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ANALYSIS TO DETERMINE THE MOST SUITABLE LOCATION FOR A PHOTOVOLTAIC SOLAR PLANT USING COPPE-COSENZA METHOD: CASE STUDY RIO DE JANEIRO – BRAZIL

Marco Pereira de Souza*[1], Luis Claudio Bernardo Moura[1], Carlos Alberto Nunes Cosenza[1], Carlos Navarro Fontanillas Brasil[1], Harvey José Santos Ribeiro Cosenza[2], Sílvio de Macedo Amaral[1] and Silvio Montes Pereira Dias[1]

[1]Universidade Federal do Rio de Janeiro (UFRJ), COPPE
[2]Universidade Federal Fluminense (UFF)

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Corresponding author:
Marco Pereira de Souza

ABSTRACT

Photovoltaic solar energy has becoming a viable and non-polluting alternative for generating electricity. In the light of this fact, this study aims to find the most suitable locations for a photovoltaic solar plant in the State of Rio de Janeiro, Brazil, considering criteria ranging from environmental, technical to economic ones. The fuzzy logic using the COPPE-COSENZA model was used to guide the generation of the criteria that were applied in the GIS (Geographic Information System).The review of articles using was used to determine selected criteria. The availability of each of the criteria combined with their relative importance generated a map of the most suitable regions for the location of the photovoltaic solar plant. The results show that the state of Rio de Janeiro has a great potential for photovoltaic solar energy generation, especially in the north coast, near the city of Campos dos Goytacazes.

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INTRODUÇÃO

Singh (2002) states that energy is a primary factor for the development and improvement of the quality oflife of the societies and, according to Goldemberg (2003), the increase in demand and consumption of electricity is caused by technological progress and the development of humanity. Consequently, obtaining this resource in a sustainable and competitive manner is crucial (TSOUTSOS *et. al.* 2005). According to Pereira *et al.* (2006), the increase of energy demand, thereduced supply of conventional fuels and the growing environmental concerns are incentives to research and develop alternatives less pollutant and renewable as energy sources. The World Bank (2019), through a reportavailable on its website, states that CO_2 from electricity generation, is a major contributor to climate change, including in Brazil. The UN (United Nations) said, in the Paris Agreement, that investing in renewable energy to cut down fossil fuel use is the best way to reduce greenhouse gas emissions and keep global temperaturerising below 1.5^{o}C, levels prior to the industrial revolution (UN, 2015). Conforming to Panwar (2011), the energy sources are divided into three types: fossil fuels, renewable and nuclear.

Renewable energy is usually defined as energy that can be "replenished" easily by nature in a short time (MIRHOSSEINI *et al.*, 2011). Nuclear power is mentioned as a "clean" source of electricity because it does not emit greenhouse gases into the atmosphere. However, it has not been well accepted by society because of the associated risks (leakage and consequently contamination by the radioactive material) there is also the storage problem generated by the radioactive waste (PEREIRA *et. al*., 2006). The EPE (Empresa de PesquisaEnergética -Energy Research Company) states that power generation through hydroelectric power, composing about 65% of the Brazilian energy matrix (EPE, 2018 - A) has itsunexplored potential mostly in the Northern Region of Brazil at the Amazon forest, which brings challenges, mainly regards environmental issues (EPE 2018 - B). Solar energy stands out in this scenario because it can be found anywhere and makes up 99.8% of all energy that reaches the surface of the Earth, making it an accessible and inexhaustible energy source (RAMEDANI *et al.*, 2013, AL -HAMISI *et al.*, 2013 and JAIN R, 2009). Thirugnanasambandam *et al.* (2009) adds that if only 0.1% of this energy is converted into electricity at a 10% efficiency rate, this amount would be enough to supply the planet's demand several times. The two main ways to generate energy from the solar source are through thermal processes (concentrated solar energy) or through photovoltaic panels (ASAKEREH *et al.*, 2014). It should be noted that concentrated solar plants need very specific conditions that, in the Brazilian case, are found only in the semiarid region (MARTINS, 2012). According to IRENA (International Rewable Energy Agency), photovoltaic solar energy is becoming increasingly competitive due to its cost reduction (IRENA, 2018). As a matter of fact,the costs of photovoltaic systems have fallen more than 100 times since 1950, and between 1980 and 2013 there was a reduction of approximately 21.5% (NEMET, 2006 and EPE 2018 - C). Investment costs in photovoltaic systems are expected to decrease by 30% between 2020 and 2050 (EPE 2018 - C) and, according to IRENA (2018), large photovoltaic plants are expected to generate electricity by 2020 at a cost of approximately $ 0.06 per kwh, competing with traditional power sources. Brazil, in 2018, had only 0.13% electricity generated via solar power (EPE, 2018 - A), although it´spotential is considerably higher than in the northern hemisphere countries, when compared at irradiation levels (MARTINS *et al.*, 2007). It is worth to highlightthat the electricity demand will grow about 200% by 2050 in Brazil (EPE, 2018 - C) and that one of the ways to supply this demand is through diversification of its energy matrix (BRIGNOL *et al.*, 2014).

