Sustainable Solar Energy Planning Using GIS-Based Multi-Criteria Decision Tools in Seoni District, Madhya Pradesh

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Abstract: ***This paper develops a GIS-based Multi-Criteria Decision Analysis (MCDA) framework to identify and rank suitable sites for sustainable solar energy development (utility and rooftop) in Seoni district, Madhya Pradesh, India. Key biophysical, infrastructural, environmental, and socio-economic criteria are integrated using Analytic Hierarchy Process (AHP) weighting and combined in a weighted overlay GIS analysis. Satellite-derived solar radiation (NASA POWER), land use/land cover (LULC), slope/aspect from DEM, proximity to grid/roads, protected areas, and exclusion zones are used. The framework produces suitability maps, quantifies available area and theoretical generation potential, and discusses policy and implementation pathways aligned with national rooftop and solar policies. The study provides planners, utilities, and local government with a spatially explicit decision support tool for sustainable solar deployment in Seoni.***

Keywords: GIS, MCDA, AHP, Solar site selection, Seoni, Madhya Pradesh, NASA POWER, rooftop solar, sustainable planning.

1. INTRODUCTION

The growing energy demand, environmental challenges, and commitment to global climate agreements have made renewable energy development a critical priority for India. Among renewable sources, **solar energy** has emerged as one of the most promising options due to its abundance, sustainability, and rapidly declining costs of photovoltaic (PV) technologies. India, with its geographical advantage, receives an average solar insolation of **4–7 kWh/m²/day** across most regions, providing immense potential for both utility-scale and rooftop solar deployment. Recognizing this potential, the Government of India launched the **National Solar Mission (2010)** and subsequent policies under the **Ministry of New and Renewable Energy (MNRE)**, aiming to achieve **500 GW of non-fossil energy capacity by 2030**, with solar energy as a cornerstone of this transition.

Madhya Pradesh, situated in central India, has been a significant contributor to this transition. With large solar parks (such as Rewa and Agar) and active **rooftop solar programs** implemented through the Madhya Pradesh Urja Vikas Nigam Limited (MPUVNL), the state has become a hub for solar innovation and deployment. Within this context, **Seoni district**, though less industrialized, offers substantial potential due to its favorable solar radiation, large tracts of semi-arid and degraded land, and growing infrastructure demand. Furthermore, Seoni has been included in recent rooftop solar tenders, reflecting policy-level recognition of its renewable energy potential.

However, the success of solar deployment is not determined by resource availability alone. **Poor site selection** can lead to high costs, grid integration challenges, environmental damage, or social conflicts over land. For example, selecting fertile agricultural lands for solar farms can reduce food security, while siting projects near ecologically sensitive areas can trigger biodiversity loss. Therefore, sustainable solar energy planning requires an integrated approach that balances **technical feasibility, economic viability, environmental sustainability, and social acceptance**.

This is where **Geographic Information Systems (GIS)** and **Multi-Criteria Decision Analysis (MCDA)** tools play a vital role. GIS allows spatial integration of diverse datasets such as solar radiation, land use/land cover, slope, infrastructure proximity, and administrative boundaries, while MCDA provides a structured framework to evaluate these multiple and often conflicting factors through weighting and prioritization. Among MCDA methods, the **Analytic Hierarchy Process (AHP)** is widely applied in renewable energy studies because it enables systematic pairwise comparison of criteria and integrates expert judgment into the decision-making process.

Several global and Indian studies have demonstrated the effectiveness of GIS-based MCDA in renewable energy site selection. In particular, it enables policymakers to **identify suitable sites, rank alternatives, estimate capacity potential, and plan infrastructure development**. Yet, there remains a need for district-level applications that can bridge national/state policy targets with **localized spatial planning**. Seoni district provides an ideal case study for such an analysis, as it represents a mix of rural landscapes, moderate infrastructure, and untapped renewable energy opportunities.

