Phuangpornpitak and Tia, 2013). Regarding the location criterion, lake areas with a distance greater than 50 km from the substation were excluded.

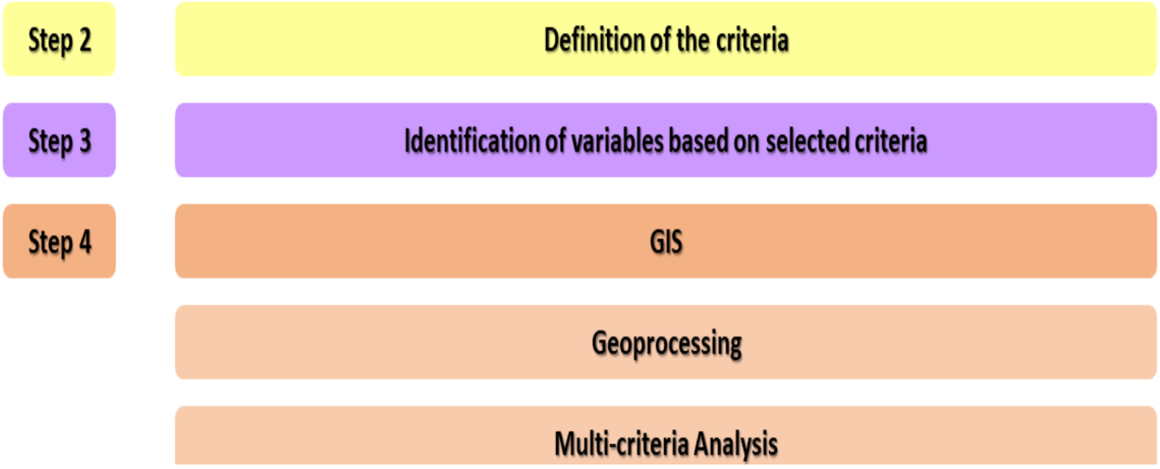
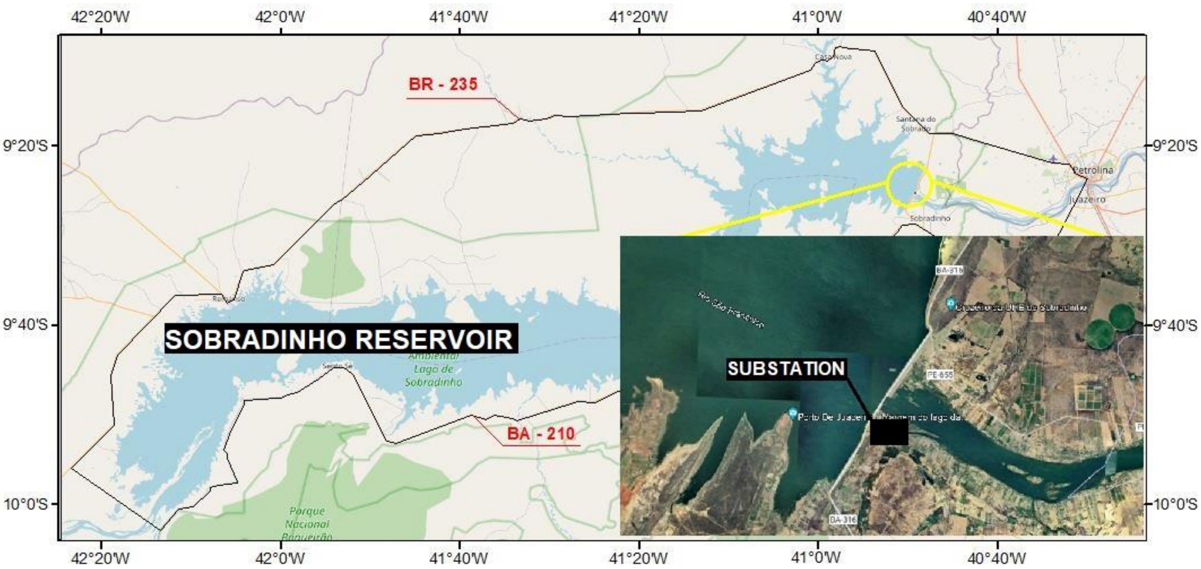


Figure 1: Methodology for selecting suitable floating systems locations.



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Fishing routes

The artisanal fishing routes in Sobradinho Lake were obtained from the survey carried out in 2017 by CHESF (São Francisco Hydroelectric Company) in the R&D program “Exploration of Solar Energy in Lakes of Hydroelectric Power Plants", where 4 GPS equipment were distributed to local fishermen to map artisanal fishing routes. From the georeferenced points, the trajectories were traced in the Google Earth software, as seen in Figure 3.

Tourist routes

The survey of commercially explored tourist navigation routes was carried out by the Transport Information and Maps Bank of the Executive Secretariat of the Ministry of Infrastructure (Faria and Morais, 2019). For this study, the route taken by the vessel Vapor do Vinho (Figure 4) was analyzed. It carries out an enotourism route through the lake to wineries in the region.