According to the CEPERJ Foundation website (Foundation for Statistics, Research and Training of Public Employees of the Rio de Janeiro State), Rio de Janeiro has an area of 43,752.8 km², being the twenty-fourth Brazilian state in territorial extension. It is part of the Southeast Region, being considered the most developed in the country and has territorial limits with all the states that compose this region (CEPERJ, 2019). Its population is, according to the IBGE (Brazilian Institute of Geography and Statistics) website, 17.2 million people (IBGE, 2019). Regarding its economy, the FIRJAN (Federation of Industries of the State of Rio de Janeiro) states that GDP per capita is 25% higher than the Brazilian average (FIRJAN, 2018). Based on this reality, it is evident the need to Research moreabout photovoltaic energy,so this article aims to contribute to this end. In order to know the most suitable location for a photovoltaic solar plant inside Rio de Janeiro State, this paper will use the AHP (Analytic Hierarchy Process) method, fuzzy logic and GIS (Geographic Information Systems) as tools. This choice is justified because thesearch of suitable location of photovoltaic solar plants has been the subject of several studies and GIS in combination with multicriteria decision analysis tools are the mostused ways to achieve these goals (ASAKEREH *et al.*, 2017).

MATERIALS AND METHODS

To determine the location of a photovoltaic solar plant in the state of Rio de Janeiro, the following steps will be followed:

- Review academic papers for the selection of localization criteria to be analyzed.
- Determine the restriction zones, places where the solar plant cannot be located.
- Interview specialists to determine the degree of importance of the selected location factors.
- Apply Coppe-Cosenza method to determine the most suitable locations for the PV plant.
- Generate de SIG map with those locations.

Defining the location of a photovoltaic solar plant is no simple task. According to San Cristóbal (2012), decision-making involves identifying and choosing alternatives to find the best solution. This requiresconsidering a diversity of factors such as: collection of the information, alternatives, values, and preferences available at any given time. In some cases, the locations with the highest incidence of sunlight are not the most suitable ones because there are other factors that play a significant role in the location of those plants. Therefore, it is necessary to take into account the complexity of the process, which involves social, environmental and economic factors. So, defining the location of the solar plant is one of the key factors to take into consideration and maximize its performance (CHEN et. Al. 2014, VON HAAREN *et al.* 2011 and YUN-NA *et al.* 2013). Thus, it is evident the need to follow the steps mentioned aboveto define the most suitable location for photovoltaic plant in the state of Rio de Janeiro.

COPPE-COSENZA Method

According to Toledo (2004), the COPPE-Cosenza model is a resource allocation model that allows the hierarchy of alternatives. The model proposed by Cosenza introduces the basic notions for evaluating locational alternatives using fuzzy sets. The model's focal point is to compare the demand that a given sector has with the territorial supply of general factors (ROSSI, 2013). Consider $F = \{f_i \mid 1, ..., n\}$ as a finite set of attributes / factors generically denoted as f. So the fuzzy set A in f is a set of ordered pairs $A = (f, \mu_A (f) \mid f \in r)$, where A is the fuzzy representation of the Request Matrix $A = (\mu_{ij})_{hxm}$ and, μ_f is the function of pertinence representing the degree of importance of the factors, which can be: Critical, Conditioning, Not Restrictive and Irrelevant. Similarly, let $B = \{(f, \mu_B (f)) f \in F\}$ where B is the fuzzy representation of the Availability Matrix B, where μ_B (f) is a membership function representing the levels of factors made available by the alternatives: Superior, Good, Regular and Weak. The next step is an operation between the matrices. The matrix $C = A \otimes B = (c_{ik})_{hxm}$ is the representative of the aggregate of the Request / Availability comparisons for each factor. Then the product $a_{ij} \otimes b_{jk} = c_{ik}$. This matriz generates a coefficient that:

- $\delta_{ik} = 1$: alternative k meets the requirement at the desired level.
- $\delta_{ik} < 1$: the alternative k doesn´t achieve the desired conditions.
- $\delta_{ik} > 1$: alternative k offers more conditions than required.

GIS

A GIS is a system designed to work with georeferenced data. These systems are used for storing, managing, analyzing and displaying geographically referenced data and it is valuable tool for planning and decision making in multiple contexts in which georeferenced data plays a relevant role (SANCHEZ-LOZANO *et al.*, 2014). Besides that, it has been increasingly used to determine the optimal location of renewable energy projects (LEWIS *et al.*, 2014). That is, a GIS can be defined as a set of tools for analyzing and editing maps and spatial data in general. In this digital map there is a georeferenced database for each generated layer (GARCÍA-CASCALES *et al.*, 2013). For this study the software used was QGIS.

