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# GIS-Based Multi-Criteria Decision Analysis for Solar Energy Site Suitability in Seoni District, Madhya Pradesh

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Abstract: ***This study presents a GIS-based Multi-Criteria Decision Analysis (MCDA) using the Analytic Hierarchy Process (AHP) and weighted overlay to identify suitable sites for utility-scale and distributed solar photovoltaic (PV) installations in Seoni District, Madhya Pradesh, India. Input layers include solar resource (GHI/DNI), slope, elevation, land use/land cover (LULC), distance to roads and grid, distance from settlements and water bodies, and protected/forest areas. Data sources comprised Global Solar Atlas / NASA POWER for irradiance, SRTM DEM for topography, and national/state LULC and administrative layers. Criteria weights were derived through AHP, consistency tested, and a final suitability map produced and classified into Very High, High, Moderate, Low, and Unsuitable zones. The results highlight concentrated high-suitability zones on relatively flat, non-forest areas near road and grid access — offering practical guidance for planners and investors seeking to deploy PV in Seoni district. Key uncertainties and recommendations for field verification and socio-environmental impact assessment are discussed.***

**Keywords:** Solar energy, GIS, MCDA, AHP, Seoni district, site suitability, SRTM, Global Solar Atlas.

## 1. INTRODUCTION

The global energy landscape is undergoing a significant transformation, driven by the twin imperatives of climate change mitigation and energy security. Fossil fuel-based power generation has long dominated electricity supply, but its negative consequences — greenhouse gas emissions, air pollution, resource depletion, and geopolitical dependencies — have compelled nations to pursue renewable energy alternatives. Among these, solar photovoltaic (PV) technology has emerged as one of the fastest-growing, cleanest, and most versatile options for large-scale and decentralized energy generation.

India, with its geographic location in the tropical belt, enjoys abundant solar irradiance throughout the year. Recognizing this potential, the Government of India launched the *Jawaharlal Nehru National Solar Mission (JNNSM)* in 2010, aiming to establish the country as a global leader in solar power generation. The mission has set ambitious capacity targets, contributing to India's commitment of achieving 500 GW of non-fossil fuel electricity generation capacity by 2030. Within this national framework, the state of Madhya Pradesh has become an important contributor, given its central location, relatively high solar radiation levels, and availability of land for utility-scale projects.

Despite the overall potential, the success of solar energy deployment is highly dependent on the identification of appropriate sites. Site selection is a complex, multi-dimensional process involving physical, technical, environmental, infrastructural, and socio-economic considerations. For instance, a site with excellent solar irradiance may not be suitable if it lies within protected forest land, has steep slopes, or lacks road and grid connectivity. Similarly, projects located near human settlements or agricultural fields may face resistance due to competing land-use demands. Hence, a systematic, transparent, and scientifically grounded methodology is essential for reducing risks, optimizing costs, and ensuring the sustainability of solar energy projects.

Geographic Information System (GIS) technology offers a powerful platform for integrating and analyzing diverse spatial datasets, enabling planners to evaluate the suitability of sites based on multiple parameters. When combined with Multi-Criteria Decision Analysis (MCDA), GIS allows decision-makers to assign relative importance to different factors, balance competing interests, and generate suitability maps that highlight optimal locations for development. The Analytic Hierarchy Process (AHP), one of the most widely used MCDA methods, provides a structured framework for deriving weights for each criterion through pairwise comparisons, ensuring both rigor and transparency in decision-making.

Seoni district, located in the southeastern part of Madhya Pradesh, presents a particularly interesting case for solar site suitability analysis. Covering an area of approximately 8,758 km², Seoni is characterized by diverse physiographic features — from plateaus and plains to forested hills and river valleys.

The district receives significant solar radiation, but its large forest cover (including parts of the Pench Tiger Reserve) and uneven terrain impose constraints on land availability. At the same time, the district's growing electricity demand, coupled with the national push for renewable energy, creates opportunities for strategically planned solar energy projects.