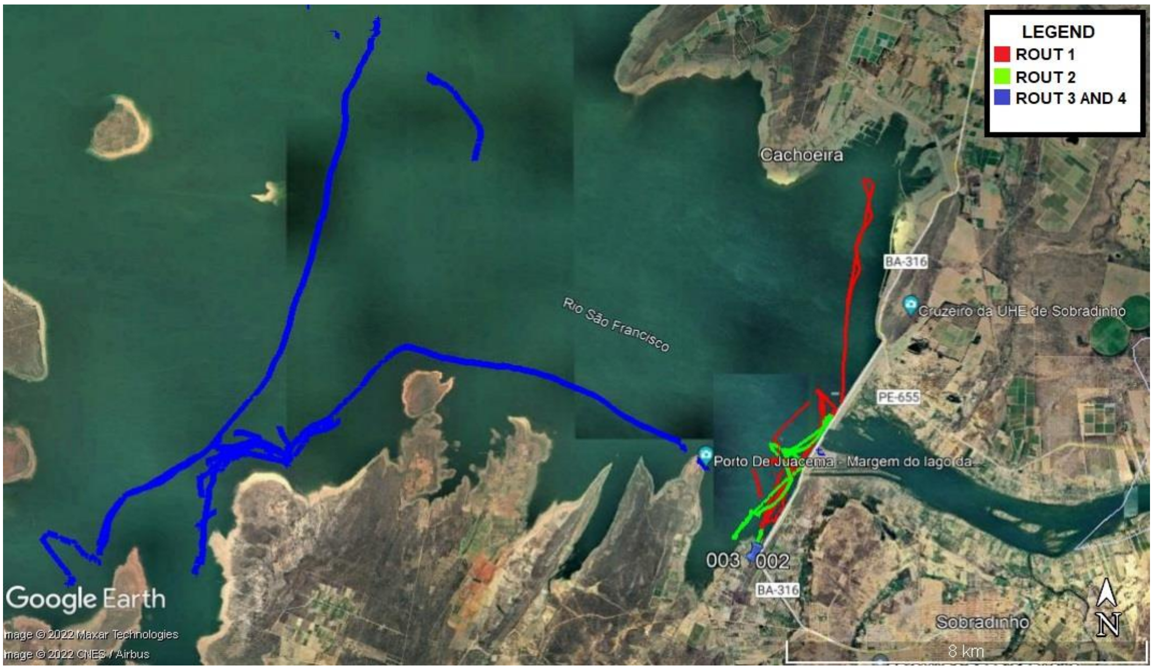

Figure 3: Artisanal fishing routes

Figure 4: Tourist navigation Vapor do Vinho

Fish farming areas

To survey fish farming areas, fish farming areas were collected data from the Company for the Development of the São Francisco and Parnaíba Valleys, Codevasf (Phuangpornpitak and Tia, 2013). These breeding sites can be seen in Figures 5.

Step 3 - Selection of criteria

The criteria were listed and submitted for approval by a group of experts in solar photovoltaic plants. After evaluation by these professionals, the criteria were separated into positive and negative indicators or restrictions. These indicators constitute the technical and environmental restrictions of the area under study.

The analysis was based on three criteria (climatic, socioeconomic, and technical-economic) and belonging to six factors or sub-criteria (direct solar radiation, temperature, fishing routes, tourist routes, fish farming areas, and distance to the substation). The criteria and factors were analyzed by specialists in the field of Electrical Engineering regarding their relevance in the implementation of floating photovoltaic plants. This analysis was performed using an online form (Figure 6) in which the specialist was able to compare a criterion and a sub-criterion regarding their importance to the others. In this step, ArcGIS 10.3 (ESRI) and QGis (OSGeo 4W) software were used. For climate criteria, solar radiation maps were obtained from The National Solar Radiation Data (NSRDB)

(Sengupta et al, 2018) and temperatures were obtained from the Global Climate and Weather Data (WorldClim).

Figure 5: Fish farming area

Step 3 - Selection of criteria

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Step 4 - GIS

Geoprocessing

In the geoprocessing stage, the structuring of the information obtained, the verification of the spatial data, and the editing of the base and database take place.

The selected criteria were modeled as layers and drawn as a raster map in a GIS environment. Thus, data that was previously vector was converted to raster format. Then, thematic maps were produced with the help of ArcGIS 10.3 software. Areas with restrictions, such as those used for fishing, tourism, and fish farming and areas with a distance greater than 50 km from the substation, were introduced in the first layers. These layers will be superimposed to obtain the map of restricted areas, which were eliminated from the total surface of the study.

Then, the layers containing the climatic criteria (solar radiation and temperature) were crossed with the layer of non-excluded areas, determining the areas with high potential for floating photovoltaic plants.

Multicriteria Analysis - Fuzzy AHP- TOPSIS

To use the AHP method, the scenario must be structured in hierarchical levels where the criteria and sub-criteria are defined to evaluate the technological options, and the expert analysis is required to define the importance of each criterion and sub-criterion from the comparison for the pair, according to the preference given between them. The importance of one attribute over the other is represented by fuzzy triangular numbers. These numbers are calculated based on the experts' judgment using linguistic terms based on the 9-level Saaty scale (Table 1) (Thari et al., 2015)

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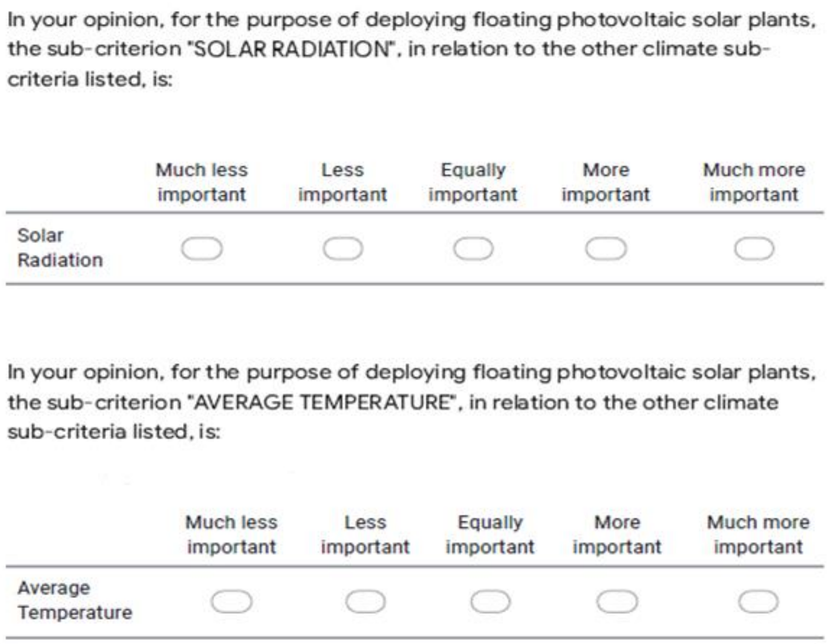

