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Geospatial Analysis and Data-Driven Techniques for Optimal Solar Power Plant Site Selection Using GIS and Multi-Criteria Decision-Making (MCDM) Models

Tanishq Sachdeva[1], Vatsalam Krishna Jha[2], Dr. Amit Pal[3]

[1]*Mechanical Engineering, tanishqsach1@gmail.com*
[2]*Electrical Engineering, vatsalamjha.dtu@gmail.com*
[3] *Professor Mechanical Engineering, amitpal@dce.ac.in*

As global energy demands continue to escalate and the transition to renewable sources such as solar energy becomes increasingly critical, efficient site selection for solar power plants is essential for maximizing both performance and sustainability. This study aims to employ a GIS-based Multi-Criteria Decision-Making (MCDM) approach to identify optimal locations for photovoltaic installations in the National Capital Territory of India. The methodology integrates Geographic Information System (GIS) tools with restrictive criteria, including land cover, road networks, and solar irradiation, while utilizing the Analytic Hierarchy Process and Technique for Order Preference by Similarity to Ideal Solution for the ranking of potential sites. Data layers were meticulously collected from satellite imagery and regional databases, followed by processing using GIS software to standardize spatial resolution and ensure compatibility.
The evaluation yielded a comprehensive ranking of alternative plots, prioritizing locations based on their proximity to ideal solutions and their overall suitability for solar energy generation. The results indicate that the MCDM-GIS approach effectively identifies top-ranking sites with high solar potential, demonstrating its utility in site selection for renewable energy projects. Moreover, this method offers a structured and replicable framework for informed decision-making, contributing significantly to sustainable energy planning in the region. The findings highlight the importance of incorporating up-to-date geographical data to enhance the feasibility of solar power plant setups. Furthermore, this study advocates for the broader application of this approach in future renewable energy initiatives, ensuring a more sustainable energy landscape.

Keywords: Geographical Information Systems, Multi-Criteria Decision Making, Solar Energy, Solar Power Plant Site Selection, Spatial Analysis, Site Evaluation.

1. Introduction

Renewable Energy in India: Energy is one of the most important commodities in the development of the economy of any nation and for improving the lifestyle. As the global energy landscape shifts toward sustainable sources, solar energy has emerged as a key player in reducing carbon footprints and addressing energy crises. The concerns over environmental degradation and climate change have nations focusing on cleaner and more sustainable energy solutions. Solar energy, in particular, has gained prominence due to its abundance, low environmental impact, and potential to meet rising energy needs [1]. Countries around the world are recognizing the need to reduce dependence on fossil fuels and are implementing policies to promote renewable energy, including solar power.

Millions of people around the globe have been gaining access to electricity in the last two decades; according to the report by Energy Access Outlook 2017, almost 1.1 billion people – 14% of the population of the world did not have access to electricity out of which 239.2 million population is from India. India contributes only 4.43% to the global renewable energy generation capacity [2]. Out of the total energy generated in India, 20.1% accounts for renewable energy sources. Of these installed renewable energy sources, solar energy has a fair share of 15.8%, as in Figure 1. The energy sector in India is growing at a fast pace, and it is expected that solar plant installation in India will increase by 360% by 2020. In many nations including India, many new government policies are being introduced to promote the shift of energy generation from conventional sources to more sustainable and renewable sources of energy [2]. India receives annual sunlight of about 2600 to 3200 hours. Delhi is the capital of India and accounts for a population of 19 million. The annual solar radiation in the national capital territory exceeds 5kWh/m^2/day [3]. Due to this high solar radiation over the region of Delhi, the generation of solar power can be increased by many times.

The selection of appropriate sites for solar power plants is critical to optimize energy output and minimize environmental impacts. Factors such as solar radiation, land use, and proximity to existing infrastructure play pivotal roles in this decision-making process. However, selecting the best location involves several challenges. Environmentally, it is essential to avoid disrupting ecosystems and biodiversity, particularly in regions with sensitive habitats [4]. Technically, access to high solar irradiance is necessary, but other considerations like terrain suitability and land availability are also important. Socially, local community acceptance can be a hurdle, as land competition with agriculture or housing may cause conflicts. Additionally, infrastructure constraints, such as the distance from transmission lines or grid capacity, can significantly affect project feasibility. These diverse factors require careful balancing to ensure that the benefits of solar energy can be fully realized without creating undue environmental or societal burdens.