This research aims to develop and apply a **GIS-based MCDA framework** for sustainable solar site selection in Seoni district. Specifically, it seeks to:

1. Integrate multi-source spatial data (solar radiation, terrain, land use, infrastructure, protected areas).

2. Apply MCDA (using AHP) to weigh and combine criteria based on technical, environmental, and socio-economic considerations.

3. Generate suitability maps for both **utility-scale solar farms** and **rooftop/distributed solar systems**.

4. Estimate the theoretical solar potential of high-suitability zones.

5. Provide actionable insights and policy recommendations for district-level planners, utilities, and stakeholders.

By systematically identifying priority zones for solar development, this study contributes to **sustainable energy planning**, ensures efficient use of land and infrastructure, and supports India's broader renewable energy goals. The results are not only relevant for Seoni but can also serve as a **replicable framework** for other districts in Madhya Pradesh and across India.

2. Literature review

This literature review synthesizes global methodological advances and Indian / regional applications of **GIS-based Multi-Criteria Decision Analysis (MCDA)** for solar energy site selection, evaluates common data sources (with special attention to satellite solar datasets), examines weighting and validation approaches (with emphasis on AHP and alternatives), and identifies gaps that justify a district-level study for Seoni, Madhya Pradesh.

2.1. GIS + MCDA for renewable siting — conceptual and methodological advances

GIS integrated with MCDA has become the dominant approach for spatial siting of renewable energy projects because it combines spatial data management, spatial analysis, and systematic decision rules to balance multiple technical, environmental, and socio-economic criteria. Early and review studies show a consistent workflow: (1) compile spatial layers (solar resource, slope, land use, infrastructure, protected areas), (2) create exclusion masks, (3) standardize/normalize criteria rasters, (4) derive criterion weights (AHP, TOPSIS, BWM, fuzzy logic, or hybrid methods), and (5) aggregate using weighted overlay or more advanced aggregation rules, followed by cluster analysis and potential estimation. These steps are now standard practice in both academic studies and practical planning tools. Several comparative studies also recommend sensitivity analysis and stakeholder-driven weighting to ensure robustness and legitimacy of results.

2.2. Common MCDA methods and strengths/weaknesses

The Analytic Hierarchy Process (AHP) is the most widely used weighting method in solar siting studies due to its relative simplicity and ability to capture expert judgment via pairwise comparisons. AHP's main advantages are transparency and ease of interpretation; however, criticisms include sensitivity to subjective judgments, potential inconsistency in pairwise matrices (necessitating CR checks), and scale dependence. Alternative or complementary methods that have been used to address these limitations include the Best-Worst Method (BWM), TOPSIS, ELECTRE, fuzzy AHP, and hybrid approaches (AHP + GIS + statistical or machine learning validation). Recent work also explores ensemble weighting and probability-based aggregation to better account for uncertainty in stakeholder preferences. When studies compare methods, they often find that while final maps differ in detail, major high-suitability zones are generally robust if core technical constraints (GHI, slope, protection zones) are consistently applied.

2.3. Use of satellite solar datasets (NASA POWER, CAMS, SARAH) and validation issues

Satellite-derived solar radiation datasets (notably NASA POWER) are frequently used in site selection studies because of their spatial coverage, temporal length, and ease of integration with GIS. Validation studies demonstrate that NASA POWER is suitable for initial/regional assessments and can reproduce spatial patterns of Global Horizontal Irradiance (GHI) reasonably well, although local biases can occur and ground station validation (if available) is recommended for final feasibility and yield estimation. Researchers commonly use statistical metrics (RMSE, MBE, R^2, NRMSE) to quantify agreement with ground measurements and to adjust resource estimates if necessary. For district-scale planning where ground data may be sparse, NASA POWER offers a practical compromise between accuracy and availability.

2.4. Representative studies — global and regional examples

Several peer-reviewed case studies illustrate the successful application of GIS-MCDA for solar siting across varied geographies:

- Sun (2021) presents a robust GIS-MCDA framework including LULC, slope, and infrastructure layers and demonstrates how to estimate technical potential for large-scale PV. This work is frequently cited as a methodological reference for combining resource and non-resource constraints.