Article Review and Selection of the Location Factors: Twenty academic articlesrelated to the most suitable location for photovoltaic solar plants were reviewed. It is important to notice that the combination of GIS and the AHP was the most used followed by the other methods like PROMETHEE and ELECTRE, a trend confirmed by Pohekar (2004). The choice of the criteria to locate the photovoltaic plant in the state of Rio de Janeiro was defined based on the survey of the reviewed articles. If the criteria appear in more than 8 of the analyzed articles it will be considered as a valid one. The other factors, that appear less than 8 pappers, will be treated as local peculiarities, such as dust for desert locations or the presence of water resources. Figure 1 shows the accounting of location criteria observed in the articles.

In this way, the following are the chosen location factors, namely: solar irradiation, average temperature, distante to transmission lines, distante to transport links, distante to urban centers, slope, azimuthand land use.

Restriction Zones

The first step is to analyze the regions in which the solar plant cannot be located, based on the restriction zones (protected areas; forests and woods; indigenous territories; quilombola territories; urban areas; water bodies). Figure 2 shows these restriction zones.

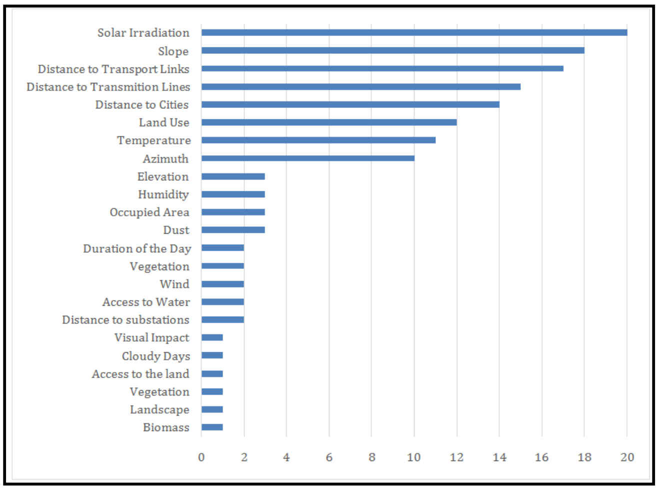

Fig. 1. Accounting of the Location Criteria- Source: The Authors

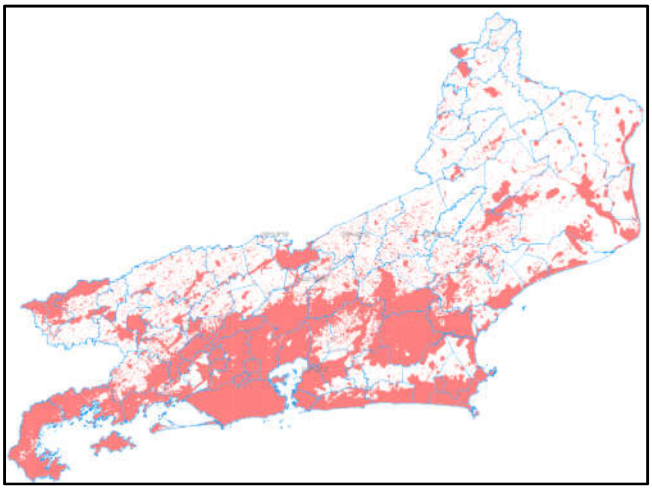

Fig. 2. Restriction Zones – Source: The Authors

Table 1. Interviews – Source: The Authors

	Solar Irradiation	Average Temperature	Distance to Transmission Lines	Distance to Transport Links	Distance to Urban Centers	Slope	Azimuth	Land Use
Critical	10	2	6	3	1	5	2	0
Conditioning	3	3	7	4	1	3	5	5
Not Restrictive	1	8	0	5	7	4	5	5
Irrelevant	0	1	1	2	5	2	2	4