In your opinion, for the purpose of deploying floating photovoltaic solar plants, the sub-criterion "SOLAR RADIATION", in relation to the other climate sub-criteria listed, is:

	Much less important	Less important	Equally important	More important	Much more important
Solar Radiation					

In your opinion, for the purpose of deploying floating photovoltaic solar plants, the sub-criterion "AVERAGE TEMPERATURE", in relation to the other climate sub-criteria listed, is:

	Much less important	Less important	Equally important	More important	Much more important
Average Temperature					

Figure 6: Part of the online form applied to experts.

Table 1. Fundamental Saaty scale (Thari et al., 2015).

Numerical Scale	Verbal Scale	Explanation
1	Both elements are of equal importance	Both elements contribute to the property equally
3	Moderate importance of one element over the other	Experience and opinion favor one element over the other
5	Strong importance of one element over the other	An element is strongly favored
7	Very strong importance of one element over the other	One element is very strongly favored over the other
9	The extreme importance of one element over the other	An element is favored by at least an order of magnitude difference
2, 4, 6, 8	Intermediate values between adjacent opinions	Used as consensus values between opinions
Increment 0.1	Intermediate values at the finest graduation of 0.1	Used for finer gradations of opinions

The AHP-TOPSIS fuzzy method applies a fuzzification process, that is, by definition, when two attributes are considered equally important (importance level equal to 1 on the Saaty scale), the triangular fuzzy number (1, 1, 1) is used. So that the other levels of importance such as a triangular fuzzy number (a1, a2, a3) can be represented, all judgments are counted in each paired comparison and simple arithmetic operations are performed to define the minimum (a1), intermediate (a2) and maximum points (a3). After the experts' opinion, the paired comparison matrices of criteria and sub-criteria are set up (Figure 7) (Thari et al., 2015).

The consistency analysis of the fuzzy paired comparison matrices can be performed as in the classical AHP method because when the crisp matrix comparison (fixed real values) A is consistent, it means that the fuzzy comparison matrix $\tilde{A}$ is also consistent. The Consistency Ratio (CR) is used to estimate the consistency of paired comparisons (Equation 1).

$$CR = \frac{CI}{RI} \tag{1}$$

The consistency index of the pair comparison matrix (CI) is calculated from the ratio between the size of the matrix (n) and its largest eigenvalue (λmax), as shown in Equation 2:

$$CI = (\lambda_{max} - n)/(n-1) \qquad (2)$$

The random consistency index (RI) was empirically determined considering a sample of 500 randomly generated positive reciprocal matrices (García-Cascales and Lamata, 2012). The values assigned to RI by Saaty, according to the matrix order (n), are shown in Table 2.

$$\begin{array}{c|c}
 & \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\
\begin{array}{c} C_1 \\ C_2 \\ \vdots \\ C_m \end{array} &
\begin{bmatrix}
(1,1,1) & (1/a_{1[1,2]}, 1/a_{2[1,2]}, 1/a_{3[1,2]}) & \cdots & (1/a_{1[1,n]}, 1/a_{2[1,n]}, 1/a_{3[1,n]}) \\
(1/a_{3[1,2]}, 1/a_{2[1,2]}, 1/a_{1[1,2]}) & (1,1,1) & \vdots & \tilde{x}_{2n} \\
\vdots & \vdots & \vdots & \vdots \\
(1/a_{3[1,n]}, 1/a_{2[1,n]}, 1/a_{1[1,n]}) & \cdots & \cdots & (1,1,1)
\end{bmatrix}
\end{array}$$

Figure 7: Pairwise Comparison Matrix *(Thari et al., 2015)..*

Table 2. Empirical values of the random consistency index (RI) (Tahri et al., 2015).

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

As a rule, when RC ≤ 0.10 consistency is accepted, otherwise it is necessary to revise the comparison matrix. In case of acceptance, weights can be obtained.

Criteria weights are determined by pairwise comparing the criteria. A total of (n-1) comparisons are required. The weights are obtained by Equation 3 [39]:

$$(w_{C_{ia}}, w_{C_{ib}}, w_{C_{ic}}) = \left[\frac{C_{ia}}{\sum_{i=1}^{n} C_{ic}}, \frac{C_{ib}}{\sum_{i=1}^{n} C_{ib}}, \frac{C_{ic}}{\sum_{i=1}^{n} C_{ia}}\right]$$

Where: wci represents the weight of the criteria for the expert i, i = 1, 2, 3, and ci the comparison between the criteria for the fuzzy pairs.

In the Fuzzy TOPSIS phase, the values of each criterion and sub-criterion are provided by the decision-makers, in the process of evaluating each technology. For this vague and subjective classification, it is common to use the five-point Likert scale, in which each point represents a level of maturity, and consequently, each level receives a fuzzy triangular numerical value (Table 3).