Geographical Information Systems (GIS), when integrated with Multi-Criteria Decision Making (MCDM) techniques, offer a powerful tool for spatial analysis and optimization, enabling stakeholders to make informed decisions. GIS enables the visualization, analysis, and management of geographic data, while MCDM assists in evaluating multiple conflicting criteria. Together, they provide a structured, data-driven framework to assess various location-based factors such as environmental, social, and economic parameters. This integration allows for the systematic evaluation of potential sites by assigning weights to different criteria, enabling the comparison of alternatives based on decision-makers priorities [5]. For example, in site selection for infrastructure projects, GIS-MCDM helps identify the most suitable locations by incorporating spatial data and weighing factors like proximity, land use, and environmental risks. This approach ensures that decision-making is more transparent, efficient, and objective, leading to optimized solutions that consider both spatial and non-spatial factors comprehensively.

The objective of this study is to evaluate and identify optimal sites for solar power plants in the National Capital Territory (NCT) of India, utilizing a GIS-based Multi-Criteria Decision Making (MCDM) approach. This study aims to employ a GIS-based MCDM approach to evaluate and select optimal sites for solar power plants in the National Capital Territory (NCT) of India, accounting for both environmental and infrastructural criteria. The methodology focuses on integrating spatial data with decision-making frameworks to assess various location -based factors such as solar radiation, land use, proximity to infrastructure, and environmental sensitivity. By considering both technical and environmental aspects, the research intends to provide a data-driven solution to the complex process of site selection for solar energy projects [6]. The scope of the study is confined to the National Capital Territory (NCT) of India, with a focus on analyzing geographical and infrastructural parameters to optimize energy output and minimize ecological impacts, ensuring sustainable solar energy development.

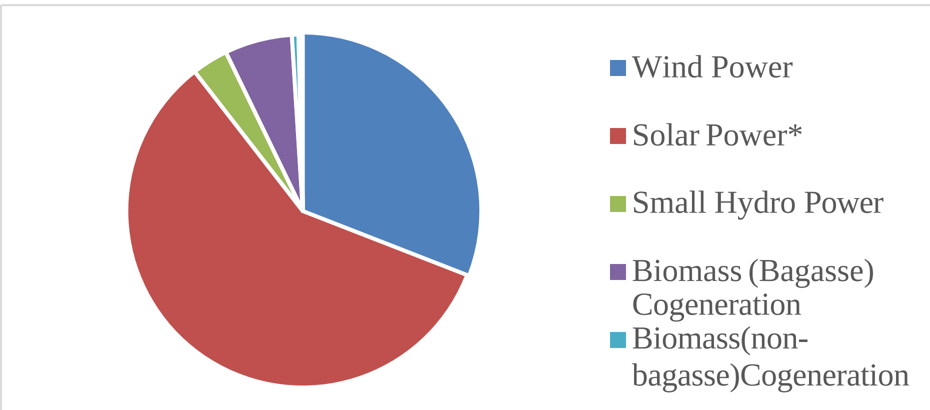

Figure 1. Distribution of renewable energy sources in India (as on 31.08.2024)

Source: https://mnre.gov.in/physical-progress/

2. Methodology

Data Collection and Preparation

The Government of India offers a good amount of geographical information to the public in

GIS formats on BHUVAN which is an online portal and can be used as a WMS (Web Map Service) in QGIS or any GIS software [7]. Data layers, including solar radiation, land use, slope, proximity to roads, and environmental sensitivity, were collected from satellite imagery and regional databases. These layers were processed using GIS software to standardize spatial resolution. For this study, most of the geographical information and layers are obtained from the BHUVAN portal. Most of the data used for this study, which was available from BHUVAN portals, was outdated, and the final areas achieved were already built up at the time of this study. Although the data was outdated, the resultant areas achieved, which were built-up areas, proved that the study would be effective for the decision-making in the setup of the solar power plants. So, the latest geographical data is necessary for this study to be effective and feasible.