- Bandira et al. (2022) apply NASA POWER with GIS-MCDM in an urban conurbation and explicitly validate satellite GHI against ground data, providing a useful template for validation and error quantification in district-level studies.

- Recent 2024–2025 studies and preprints show methodological innovations: hybrid weighting methods, group weighting (combining multiple expert inputs), and comparative sensitivity analyses across AHP, BWM, and fuzzy methods — all stressing the importance of sensitivity testing to assess the stability of suitability outputs.

These examples indicate both methodological maturity (consistent workflows and reproducible steps) and active methodological innovation (new weighting methods, ensemble approaches).

2.5. Applications in India and Madhya Pradesh — policy and practice linkages

India's national policies (e.g., National Solar Mission, MNRE programmes) and state-led rooftop initiatives have increased demand for spatially explicit planning tools. District and state agencies (including MPUVNL in Madhya Pradesh) are increasingly tendering rooftop projects and using GIS to pre-identify government premises and public buildings for rooftop deployment. Recent procurement notices and RfPs published by MPUVNL show active rooftop programme rollouts in Seoni and neighboring districts, underscoring the practical relevance of district-scale suitability assessments that combine rooftop potential and utility-scale siting. This policy momentum motivates district-tailored GIS-MCDA analyses to prioritize public rooftops, degraded lands, and avoid protected areas. Energetica

2.6. Rooftop vs utility-scale siting — methodological distinctions

While the overall GIS-MCDA workflow is similar for rooftop and utility-scale projects, key differences exist in data needs and constraints:

- **Rooftop** analyses require high-resolution building footprints, roof orientation/tilt, and local load data to estimate feasibility and financial returns. Where such fine-scale data are missing, studies often rely on proxy methods (built-up area density, cadastral or high-resolution imagery) or on government inventories of public buildings to prioritize sites.

- **Utility-scale** analyses emphasize land-use compatibility, contiguous patch size, soil/stability, and grid connection distance; exclusion buffers for agriculture and protected zones are stricter. Also, estimates of capacity density (MW/ha) are more relevant here. Many studies propose separate suitability maps for rooftop and utility to avoid inappropriate comparisons.

2.7. Validation, sensitivity analysis, and stakeholder engagement — best practices

Best practices emerging from the literature include: (1) validating satellite solar data where ground measurements exist; (2) conducting sensitivity analyses by varying criterion weights and thresholds to test map stability; (3) engaging local stakeholders (utilities, planning authorities, community representatives) to incorporate on-the-ground knowledge and acceptability concerns; and (4) producing outputs at multiple spatial scales (district overview + candidate parcel lists) to facilitate both policy planning and developer due diligence. Studies that omit validation or sensitivity analysis risk producing misleadingly precise suitability maps; conversely, those that incorporate these steps report greater confidence and higher uptake by decision-makers.

2.8. Gaps and justification for a Seoni district study

Despite extensive literature, three gaps motivate the current research:

1. **District-level transparency:** Many national/state studies provide high-level maps but lack district-level, parcel-oriented outputs needed by local planners and utilities. Seoni represents a case where targeted outputs (rooftop lists for government buildings, contiguous parcels for small utility parks) are actionable.

2. **Integration of rooftop tenders with spatial prioritization:** Recent MPUVNL tenders in Seoni (2025) show demand for rooftop development; however, there is limited publicly available spatial prioritization that directly links tendered sites and district suitability mapping. A GIS-MCDA that simultaneously maps rooftop and utility opportunities bridges policy and implementation.

3. **Methodological robustness for local constraints:** Many studies use AHP without extensive sensitivity or local stakeholder calibration. Combining AHP (or hybrid weighting) with sensitivity testing, and explicit validation of NASA POWER at the district/nearby station scale, will enhance confidence in outputs for Seoni planners.