Table 3. Linguistic terms and their respective numerical values [07]

Description	Maturity level
Very Low (VL)	1
Low (L)	2
Moderate (M)	3
High (H)	4
Very High (VH)	5

From the linguistic terms and the respective fuzzy values, the decision matrix $\tilde{D}$ is constructed (Figure 8). In the matrix $\tilde{D}$, xij represents the value of alternative Ai concerning criterion cj, W = [w1, w2, . . ., w10] is the weight vector associated with the criteria, Am is the alternatives and xmn are the values indicated by the decision-makers. As a rule, when RC ≤ 0.10.

$$\tilde{D} = \begin{array}{c|c} & \begin{array}{cccc} w_1 & w_2 & \cdots & w_n \\ c_1 & c_2 & \cdots & c_n \end{array} \\ \hline \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \end{array} \qquad i = 1, 2, \ldots, m; j = 1,2, \ldots, n$$

Figure 8. Decision matrix - Fuzzy TOPSIS method [07]

The matrix $\tilde{D}$ is normalized so that the scale is the same for all criteria (Equation 4). Criteria weights in decision-making problems do not have the same average and do not all have the same importance. The weighted normalized value vij is calculated by Equation 5.

$$\bar{n}_{ij}, = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m}(x_{ij})^2}} \quad j = 1, 2, \ldots, n; i = 1, 2, \ldots, m \quad (4)$$

$$\underline{v}_{ij}, = w_{ij} \otimes \underline{n}_{ij} \quad j = 1, 2, \ldots, n; i = 1, 2, \ldots, m \quad (5)$$

According to Equation 6 and Equation 7, respectively.

$$A^{+} = \{\tilde{v}_1^{+}, \tilde{v}_2^{+}, \ldots, \tilde{v}_m^{+}\} \quad (6)$$

$$A^{-} = \{\tilde{v}_1^{-}, \tilde{v}_2^{-}, \ldots, \tilde{v}_m^{-}\} \quad (7)$$

Where and $\tilde{v}_1^{+} = (1, 1, 1)$ and $\tilde{v}_1^{-} = (0, 0, 0)$. The distance to PIS (D+) and NIS (D-) is calculated by Equation 8 and Equation 9, respectively.

$$D_i^{+} = \sum_{j=1}^{n} d_v \left(\bar{v}_{ij}, \tilde{v}_j^{+}\right) \quad (8)$$

$$D_i^{+} = \sum_{j=1}^{n} d_v \left(\bar{v}_{ij}, \tilde{v}_j^{+}\right) \quad (9)$$

Finally, the CCi approximation coefficients are calculated for each of the evaluated alternatives, according to Equation 10. The value of CCi varies between 0 and 1. The closer to 1, the higher the priority of the alternative. With this, the final ranking of the alternatives evaluated with the CCi values is defined.

$$\mathrm{CCi} = (\mathrm{D_i^{-}})/(\mathrm{D_i^{+}} + \mathrm{D_i^{-}}) \quad (10)$$

Results and discussion

This section presents the results of the potential sites for sustainable development of solar photovoltaic plants appropriate to the reality in Sobradinho Lake.

4.1. Classification of input criteria

The five-point Likert scale was used to classify the sub-criteria. The maturity levels considered were: 1 - very low; 2 - low; 3 - moderate; 4 - high; and 5 - very high (Table 4).

As shown in Table 4, The climatic criterion was considered the most important in the evaluation of sites with potential for the development of photovoltaic projects, since even if the studied site presents all the criteria at optimal levels, the solar radiation is not satisfactory, this area will not be a good place to install a photovoltaic plant. Thus, the sub-criterion direct normal irradiation followed by the average temperature presented the highest weight coefficients in this study. The socio-economic and location criteria obtained lower weight coefficients.

Grades were assigned between the values of 1 to 5, following the Likert scale. Regarding climatic criteria, the higher the irradiation and temperature, the higher the score, that is, the more favorable the area is for project implementation. Although the temperature of 25º is considered the critical temperature by the manufacturers, it is at this temperature that the highest efficiency occurs in the system. Regarding the socioeconomic criterion, regardless of the sub-criterion, the score decreases as one approaches the fishing routes, tourism, or fish farming areas, as these areas are not favorable for the implementation of the plants. Regarding the location criterion, the opposite occurs, the closer to the substation, the higher the score received by the location. As the construction costs of new transmission lines are, in general, very high and depend on the voltage level of the line and its length, the solar plant must be positioned as close as possible to transmission lines with load capacity.

Geoprocessing

First, a map of direct solar radiation was prepared, based on the data from NSRDB (Figure 9).

Based on the input data, maps were prepared for the other selected criteria: average annual temperature (Figure 10), distance to the substation (Figure 11), distance from fishing routes (Figure 12), distance from fish farming areas (Figure 13) and distance from tourist routes (Figure 14).

Multicriteria analysis – Fuzzy AHP-TOPSIS

From the results obtained in the previous step, it was possible to rank a list of criteria and sub-criteria for the application of the model.

Fuzzy AHP

The criteria and sub-criteria were ranked based on the experts' assessment, as shown in Table 5.

After the decision rule for each scenario was established, the pairwise comparison between the criteria was performed. The consistency ratio (CR) and the values found for the highest eigenvalue (λmax) and the judgment consistency index (CI) are shown in Table 06. As the CR value was equal to 0.10, the estimate of the sub-criteria values was also confirmed as consistent. Final weights of sub-criteria are shown in Table 7.

Fuzzy TOPSIS

After defining the weights of the criteria that influence the location where the floating plant will be implemented, the alternatives were evaluated using the fuzzy TOPSIS method. The evaluation matrix was normalized, resulting in the normalized and weighted matrix $\tilde{V}$, from Equation 4 and Equation 5. Then, the distances between these data and the ideal positive and negative fuzzy solutions were calculated, which are the maximum and minimum values of each criterion and sub-criterion. After this step, the A+ and A− distance matrices were generated, through equations 6 and 7, respectively, and, finally, the approximation coefficient (Cci) of the criteria and sub-criteria was calculated. The results can be analyzed in Table 08 and Table 9. The best alternatives according to CCi are in descending order. The results defined with the referred coefficient will be counted in ArcGis 10.3.