Criteria Selection

The site selection process involved evaluating several criteria essential for determining the feasibility of a solar power plant. Five primary criteria were selected:

- Solar Radiation Potential: Key factor due to its direct impact on the efficiency and output of solar panels.
- Land Availability: Availability of open, non-residential land is crucial for the installation of large-scale solar projects.
- Proximity to Transmission Lines: Essential for connecting the solar power plant to the electrical grid.
- Environmental Impact: Focused on minimizing disruption to ecosystems and biodiversity.
- Topography: Flat or gently sloping land was preferred for optimizing solar panel placement. These criteria were chosen due to their direct influence on both the operational efficiency of the solar power plant and its environmental sustainability. Weights for each criterion were determined using the Analytical Hierarchy Process (AHP) [8].

MCDM Framework

MCDM in Renewable Energy: In today’s world, there are competing alternatives in every field, and there is a need to evaluate all the possible competing alternatives and come up with the best suitable alternative. The basic idea of the MCDM approach is the selection of the most suited alternative out of all the possible alternatives based on the different criteria used for evaluating an alternative. A widely used and reliable methodology for multi-criteria decision-making is the Analytical Hierarchal Process (AHP). Introduced by Saaty, this method can be used for complex decision problem-solving. A multi-level hierarchical structure is developed with the help of the AHP technique among the criteria, sub-criteria, and alternatives. In this paper, we will be looking at the application of AHP to determine the different criteria weights which will further help in the decision problem [9].

The second method that will be used to rank the alternatives is the Technique for Order Preference by Similarity to the Ideal Solution - TOPSIS. In the TOPSIS technique, we tend to achieve a ranking of the competing alternatives in order of their preference by the closeness index which is the relative closeness of the alternative to the positive ideal solution and distant from negative ideal solution [10]. In this study, this technique will be used in determining and selecting the most suitable and appropriate location with respect to the governing criteria for the placement of a photo-voltaic/solar power plant.

There can be various fields where MCDM techniques are employed Kamran Rezaie used MCDM for the evaluation and selection of the best location for the underground dam construction [11]. Ahmet Beskese used MCDM to select a suitable landfill site in Istanbul [12]. Juan M. Sánchez-Lozano evaluated the solar farms' locations in south-eastern Spain using GIS -MCDM methodology [13]. José Pablo Bonilla Valverde used GIS-MCDM analysis in Costa Rica to identify suitable intrinsic sites [7]. In 2010, PV site suitability analysis with the help of GIS-based spatial fuzzy multi-criteria evaluation was done [14]. Application of TOPSIS technique for financial performance evaluation of technology firms in Istanbul stock exchange market [15].

Geographical Information System (Gis)

A computer application used to store, manage, manipulate, and publish all types of geographical information. Geographical information refers to the information about the location on the surface of the Earth using the location as the main variable [16]. GIS software has functions to add, manage, edit, analyze, and export all kinds of geographical information. The features of geography on Earth are used as layers, which can be placed on top of each other. These features are depicted as points, lines, and areas. These features range from elevation, land slope, temperature, land cover, water bodies, soil profile, etc.

There are two ways to conceptualize the data used by a GIS application – vector model and raster model. The raster model is represented by points, lines, and coordinates. The raster model is used to represent satellite images and elevation areas, while the vector model is used to represent country or state boundaries, waterways, roads, etc. Today, there is large variety of GIS application in the market. Many are paid and some are free and available online [17]. For this study, QGIS which is an open-source geographical information software was used. It can easily use raster and vector information and it has all essential tools to analyze and manage the data. With QGIS, it is also possible to access online services – WFS (Web Feature Service), WMS (web Map Service), WCS (Web Coverage Service). Apart from this, it is freely available online.

Multi-Criteria Decision Making (MCDM) Techniques

In today’s world, decision-making is involved in every aspect of life. The basic idea of decision -making evolves from the selection or making a choice between the various options and alternatives available. To study this and further implement this ideology in decision- making, researchers came up with a multiple-criteria decision-making approach to get an evaluation of all the feasible and competing alternatives with respect to different criteria and selecting the best alternative [18]. There are mainly three steps involved in solving a multi- criteria decision problem:

1. Defining the problem and determining the objectives.

2. Determining the criteria and the alternatives.

3. Associating the numerical values the the alternatives for their evaluation with respect to the criteria.

4. Ranking the alternatives according to their feasibility with respect to the criteria.

Analytical Hierarchy Process (AHP)

The analytical Hierarchy Process (AHP) is one of the most widely used MCDM approaches for dealing with complex decision-making problems and selecting suitable alternatives among the available alternatives. AHP was first developed by Saaty, and as the name depicts, AHP involves the division of the problem in a hierarchy of criteria, sub-criteria, and alternatives and a pair-wise comparison is done for every criteria, and sub-criteria to achieve a comparison matrix and finally achieve the weights of every criteria [19]. The Saaty scale as shown in figure 1 is used to do this pair-wise comparison.