2.9. Synthesis and research contribution

The literature shows a mature set of GIS-MCDA tools and growing methodological refinements (hybrid weighting, validation protocols). For Seoni district, the contribution of this study is threefold: (1) produce **actionable, district-scale suitability maps** for both rooftop and utility applications linked to recent MPUVNL tendering; (2) combine **AHP-based weighting with sensitivity analysis** and satellite data validation (NASA POWER) to improve robustness; and (3) generate **parceled candidate lists and generation estimates** that local utilities and district planners can use for procurement and grid-integration planning. This targeted application fills a practical gap between state/national policy ambitions and district-level implementation needs.

3. STUDY AREA: SEONI DISTRICT, MADHYA PRADESH

Seoni district (southern Madhya Pradesh) comprises rural and semi-urban settlements, varied topography (including Pench National Park buffer in parts), and an electricity distribution network under MPUVNL. The district has been included in recent rooftop tendering and government deployment efforts, indicating active local interest in solar rooftop and utility projects. This makes Seoni a pragmatic test case for district-level solar planning.

4. DATA SOURCES AND PREPROCESSING

Major datasets (inputs) used:

1. **Solar resource:** Satellite-derived surface solar radiation and meteorological parameters — NASA POWER (monthly/daily average global horizontal irradiance, clearness index). Use POWER for site-specific time-series and long-term averages.

2. **Digital Elevation Model (DEM):** SRTM 30m (or ALOS) to compute slope and aspect.

3. **Land use / Land cover (LULC):** Recent LULC maps (satellite classification, e.g., Landsat/Sentinel-derived), to identify built-up, agricultural, forest, water bodies.

4. **Protected areas/eco-sensitive zones:** National/state protected area shapefiles (Pench NP buffer, reserve forests).

5. **Infrastructure:** Grid substations, medium/low voltage lines (where available), major roads, settlements. Local utility data and MPUVNL project lists aid locating prioritized rooftop or government building candidates.

6. **Soil & slope constraints:** Soil type maps for mounting feasibility; slope thresholds from DEM.

7. **Administrative boundaries:** District and village polygons.

Preprocessing steps: reproject all layers to a common projected CRS (e.g., UTM zone appropriate for Seoni), resample to a common cell size (recommended 30 m for district scale), compute slope/aspect from DEM, derive distance rasters for proximity criteria, and create binary exclusion masks (water bodies, protected areas, slopes > certain thresholds).

5. CRITERIA SELECTION AND JUSTIFICATION

Based on literature and local context, the following criteria are recommended (grouped):

Resource & terrain (technical)

- Annual average Global Horizontal Irradiance (GHI) — higher is better. (NASA POWER).
- Slope — flatter slopes preferred (<5° ideal; up to 15° possible with extra cost).
- Aspect — south-facing aspects preferred for fixed tilt in northern hemisphere.

Land suitability & constraints (environmental/social)

- Land use class — exclude dense forests, water bodies, and prime agriculture; prefer degraded lands, fallow, industrial areas, rooftops (for rooftop scenario).
- Protected / ecologically sensitive areas — exclude (hard constraint).

Accessibility & cost (economic)

- Proximity to transmission/substation and roads — closer reduces balance-of-system and O&M costs.
- Proximity to settlements (for rooftop/ distributed generation): higher priority for rooftops near load centers.

Regulatory & policy

- Government land and municipal properties for rooftop on public buildings (policy preference). MPI and MNRE rooftop schemes often prioritize government premises.

6. WEIGHTING METHOD — AHP

Analytic Hierarchy Process (AHP) is used to derive criterion weights from pairwise comparisons. Below is an example AHP workflow and an illustrative weight set (adaptable after stakeholder consultation):

1. Define goal (optimal solar site).

2. Criteria groups: Resource (GHI), Terrain (slope/aspect), Land Use/Environment, Accessibility, Policy/administrative.

3. Pairwise comparison and normalization produce weights. (The user/researcher should run the AHP matrix interactively; below is an example weight distribution to use as starting point.)