Table 4. Classification of criteria and sub-criteria by the Fuzzy AHP-TOPSIS method.

Criteria	Labels	Sub-Criteria	Classes	Grades
Climatic	C1	Direct Normal Irradiation (kWh/m2·day)	< 5.0	1
			5.0–5.5	2
			5.5–6.0	3
			6.0–6.5	4
			> 6.5	5
	C2	Average Temperature (ºC)	<13	1
			13-15	2
			15-18	3
			18-21	4
			>21	5
Socioeconomic	S1	Fishing routes (m)	0 – 5	1
			5 – 10	2
			10 – 15	3
			15 – 20	4
			> 20	5
	S2	Fish farming areas (m)	0 – 2	1
			2 – 4	2
			4 – 6	3
			6 – 10	4
			> 10	5
	S3	Tourist routes (m)	0 – 5	1
			5 – 10	2
			10 – 15	3
			15 – 20	4
			> 20	5

			0 – 10	5
			10 – 20	4
Location	L1	Distance to substation (km)	20 – 30	3
			30 – 40	2
			> 40	1

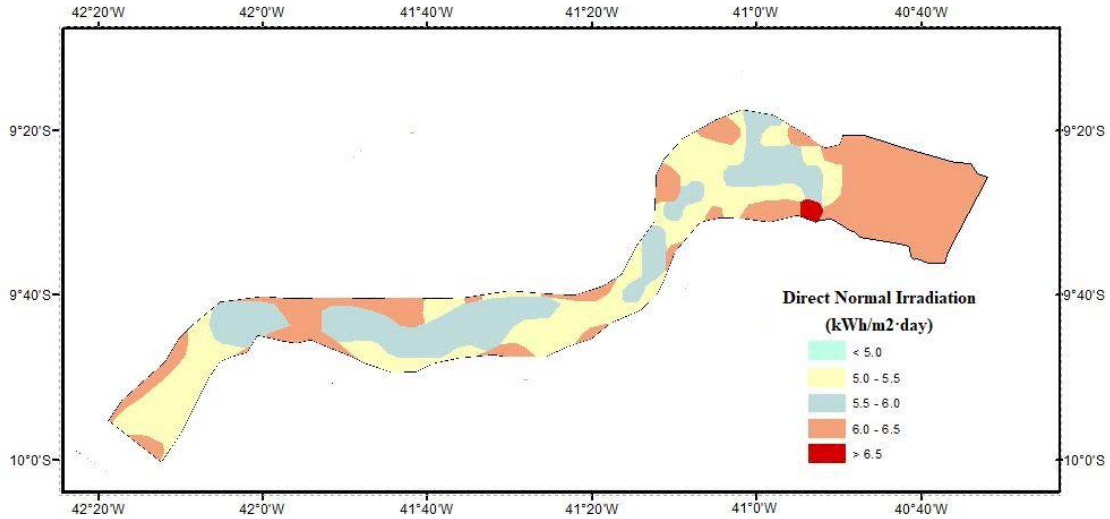

Figure 9. Map of direct solar radiation

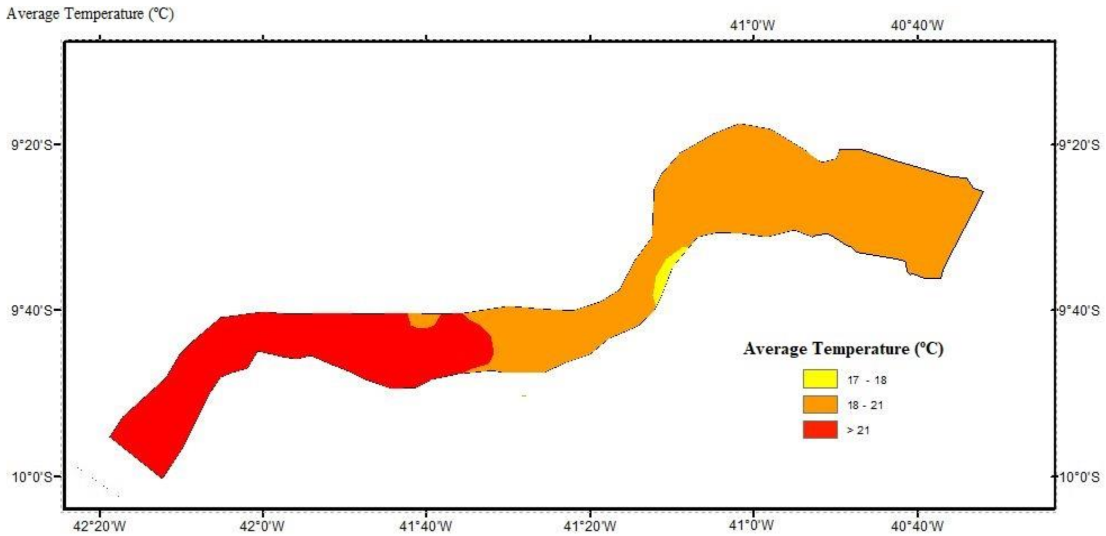

Figure 10. Map of average annual temperature.