Table 1. Saaty scale for pair-wise comparison [19]

Definition	Numerical Value
Equally Important	1
Moderately Important	3
Strongly Important	5
Very Strongly Important	7
Extremely Important	9
Intermediate values	2, 4, 6, 8

This paper uses AHP technique in order to compute the criteria weights which will be further helpful in evaluating the different competing alternatives and selecting the one which is the most appropriate alternative. According to Saaty scale, for n number of criteria, an nxn matrix is made where p_{ij} is the comparison value according to the Saaty scale.

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix}$$

(1)

From above matrix, we obtain a normalized matrix $\bar{P}$ of the criteria as,

$$\bar{p}_{ij} = \frac{p_{ij}}{\sum_{i=1}^{n} p_{ij}} \quad (2)$$

From the normalized matrix, the weight vector w is obtained by taking the average of the rows,

$$w_i = \frac{\sum_{j=1}^{n} \bar{p}_{ij}}{n} \quad (3)$$

This weight vector will be used in TOPSIS to evaluate and rank the competing alternatives and achieve the best alternative.

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS – Technique for Order Preference by Similarity to Ideal Solution is an MCDM technique used to evaluate and rank the different competing alternatives with respect to the chosen criteria and obtain the right and most appropriate alternative which is closest to the ideal solution and is most distant from the non-ideal solution. In other words, the distance for this alternative from the Positive Ideal Solution (PIS) and from the Negative Ideal Solution (NIS) will be the shortest and largest, respectively [20]. TOPSIS technique involves six major steps for ranking the alternatives, as in Figure 2.

1. Formation of the original decision matrix P of dimension mxn, where the number of alternatives is denoted by m and the number of decision criteria by n,

$$P = \begin{bmatrix} p_{11} & \cdots & p_{1n} \\ \vdots & \ddots & \vdots \\ p_{m1} & \cdots & p_{mn} \end{bmatrix} \quad (4)$$

2. Normalization of the decision matrix D,

$$d_{ij} = \frac{p_{ij}}{\sqrt{\sum_{i=1}^{m} p_{ij}^2}} \quad (5)$$

3. Calculating the weighted normalized matrix S by taking the decision matrix D which was normalized in the previous step and multiplying it with the weight vector w_j obtained from AHP technique,

$$s_{ij} = w_j * d_{ij} \quad (6)$$

4. Determining the PIS (S^+) and NIS (S^-) solutions,

$$S^+ = \{s_1^+, s_2^+, \ldots, s_n^+\} = \{(\text{Max } s_{ij} \mid j \in J), (\text{Min } s_{ij} \mid j \in J')\} \quad (7)$$

$$S^- = \{s_1^-, s_2^-, \ldots, s_n^-\} = \{(\text{Min } s_{ij} \mid j \in J), (\text{Max } s_{ij} \mid j \in J')\} \quad (8)$$

5. Calculation of separation measures d_i^+ and d_i^-

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (s_{ij} - s_j^+)^2}, \quad (9)$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} (s_{ij} - s_j^-)^2} \quad (10)$$