Illustrative example weights (normalized):

- GHI (Resource): 0.35
- Land Use/Environment: 0.20
- Accessibility (distance to grid/road): 0.20
- Slope/Aspect (Terrain): 0.15
- Policy/administrative preference (public buildings): 0.10

7. GIS WORKFLOW & MCDA IMPLEMENTATION

1. **Create exclusion mask:** Protected areas, water bodies, urban dense cores (if for utility), slopes greater than threshold, and other no-go zones.

2. **Prepare criterion rasters:** Reclassify GHI into suitability classes (e.g., >5.5 kWh/m²/day = highest), slope into classes, distance to grid and roads into classes, LULC into suitability classes, rooftop potential map from building footprints. Use 30 m raster cell.

3. **Standardize rasters:** Rescale each criterion to a common suitability scale (0–1 or 1–5).

4. **Apply weights:** Weighted overlay: Suitability = Σ (weight_i × standardized_i).

5. **Produce final suitability map:** Classify results into Very High, High, Moderate, Low suitability.

6. **Cluster analysis:** Identify contiguous patches above suitability thresholds sized for different project scales (e.g., >5 ha for utility-scale).

7. **Potential estimation:** For each suitable patch estimate available area × panel efficiency × irradiation × performance ratio to compute theoretical annual generation (MWh). Use NASA POWER GHI averages for each patch.

8. RESULTS

- **Suitability maps** for the district (Very High, High, Moderate) for (a) utility-scale, (b) rooftop clusters, and (c) distributed rooftop scenario.
- **Table of top candidate parcels**: ID, centroid coordinates, area (ha), mean GHI, distance to nearest substation, expected annual generation (MWh).
- **Area & capacity summary**: total area in Very High & High suitability classes; theoretical MW capacity assuming a specific capacity density (e.g., 1 MW per 5–8 ha depending on layout).
- **Sensitivity analysis**: maps showing changes in top-ranked sites when resource weight is increased/decreased.
- **Validation:** compare satellite GHI to any available ground measurements or use other published solar maps (Solar Atlas / SRRA adjustments) to validate spatial patterns.

9. DISCUSSION

- Seoni's mapped suitability identifies both rooftop opportunities (municipal buildings, schools, government premises) and medium-sized utility sites outside ecologically sensitive zones. Recent MPUVNL rooftop tenders demonstrate demand and policy alignment, reinforcing the need for such spatial planning tools to target investment and planning.
- Environmental constraints (Pench buffer and reserve forests) are major exclusion factors and require careful consultation.
- Proximity to substations is a limiting factor; clustered rooftop deployment in municipal and institutional roofs can reduce transmission requirements and align with MNRE rooftop schemes.

10. POLICY & IMPLEMENTATION RECOMMENDATIONS

1. **Use suitability maps to prioritize government rooftops and degraded land for early projects** to reduce social conflict.
2. **Coordinate with MPUVNL and distribution utility** to plan grid upgrades in identified high-suitability clusters.
3. **Incorporate local stakeholder consultation** especially where suitability overlaps agricultural lands or near protected areas.
4. **Adopt a phased deployment**: rooftop (municipal/public buildings) → rooftop for commercial clusters → utility-scale on degraded/industrial lands.
5. **Make GIS outputs public** (interactive web map) to attract private developers and to ensure transparency.

11. LIMITATIONS & FUTURE WORK

- Accuracy depends on underlying spatial datasets (LULC, grid lines). Where utility data is incomplete, on-ground surveys are required for fine-scale planning.
- Rooftop potential estimation requires high-resolution building footprints and roof orientation data (LiDAR or high-res imagery).
- Future work: integrate economic layers (land cost, tariffs), life-cycle environmental impact assessment, and micro-siting using high-resolution solar resource measurement campaigns.

12. CONCLUSION

A GIS-MCDA framework combining satellite solar data, terrain, land use, environmental, and infrastructure criteria yields a transparent and practical decision support tool for sustainable solar energy planning in Seoni district. The methodology supports both utility and rooftop planning, aligns with national rooftop initiatives, and can be used as a template for other districts in Madhya Pradesh and India.

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