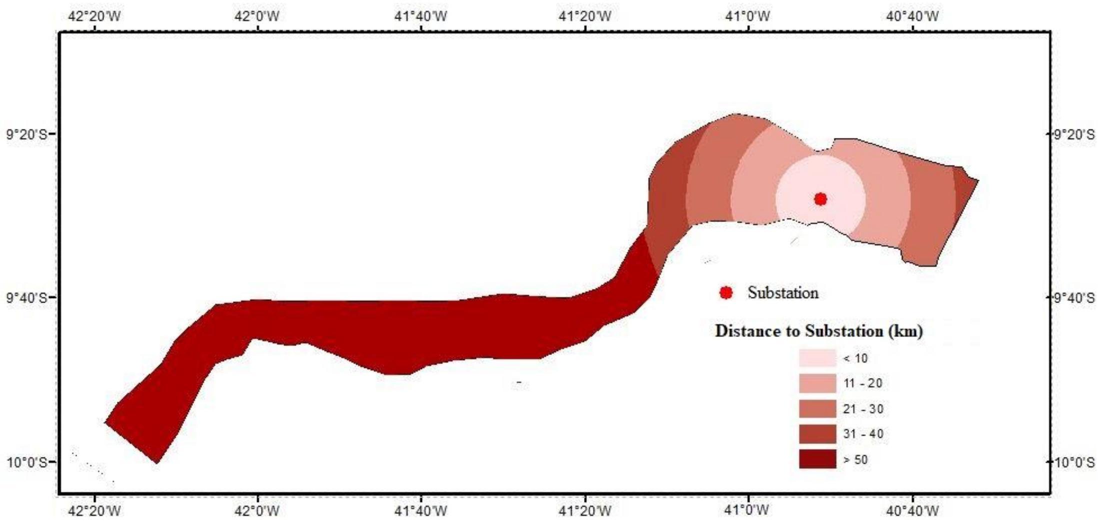

Figure 11. Distance to substation.

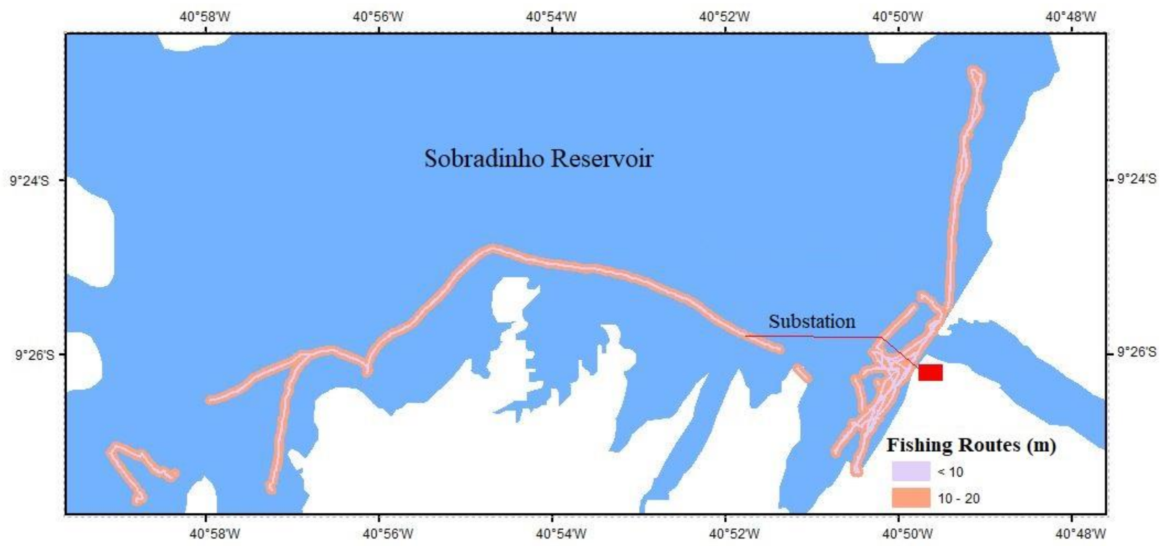

Figure 12. Distance from fishing routes.

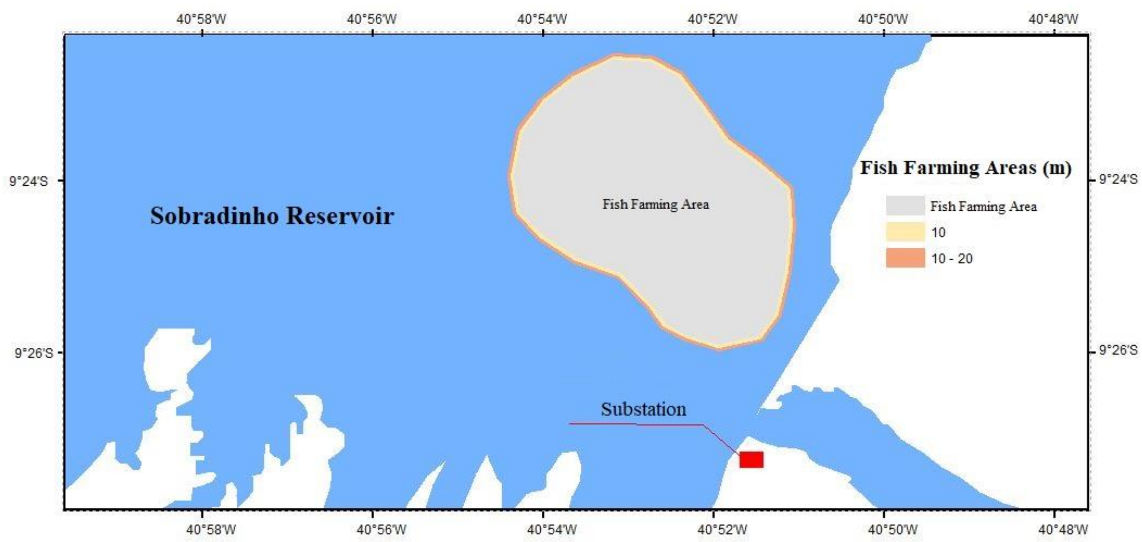

Figure 13. Distance from fish farming areas.