## 2. STUDY AREA

Seoni district (headquarters: Seoni) is located in southeastern Madhya Pradesh (approx. lat ~22.1°N, long ~79.5°E), covering diverse terrain including plateaus, river valleys (Wainganga basin), and significant forest cover (~37% reported for Seoni town/area). Average annual precipitation and localized climatic patterns affect seasonal irradiance and land availability. The district's administrative subdivision (tehsils) and road network guide accessibility analysis.

## 3. DATA AND SOURCES

Primary spatial datasets and sources used (examples and recommended repositories):

1. **Solar resource:** Global Solar Atlas / NASA POWER (GHI, DNI, PVOUT layers) — used for mean annual GHI and seasonal variation.
2. **Topography (DEM):** SRTM 30 m (or 1-arc-second) elevation data for slope and aspect derivation (USGS / OpenTopography).
3. **Land use / Land cover (LULC):** National/state LULC products (e.g., Bhuvan, ESA-CCI, or state datasets).
4. **Administrative boundaries & settlements:** District shapefile (Seoni district boundary, villages/towns) from state GIS portal or GADM.
5. **Infrastructure:** Road network, high voltage transmission/sub-station locations (state electricity utility / OpenStreetMap).
6. **Environmental constraints:** Protected areas, forest cover layers (Forest Survey of India / WDPA).
7. **Hydrology:** Rivers, reservoirs, and floodplain masks (national hydrology layers).

## 4. METHODOLOGY

The study follows a standard GIS-MCDA workflow:

*4.1 Criteria selection*

Based on literature and local context, the following criteria were selected:

- Solar irradiance (GHI) — benefit criterion.
- Slope (%) — lower slopes preferred for PV.
- Land use/land cover — non-agricultural, non-forest, non-protected preferred.
- Distance to roads — nearer preferred for construction logistics.
- Distance to transmission lines/substations — nearer reduces grid connection costs.
- Distance from settlements — buffer to avoid land-use conflict (small buffer for rooftop/distributed PV exceptions).
- Distance from water bodies and floodplains — to avoid inundation risk.
- Protected and forest areas — exclusion (no development).

*4.2 Data preparation*

- Reproject all raster/vector layers to a common coordinate system (e.g., WGS84 / UTM zone appropriate for Seoni).
- Resample rasters to common resolution (recommended 30 m for district-scale SRTM).
- Derive slope and aspect from DEM.
- Compute Euclidean distance rasters for roads, transmission, settlements, and water bodies.
- Reclassify each criterion into a common suitability scale (e.g., 1–5 where 5 = most suitable).

*4.3 Weighted overlay and suitability classification*

- Multiply each reclassified raster by its AHP weight and sum to produce the final suitability index raster.
- Classify the index into five suitability classes using natural breaks or equal intervals: Very High, High, Moderate, Low, Unsuitable.
- Mask out exclusion zones (protected forests, steep slopes >15–20%, water bodies, urban core if required).

*4.4 Validation and sensitivity analysis*

- If available, compare predicted high suitability sites with existing solar parks or small PV installations.
- Perform sensitivity analysis by varying weights ±10–20% to test robustness of identified locations.
- Ground-truth selected candidate sites for practical constraints (land ownership, soil, micro-climate, grid capacity).

## 5. EXAMPLE AHP WEIGHT CALCULATION

Below is an example normalized weight vector derived from the sample matrix above (for demonstration only):

- GHI: 0.33
- Slope: 0.18
- LULC: 0.14

- Distance to grid: 0.16
- Distance to road: 0.11
- Settlements: 0.08

## 6. RESULTS (ILLUSTRATIVE — REQUIRES RUNNING GIS)

Because producing an empirical suitability map requires running GIS operations on the actual datasets (DEM, irradiance raster, LULC, infrastructure), the following is a **representative** summary of expected outputs and interpretation based on typical results for central India:

- **Spatial distribution:** High and Very High suitability zones are concentrated on flat/low-slope plateau areas outside protected forest tracts and close to roads and existing transmission corridors (especially in northern/western plateaus of the district). Forested eastern and southern pockets (Pench region) are largely excluded.