6. Computing the relative closeness (C_i) between different alternatives and the ideal solution,

$$C_i = \frac{d_i^-}{d_i^+ + d_i^-} \quad (11)$$

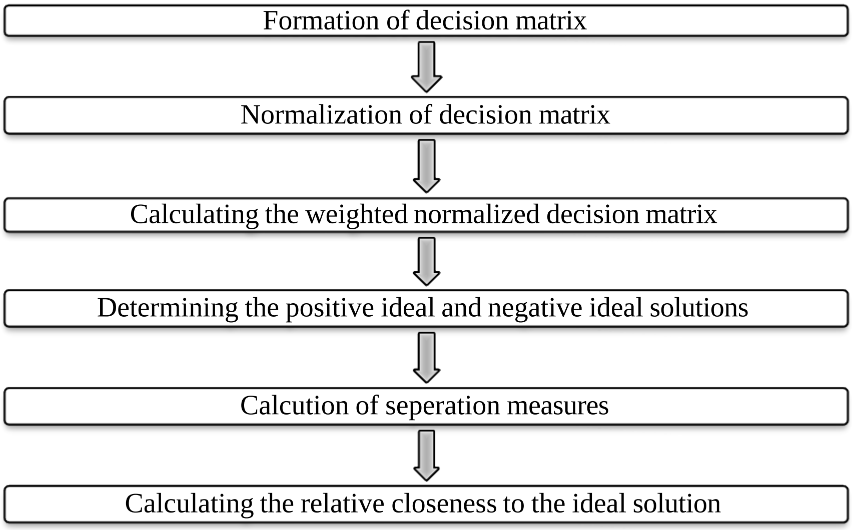

Figure 2. TOPSIS algorithm

f is a decimal value which is greater than 0 and less than 1. The higher value of f denotes the better solution. Using the values of f the ranking of alternatives is generated.

3. Results and Discussion

Site Ranking and Spatial Distribution

Application of GIS-MCDM approach in deciding the location of solar power plant

This study is done in two different phases; the development of the method to obtain the suitable area for study is done in the first phase. This suitable area was filtered and refined by applying the restrictions. At the end of first phase, the suitable alternative plots are obtained. These suitable plots are ready for evaluation. The second phase includes the evaluation of suitable plots using MCDM techniques. The initial step in the second phase consists of the development of the decision criteria: a hierarchy of criteria and sub-criteria are made, and their respective weights are found or generated using the Analytical Hierarchy Process (AHP). The suitable alternative plots are then evaluated with respect to the criteria and their weights obtained in the first step and TOPSIS is used to achieve a ranking among the suitable plots [21]. This complete process would help achieve a rank, and a further selection of the most suitable plot for solar power plant installation can be made.

The geographical data that was obtained was further processed on the open-source GIS software – QGIS. The data was obtained in the form of thematic layers. Data layers, including solar radiation, land use, slope, proximity to roads, and environmental sensitivity, were collected from satellite imagery and regional databases. These layers were processed using GIS software to standardize spatial resolution. The layers contain all the necessary information needed for the establishment of the method for obtaining the suitable area for the placement of the photo-voltaic/solar power plants. Further, many restrictions are taken into account for limiting the area to get to the potential plots that can be considered for the set up of solar power plants. These restrictions are administrative and environmental aspects of the area that would limit and help in achieving the potential plots.

Phase 1: Determining the plots suitable for the study

The layers used for the study include the land cover of Delhi in 2011-12, land slope and orientation, average annual temperature, average solar irradiation potential, and agrological capacity. Due to the consistency in the land slope and orientation, average annual temperature, and average solar irradiation potential over the whole region of Delhi, the key thematic layer for achieving the suitable area is the land cover/land use. The aim of this phase is to apply the restriction and eliminate the areas that cannot support the setup and installation of a photo-voltaic/solar power plant. This can be seen in Figure 3. For the selection of suitable areas, barren/wastelands were selected. Wastelands are lands that are degraded and underutilized due to inappropriate water and soil management in the area or due to natural causes [22].

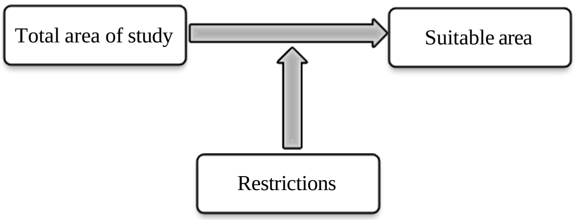

Figure 3. Restrictions application diagram.

The wastelands are broadly classified into gullied/ravenous land, salt-affected land, barren rocky, scrubland, sandy area, and ran area; for this study, we selected the scrub land due to the high volume of shallow and skeletal soil, low fertility due excessive erosion, chemical degradation, and excessive aridity. The total area under study is 1483 km^2 as seen from figure 4. As a result, a final layer is obtained which represents all the suitable plots. The application of restrictions resulted in the total suitable area of 62.18 km^2 which accounts for about 4.19% of the total area under study [23], that can be seen in Figure 5.