Table 2. Classes for the Factors– Source: The Authors

Factor	Classes
Solar Irradiation	Higher for X> = 4900; Good for 4900> X> = 4650; Set to 4650> X> = 4400; Weak for X <4400, where X = mean global irradiation (Wh / m2.day)
AverageTemperature	Higher for X <= 15ºC; Good for 15ºC <X <= 20ºC; Adjustto 20ºC <X <= 25ºC; Weakto X> 25ºC, where X = annualaveragetemperature in degrees celsius
DistancetoTransmission Lines	Higher for 0 <X <= 5km; Good for 5 <X <= 10km; Regular for 10 <X <= 15km; Weak for X> 15Km, where X = Distanceoftransmissionlines
DistancetoTransport Links	Higher for 0 <X <= 2.5km; Good for 2.5 <X <= 5km; Regular for 5 <X <= 7.5km; Weak for 7.5> X, where x = distancefromhighways
DistancetoUrban Centers	Higher for 0 <X <= 5km; Good for 5 <X <= 10km; Regular for 10 <X <= 15km; Weak for X> 15Km, where x = distancefromurbanareas
Slope	Higher for 0 <X <= 2; Good for 2 <X <= 5; Set to 5 <X <= 10; Weak for X> 10, where x = slope (%) oftheterrain
Azimuth	Higher for slope<2% orazimuth = north; Good for azimuth = northeastornorthwest; Regular for azimuth = eastorwest; Weaktoazimuth = south, southeastorsouthwest
Land Use	Higher for agriculturalaptitude = VeryLow; Good for agriculturalaptitude = Low; Regular for agriculturalsuitability = Mediumto High; Poor for agricultural fitness = High

Analyzing figure 2, it can be seen that, according to the selected criteria to restrict the location of the photovoltaic solar plant, the impossibility of locating it in most of the metropolitan region of Rio de Janeiro, due to the high degree of urbanization, another factor that restrict several areas is the protected zones.

Interviews: The questionnaires, applied on specialists in photovoltaic solar energy using the "Google Forms" tool, which gives the flexibility to obtain answers from more distant locations. They were analyzed to determine the degree of importance (critical, conditioning, not restrictive or irrelevant) of the prevNoiously selected location factors. A total of 14 expert responses were obtained for this work. The table 1 shows briefly how these were distributed by each of the criteria.

Defining the Classes For the Location Factors: The factor classes (supply levels) were grouped according to Natural Breakes (Jenks) for the factors that need to be represented in numerical form (for example, solar irradiation). This definition allows an appropriate exposure of the data based on the identification of groups of analogous values and the maximization of the difference between classes (LONGLEY *et al.*, 2005).

RESULTS

The eight location factors selected were compared according to their relative importance estimated through the application of a questionnaire with specialists for the application of the COPPE-COSENZA model. After this, experts determined the degree of importance of the various factors and, by weighing the result of all of them, it was possible to generate the map of location possibilities, using the COPPE-COSENZA model. It is important to note that each specialist had their weight determined equally for the use of the COPPE-COSENZA method. In this map, the values greater than or equal to 1 represent the suitable locations for the installation of the photovoltaic solar plant. Analyzing Figure 3, it can be seen that the region most suitable for receiving large-scale photovoltaic solar energy projects is the municipality of Campos dos Goytacazes and surroundings (north coast of the state). Other very favorable regions are an area close to the metropolitan region of the city of Rio de Janeiro and in the interior of the Region of the Lakes. The mountainous region of the state had the lowest rates for the suitability of the photovoltaic solar plant, as well as the cities of Resende, Volta Redonda and surroundings. Another factor that drew attention was the extension of the restriction zone, which occupies a considerable part of the state. This is due to the state's environmental conservation units and urban areas.

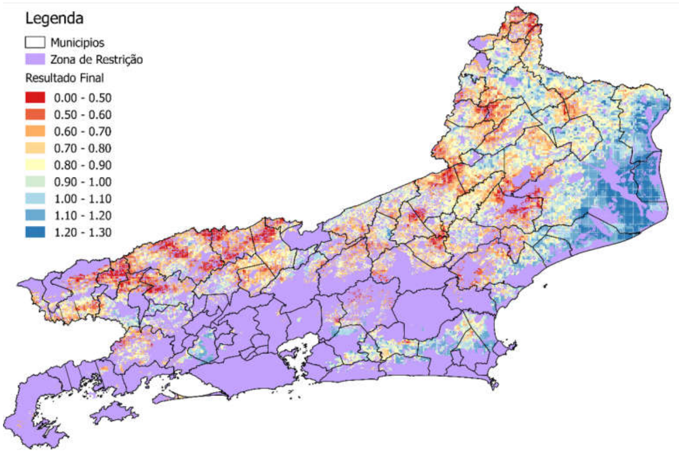

Fig. 3. Final Results – Source: The Authors

DISCUSSION

In this study, the best regions for the location of a photovoltaic solar plant were defined using the combination of fuzzy logic, through the Coppe-Cosenza method, in conjunction with the GIS (Geographic Information Systems). Eight location factors were analyzed (ranging from environmental to infrastructural factors). The results showed that Rio de Janeiro, despite having a wide region where it is not possible to install the solar photovoltaic plant, due to environmental restrictions (conservation units) and urban areas, has a good potential for the installation of solar photovoltaic plants, especially in the northern part of the state. It should be noted that this study depended on the availability and quality of the data, especially the georeferenced ones, which can generate slightly different results when they are updated.

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