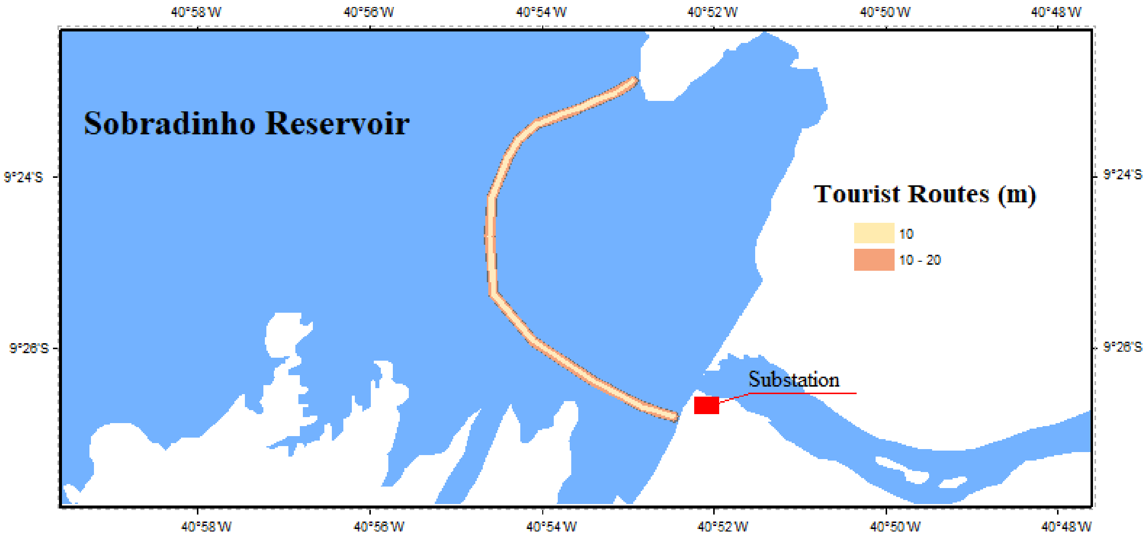

Figure 14. Distance from tourist routes.

Table 5. Classification of criteria and subcriteria using the Fuzzy AHP-TOPSIS method.

Expert	Order of importance of criteria
1	C1 > C2 > S1.> S2 = S3 > L1
2	C1 > C2 > S1= S2 = S3 = L1
3	C1 > C2 > S1.> S2 = S3 > L1

Table 6. Consistency ratio of criteria matrices.

		RC	λmax	IC
Climatic	0.464			
Socioeconomic	0.172	0.10	6.56	0.11
Location	0.364			

Table 7. Criteria weights using the Fuzzy AHP method.

Criteria	Weight
Climatic	0.464
Socioeconômic	0.172
Location	0.364

Table 8. Distance from criteria for PIS (D+), NIS (D-), and CCi approximation coefficients.

Dimension	di+	di-	CCi	Classification
Climatic	0.091	0.082	0.772	1
Socioeconomic	0.120	0.047	0.112	3
Location	0.021	0.099	0.238	2

Table 9. Distance from sub-criteria for PIS (D+), NIS (D-), and CCi approximation coefficients.

Sub-criterion	di+	di-	CCi	Classification
C1	4.547	5.001	0.477	1
C2	4.223	4.907	0.456	2
S1	1.442	2.826	0.227	5
S2	3.201	4.231	0.331	4
S3	1.357	2.004	0.212	6
L1	3.221	3.927	0.382	3

Results of the fuzzy AHP-TOPSIS method

The fuzzy-AHP method was used to calculate the pairwise comparison matrix. The decision data were organized hierarchically after discussions with specialists in the area regarding the specificity of the region. The results of the paired comparisons of this study are acceptable and the values are consistent since the consistency ratio (CR) does not exceed the value of 0.10.

Based on the analysis of the weights of the criteria and sub-criteria by the fuzzy TOPSIS method, it can be noted that the climatic criterion is the most dominant with a weight of 47%. This statement is correct because the production of electrical energy is directly linked to the amount of solar irradiation. Therefore, to be competitive in the solar market, suitable locations for photovoltaic plants must be in well-irradiated locations.

Location is the second most important criterion in AHP-TOPSIS fuzzy analysis. This is understandable as the costs of building new transmission lines are generally very high and depend on the voltage level of the line and its length. Therefore, it is more feasible, both technically and financially, for the solar plant to be positioned as close as possible to transmission lines with load capacity. The weight of the location criterion is 36%.

The socioeconomic criterion was the least important, with a weight of 17%. This can be justified by the fact that the routes and breeding sites can be diverted, and the routes do not occupy as much space in the lake area.

Multicriteria analysis – Fuzzy AHP-TOPSIS

The input data used in the GIS model needed to undergo raster processing and spatial analysis operations for the implementation of integrated multi-criteria analysis in ArcGIS Software 10.3.

From these operations, six input layers were, used in the spatial analysis: direct solar radiation and temperature, distance from fishing and tourism routes, distance from fish farming areas, and distance from the substation.

The Weighted Sum tool available in the Spatial Analyst ArcGIS 10.3 extension was used to combine these six layers of inputs and assign them the weights defined by the AHP-TOPSIS fuzzy analysis, thus obtaining the most suitable locations for installing floating photovoltaic plants. If necessary, this model can be modified using different criteria or weights, which facilitates the replication of the method for other studies. The result was a map of the areas that met all the conditions and criteria established (Figure 15). The resulting potentials were classified into four categories: Very High, High, Medium, and Low.