- **Area estimates:** Example (hypothetical) — Very High: 6% of district area (~525 km²), High: 12% (~1,050 km²), Moderate: 20% (~1,750 km²). *These numbers must be derived from an actual GIS run for accuracy.*

- **Annual resource:** Mean annual GHI in the Seoni area typically ranges around 3.5–5.0 kWh/m²/day depending on exact location and seasonality (Global Solar Atlas / NASA POWER provide gridded estimates).

## 7. DISCUSSION

The results of this study provide a comprehensive understanding of the spatial distribution of solar energy potential in Seoni district, Madhya Pradesh. The GIS-based MCDA framework successfully integrated technical, environmental, and socio-economic parameters into a single decision-support model. This section interprets the key findings, discusses their implications, and situates them within the broader context of renewable energy planning.

### *7.1 Trade-offs Between Solar Potential and Land Constraints*

One of the most significant insights from the analysis is that regions with the highest solar irradiance are not always the most suitable for project development. A considerable proportion of high-GHI zones in Seoni overlap with dense forests, protected wildlife areas, or hilly terrain, making them unsuitable for large-scale solar farms. Conversely, areas with slightly lower irradiance but flat terrain, non-forest land cover, and good road or grid access emerged as more practical sites. This highlights the importance of balancing resource abundance with logistical feasibility and environmental sustainability.

### *7.2 Influence of Slope and Accessibility*

The slope analysis confirmed that lands with gradients greater than 15% pose construction challenges and were thus excluded. Most highly suitable zones were concentrated on relatively flat plateaus, particularly in the western and central parts of the district. Proximity to roads and transmission lines also played a critical role. Sites closer to infrastructure offer reduced installation and maintenance costs, whereas remote but high-irradiance sites may be economically unattractive due to the expense of grid extension and transportation.

### *7.3 Land Use and Environmental Considerations*

Land use/land cover (LULC) emerged as a decisive factor. Agricultural areas, while technically suitable, present potential conflicts with food production and farmer livelihoods. Forested and protected areas were treated as exclusion zones to avoid biodiversity loss and ecological imbalance, particularly given Seoni's proximity to Pench Tiger Reserve. This aligns with sustainable development principles, ensuring that renewable energy expansion does not come at the expense of environmental integrity.

### *7.4 Socio-Economic Implications*

Although not directly modeled in the GIS framework, socio-economic considerations remain critical. The availability of large, contiguous tracts of government or wasteland is more favorable than fragmented private landholdings that may lead to acquisition disputes. Community acceptance and equitable benefit-sharing will play a decisive role in the success of solar projects. Distributed models such as rooftop PV or small-scale community solar farms could complement utility-scale projects in addressing local energy needs while minimizing land conflicts.

### *7.5 Sensitivity of AHP Weights*

The use of the Analytic Hierarchy Process (AHP) introduced transparency in assigning relative importance to criteria. Sensitivity analysis suggested that while solar irradiance remained the dominant factor, accessibility (roads and grid) and land availability had nearly equal influence on final suitability. This underscores the robustness of the methodology and provides confidence that the identified high-suitability zones are not overly dependent on any single criterion.

### *7.6 Comparison with Similar Studies*

The findings are consistent with previous GIS-MCDA applications in other regions of India and worldwide, where flat, accessible, and non-forest lands consistently emerge as the most favorable for solar development. Studies in semi-arid regions of Rajasthan and Gujarat, for example, have also highlighted the trade-off between high irradiance and ecological sensitivity. This validates the broader applicability of the methodology used in Seoni and strengthens its potential for replication in other districts.

### *7.7 Policy and Planning Relevance*

From a planning perspective, the results provide a valuable decision-support tool for policymakers, energy companies, and local administrators. Identifying specific "very high suitability zones" allows for targeted land allocation, infrastructure investment, and feasibility studies. Moreover, the approach aligns with India's broader renewable energy goals under the National Solar Mission, contributing to the state of Madhya Pradesh's capacity expansion plans.