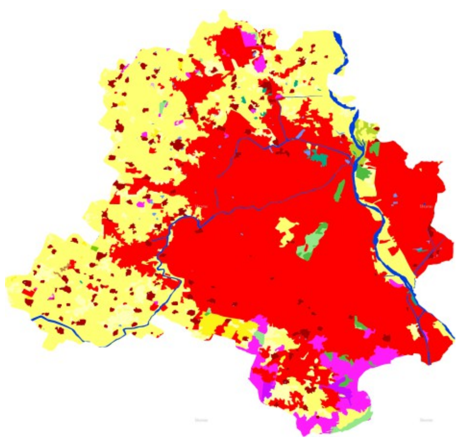

Figure 4. The area under study – Delhi land-use/land-cover 2011-12

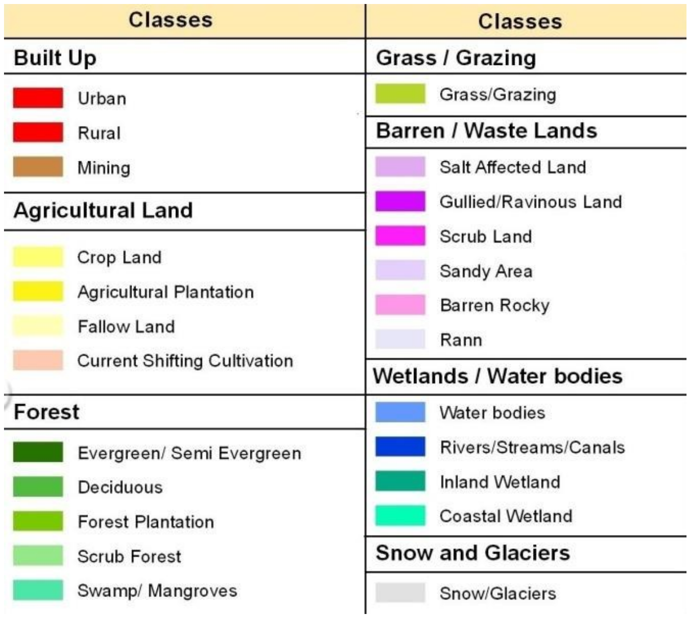

Figure 5. Land Cover in Delhi 2011-12.

One more restriction to be applied for filtering out the unsuitable plot is to select the plots which are capable of generating higher energy levels; therefore the minimum area of the plot is attained from the number of solar panels capable of generating the minimum required electricity. The plots on which construction was already done were considered unsuitable as well [24]. Finally, after the plots were eliminated, the installation of solar power plants was unsuitable, and a map with all the suitable plots was obtained, see Figure 6.

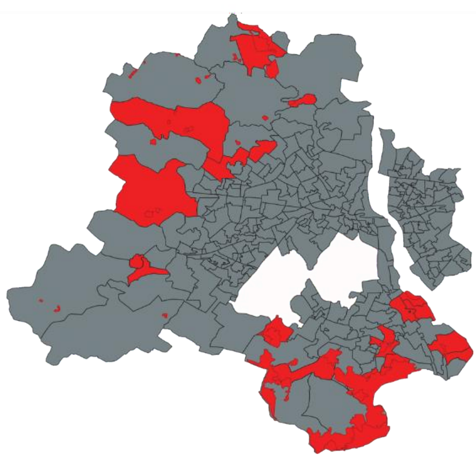

Figure 6. Suitable area

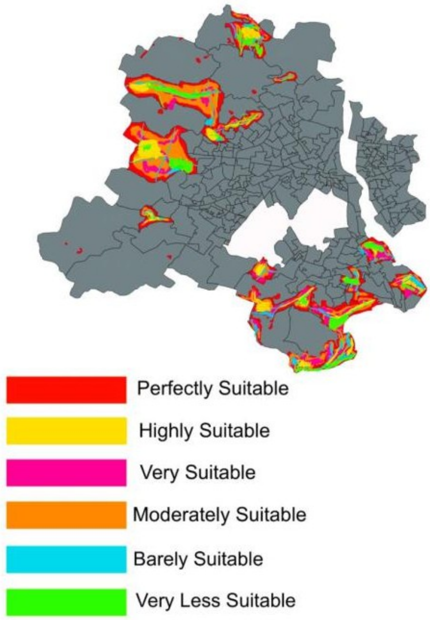

Figure 7. Ranking of area using TOPSIS

Phase 2: Evaluating the suitable plots

Till now, the restrictions have been applied and the suitable alternative plots have been obtained. In this phase we will take the decision criteria and factors into account and achieve an evaluation and ranking of all the suitable plots using MCDM techniques – AHP and TOPSIS. The best operation of a photo-voltaic/solar plant is dependent on the supporting location and infrastructure [25]. Thus, for this study, environmental, geomorphology, location, and climate were chosen to be the criteria. The criteria were further subdivided into the factors as shown in figure 7.