The areas with high or medium potential when added together represent a total of 24.04% of the total lake area. It is important to point out that the estimates should not be restricted to the criteria evaluated in this study. An economic evaluation is essential, given that this criterion is fundamental for investment planning. As a result, a more detailed analysis of this criterion is suggested to analyze possible flaws in the methodology. Table 10 shows the areas of each potential class and their percentages of the total area of the Sobradinho Dam.

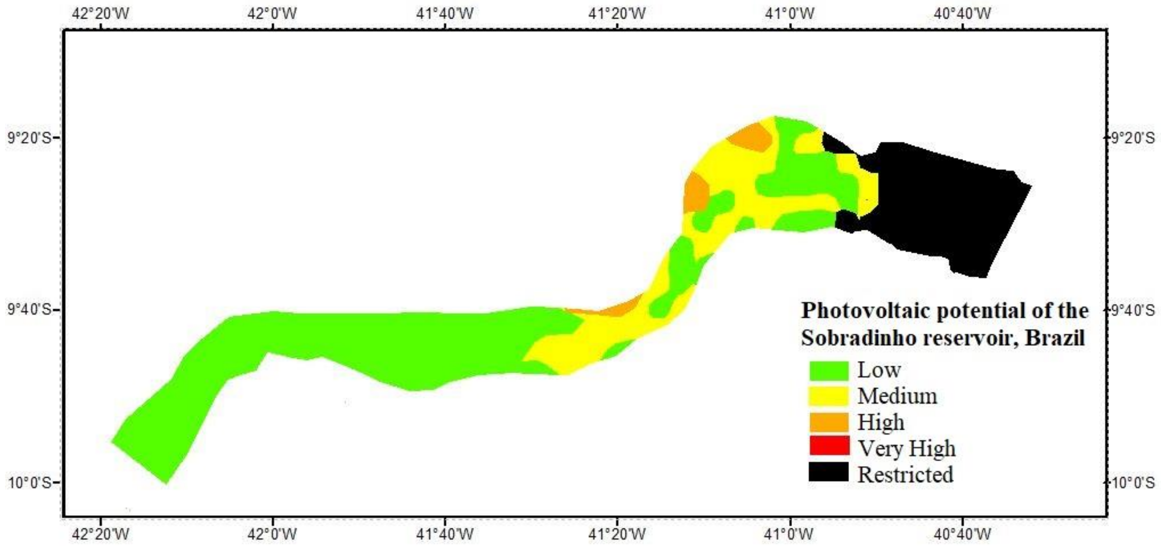

Figure 15. Locations with potential for installation of floating photovoltaic plants.

Table 10. Areas of each potential class and their percentages about the total área.

Potential	Color on the map	Area (km2)	Area (%)
Very High	Red	0.00	0.00
High	Orange	110.35	3.43
Medium	Yellow	663.50	20.61
Low	Green	1735.80	53.92
Restricted	Black	709.42	22.04

The analysis of various methods for selecting floating photovoltaic (FPV) system locations reveals complementary approaches with different emphases. The methodology applied at Lake Sobradinho, combining multi-criteria analysis with GIS and techniques such as Fuzzy AHP-TOPSIS, offers a robust quantitative approach for mapping and weighting suitable areas. In contrast, the study by Piana et al. (2021) on artificial mountain lakes proposes a qualitative checklist that emphasizes identifying difficulties and means of remediation, highlighting the importance of dialogue among diverse stakeholders. Both methodologies converge in recognizing that site selection should transcend purely economic and energy yield considerations.

Climatic factors, especially solar radiation and temperature, received high priority in the Lake Sobradinho study, aligning with observations by Sulaeman et al. (2021) regarding the high solar irradiation potential in Brazil, including the Amazon region.

Regarding socioeconomic and environmental aspects, the Lake Sobradinho study explicitly considered the impact on pre-existing activities such as fishing, tourism, and fish farming. Although these criteria received less weight compared to climatic ones, various studies (Sulaeman et al., 2021; Piana et al., 2021; Ma et al., 2021; Nobre et al., 2023) emphasize their relevance for public acceptance and social viability of projects. Sulaeman et al. (2021) note that appropriate FPV designs can facilitate local fishing and coexistence with aquatic life. Benjamins et al. (2024) point out that environmental impact assessments (EIA) and social impact assessments (SIA) are crucial, although the scarcity of information on FPV impacts, particularly in marine environments, represents a significant challenge.

Technical-economic criteria, such as distance to electrical substations, were considered in the Lake Sobradinho study primarily from the perspective of grid connection. Other studies expand this analysis to include technical-economic performance of systems and integration with existing infrastructure. The synergy with hydroelectric dams in reservoirs is frequently highlighted as a means to increase efficiency, reliability, and flexibility of the electrical system.

Although the present study did not directly evaluate impacts on water quality in the site selection phase, research such as that by Ma et al. (2021) on Lake Oostvoornse identified significant reduction in light intensity under FPV systems (73-100%). The potential for such impacts could influence the weighting of criteria in future studies or in the mitigation phase.

Conclusions

The criteria chosen for the analysis of sites with potential for the implementation of floating systems were classified into three categories: climatic, socioeconomic, and location. The methodology used in the study combines GIS with a multi-criteria decision analysis method (fuzzy AHP-TOPSIS) to identify locations with the potential for fluctuating photovoltaic generation. This combination allows a GIS to be used to collect and organize the information to be provided to the AHP. The case study using the proposed methodology allowed us to conclude that Sobradinho Lake can be considered as an alternative for the exploration of the floating solar resource. The sites with high or medium potential when added together represent a total of 24.04% of the total lake area. In the multicriteria decision analysis method (fuzzy AHP-TOPSIS), different criteria or weights can be used, which facilitates the replication of the method for other studies.

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