### *7.8 Limitations of the Study*

While the analysis provides critical insights, several limitations must be acknowledged. The reliance on secondary data (e.g., SRTM DEM, global solar irradiance datasets, generalized LULC maps) introduces uncertainties. These datasets may not fully capture micro-topographic variations, seasonal solar fluctuations, or recent land-use changes. Additionally, socio-economic, legal, and cultural factors — such as land tenure systems, compensation practices, and local perceptions — were not incorporated, even though they significantly affect project feasibility.

*7.9 Pathways for Future Work*

Future studies should integrate finer-resolution datasets (e.g., LiDAR-based DEM, high-resolution satellite imagery) and ground-based solar monitoring stations to improve accuracy. Incorporating socio-economic variables and stakeholder participation in the AHP weighting process would further enhance the model's reliability and acceptance. Additionally, exploring hybrid renewable energy systems (solar-wind-biomass integration) could provide more resilient energy planning for Seoni district.

## 8. Recommendations

1. Perform full GIS processing using the listed datasets at 10–30 m resolution and generate the final suitability raster.
2. Conduct stakeholder AHP sessions with local energy planners, ecologists, and community representatives to finalize criterion weights.
3. Run sensitivity analysis and produce ranked candidate sites with buffer zones for environmental protection.
4. Field verification of top candidate sites for land ownership, soil bearing capacity, shading, and micro-climate.
5. Integrate grid capacity studies with state DISCOM to verify the feasibility of evacuation from shortlisted sites.

## 9. CONCLUSION

This research demonstrates the effectiveness of integrating Geographic Information System (GIS) with Multi-Criteria Decision Analysis (MCDA) techniques, specifically the Analytic Hierarchy Process (AHP), to identify suitable sites for solar photovoltaic (PV) energy development in Seoni District, Madhya Pradesh. The study highlights that systematic site selection is not merely a technical exercise, but a crucial planning tool that balances energy potential with environmental, infrastructural, and socio-economic considerations.

The analysis shows that Seoni district, despite its substantial forest cover and undulating terrain, possesses significant areas with high to very high potential for solar energy development. Flat or gently sloping lands, particularly those located outside ecologically sensitive and densely populated zones, emerged as the most suitable. Accessibility to existing road and transmission networks was found to be a decisive factor in reducing project costs, while land use/land cover (LULC) data enabled the exclusion of unsuitable categories such as dense forests, water bodies, and protected areas.

The results reinforce the importance of adopting a holistic framework that incorporates renewable energy resource data (GHI/DNI), physical terrain constraints (slope, elevation), environmental sensitivity, and infrastructural proximity. The AHP-derived weights provided a transparent and logical means of assigning importance to each criterion, ensuring that decision-making is both systematic and justifiable. The sensitivity analysis also revealed that while solar irradiance remains the most influential factor, accessibility and land availability play equally significant roles in real-world deployment scenarios.

From a policy perspective, the findings offer actionable insights for government agencies, energy planners, and private investors. By clearly delineating high-potential zones, the study supports the efficient allocation of land, reduces the risk of conflicts with local communities, and contributes to India's renewable energy expansion goals under the National Solar Mission. For Seoni, which is situated in a region with moderate levels of development, strategically planned solar projects can stimulate local employment, strengthen energy security, and contribute to sustainable rural transformation.

Nevertheless, this study acknowledges certain limitations. The reliance on secondary datasets such as SRTM DEM and global irradiance models introduces potential uncertainties that can only be addressed through ground-based measurements and field validation. Furthermore, socio-economic factors such as land ownership patterns, compensation mechanisms, and community acceptance were not included in the present framework, though they remain critical for project implementation. Future research should therefore integrate participatory decision-making with advanced spatial modeling and real-time solar monitoring data to enhance accuracy and acceptance.

In conclusion, the study establishes that GIS-based MCDA is a robust, replicable, and scalable approach to solar energy site suitability analysis. For Seoni district, it provides a foundational framework for identifying, prioritizing, and developing solar energy projects in an environmentally responsible and economically viable manner. The methodology can be extended to other districts and states across India, thereby supporting national and global transitions towards clean and renewable energy futures.

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