The plots were subjected to the factors because factors like agrological capacity, land slope, land orientation, distance from power stations, distances from roads, solar irradiation potential, and average temperature highly influence the selection of a plot for a suitable and viable operation. Table 2 shows the weights of the respective factors generated by the AHP methodology, given in sub-section 3.1. These weights represent the importance of the factors in assessing the suitable plots. A literature search was done to find the weights of the factors. The climate criteria further become a less important criterion because of the consistency in the irradiation potential and average temperature throughout the region.

The decision process is further completed using the TOPSIS technique, and a ranking of all the suitable plots is obtained, as stated in sub-section 3.2. The minimum area suitable for generating a bare minimum amount of energy to support the surrounding area and colony can be calculated from the formula for the energy per unit area for a solar unit as given below [26],

$$E = A \times r \times H \times PR \quad (12)$$

Where,

E = Total energy generated (kWh)

A = Total area (m^2)

r = Yield of the solar panel (%)

H = Annual average solar radiation ($kWh/m^2/year$)

PR = Performance ratio

As the number of suitable plots can be very high, the plots can be further categorized into highly suitable, fairly suitable and poor on the ranking obtained.

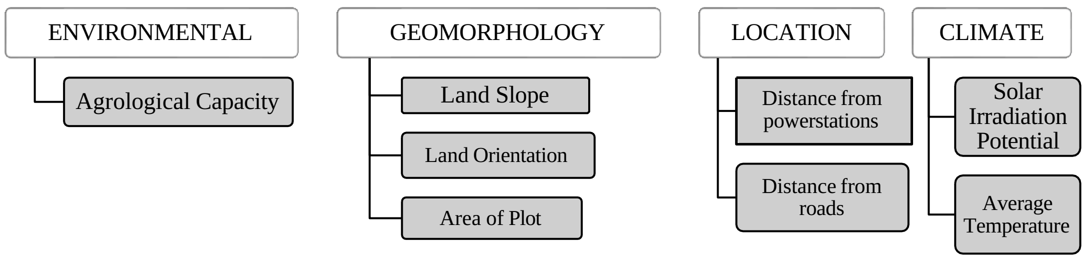

Figure 7. Hierarchy of Criteria and Factors

Table 2. Weights of Factors

Criteria	Factor	Weights (%)
Environmental	Agrological Capacity	2.8507
Geomorphology	Land Slope	4.3882
	Land Orientation	5.8067
Location	Area of Plot	15.3180
	Distance from power-stations	10.0668
	Distance from roads	4.7156
Climate	Solar Irradiation Potential	35.9434
	Average Temperature	20.9104

4. Conclusion

This study demonstrates that a GIS-based Multi-Criteria Decision-Making (MCDM) approach is highly effective in evaluating and prioritizing potential sites for solar power plants. By integrating a comprehensive set of environmental, technical, and social criteria, the methodology provides a balanced and sustainable framework for site selection. The combined AHP-TOPSIS framework proved instrumental in analyzing critical factors, including solar radiation, land availability, environmental impact, and proximity to essential infrastructure, thereby facilitating a robust decision-making process.

As global energy demands escalate, transitioning to renewable sources like solar energy is imperative. This study offers a practical tool for identifying optimal locations for photovoltaic installations, contributing significantly to sustainable energy planning. However, challenges such as data accessibility and the qualitative nature of some criteria persist. The conversion of qualitative factors into quantifiable measures necessitates further expertise, and the availability of up-to-date geographical data can be inconsistent. Moreover, proficiency in GIS is essential for conducting accurate analyses.

Future research should focus on integrating real-time data into this framework and expanding its application to other renewable energy technologies, which would enhance its versatility and effectiveness. Despite these limitations, this study lays a solid foundation for future investigations and provides a valuable strategy for selecting efficient and environmentally friendly sites for solar power generation. In conclusion, the GIS-MCDM methodology not only serves as an effective tool for site selection but also holds potential for refinement and broader application across various renewable energy sectors, ultimately supporting the development of a more sustainable energy future.

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