Vol.3, No.4, Page 999- 1007, 2025 https://doi.org/10.59628/jast.v3i4.2068 ISSN 2958-9568 JAST

SUN PUBLISHER

مجلة جامعة صنعاء للعلوم التطبيقية والتكنولوجيا
Sana'a University Journal of Applied Sciences and Technology
https://journals.su.edu.ye/index.php/jast/

Suitability Analysis of Solar Energy Plant Sites in Yemen Using AHP, BWM, and GIS Methods

A. N. Algawbery , M. A. Shukri * and M. K. AL-Moutawakel

Department of Physics, Faculty of Science, Sana'a University, Sana'a, Yemen

*Corresponding author: mshukri@su.edu.ye

Abstract

The study presents a comprehensive evaluation of optimal locations for solar energy facilities in Yemen by combining Geographic Information System (GIS) technology with Multi-Criteria Decision-Making (MCDM) methodologies. It identifies twelve crucial criteria, assigning weights through the Analytical Hierarchy Process (AHP) and subsequently validating them using the Best-Worst Method (BWM). A weighted overlay analysis conducted in GIS resulted in a national suitability map, indicating that the eastern, southern, and northern regions of Yemen are particularly well-suited for solar energy development. The findings reveal that 30.84% of the country is classified as highly suitable, while 69.16% is moderately suitable, and merely 0.0022% is deemed less suitable for solar installations. The sensitivity analysis highlights the significant influence of weighting the criteria, as even slight modifications to factors such as Global Horizontal Irradiance (GHI) and slope can lead to substantial changes in suitability assessments. Overall, the integration of AHP, BWM, and GIS is shown to create a robust framework for solar site selection, providing practical guidance for policymakers and energy planners in Yemen.

Article Info

Keywords:
Solar Energy, Site Suitability Analysis Yemen Renewable Energy Planning, Multi-Criteria Decision (MCD), Best-Worst Method (BWM).

Article History:
Received: 20-July-2025,
Revised: 6-August-2025,
Accepted: 20-August-2025,
Available online: 28 August 2025.

1. INTRODUCTION

1.1. Background

Driven by the global imperative to adopt sustainable resources, solar energy has emerged as a key alternative to conventional fossil fuels, playing a vital role in satisfying global energy requirements [1, 2]. Due to its potential to reduce greenhouse gas emissions, solar energy has become integral to international energy policy and climate change mitigation frameworks [1, 2]. Nevertheless, the successful implementation of solar energy projects is contingent upon specific environmental and geographical conditions, including solar irradiance, ambient temperature, and topography. These factors are critical in determining the operational efficiency and economic viability of photovoltaic systems [3, 4].

The availability of solar energy varies significantly by location. Consequently, the optimal performance of photovoltaic panels is typically observed in regions characterized by high solar radiation, a condition frequently correlated with equatorial proximity [5]. Ambient temperature is another critical factor affecting photovoltaic efficiency. High temperatures can diminish energy conversion by increasing electrical resistance, while extremely low temperatures may also degrade component performance [3]. Although Yemen possesses significant solar energy potential, its development is impeded by formidable challenges, such as inadequate energy infrastructure, limited financial resources, and persistent political instability [5–7]. Therefore, optimizing the performance and economic feasibility of solar projects in Yemen requires meticulous site selection based on a rigorous analysis of solar radiation, temperature, land suitability, and geographical constraints [8, 9].

1.2. Literature Review

Site suitability evaluation is fundamental to sustainable energy strategy. An extensive body of literature demonstrates the application of Multi-Criteria Decision-Making

(MCDM) techniques, such as the Analytical Hierarchy Process (AHP) and the Best-Worst Method (BWM), in conjunction with Geographic Information Systems (GIS) for locating optimal solar energy sites [10, 11]. This research consistently emphasizes the importance of criteria like solar irradiance, land use/land cover (LULC), topography (slope and aspect), and proximity to key features, including transportation networks, urban centers, heritage sites, and coastlines.

The AHP, introduced by Saaty [12], is valued for its capacity to deconstruct complex problems into a hierarchical structure and synthesize quantitative data with qualitative expert opinion. This method, frequently coupled with GIS, has been applied in numerous solar site suitability studies globally. For instance, Koc et al. [8] in Turkey highlighted the primary importance of solar radiation. Uyan [9] applied an integrated AHP-GIS approach to map suitable locations in Turkey's Karapinar region. Saraswat et al. [13] identified solar farm sites in India using GIS-based MCDM, considering solar radiation, LULC, and proximity to the electrical grid. Other studies by Jbaihi et al. [14] and Ali et al. [15] further demonstrate the effectiveness of AHP-GIS in renewable energy planning.

The BWM, developed by Rezaei [11], offers an alternative approach requiring fewer pairwise comparisons than AHP, improving consistency and reducing expert cognitive load [11, 16]. BWM focuses on comparisons relative to the best and worst criteria, enhancing reliability [16]. Studies integrating BWM with GIS, such as Trivedi et al. [17] and Pamučar et al. [18], have highlighted its efficiency and applicability in renewable energy assessments.

GIS technology plays a crucial role by providing a platform for spatial data management, analysis, and visualization. Integration with MCDM techniques enables the incorporation of diverse geographical, environmental, and infrastructural factors into suitability assessments [10]. GIS facilitates the creation of suitability maps through weighted overlay analysis, visually representing the spatial distribution of suitable areas [19, 20]. Despite these advancements, reliance on expert judgment introduces subjectivity, and data availability or quality can constrain analyses, particularly in Yemen [21–24].

1.3. Research Gap and Justification

While GIS and MCDM have been widely applied for solar site suitability worldwide, research explicitly focused on Yemen remains scarce despite its vast solar potential and urgent energy needs [25, 26]. Existing studies often address broader regional assessments [27, 28] or focus on policy issues [29, 30] and solar irrigation [31], without providing a comprehensive, nationwide suitability analysis. Yemen's distinctive context—characterized by prolonged conflict, infrastructural deficits, and unique geographical conditions [31]—requires a customized assessment framework.

Three primary research gaps are evident:

- Geographic gap: Neighboring countries, such as Saudi Arabia and Oman, have been studied, but detailed national analyses for Yemen are missing.
- Methodological gap: Although AHP is commonly applied, its results are rarely validated against other MCDM methods, such as BWM, within this regional context.
- Contextual gap: Models designed for stable regions cannot be directly applied to Yemen due to conflict, political instability, and infrastructural limitations.

To address these gaps, this study develops an integrated AHP-BWM-GIS methodology tailored to Yemen, enhancing both methodological rigor and practical applicability.

1.4. Research Aims, Questions, and Contribution

This study aims to develop a robust decision-support framework for solar energy site selection in Yemen by integrating the Analytic Hierarchy Process (AHP), the Best–Worst Method (BWM), and Geographic Information Systems (GIS). The framework addresses Yemen's urgent energy challenges by identifying optimal solar development zones, ensuring methodological rigor, and providing policy-relevant guidance.

To achieve this aim, the study is guided by the following research questions:

- What are the most influential environmental, geographical, and infrastructural criteria for solar site suitability in Yemen?
- How do criteria weights derived from AHP compare with those obtained from BWM in terms of consistency and reliability?
- What is the spatial distribution of suitable zones when applying an integrated AHP–BWM–GIS framework?
- How sensitive are suitability outcomes to variations in key criteria such as Global Horizontal Irradiance (GHI) and slope?
- What actionable recommendations can be drawn for energy planning, investment, and policy design in Yemen's renewable energy sector?

These questions are addressed through the following hypotheses:

- H1:Eastern, southern, and northern regions of Yemen possess the highest suitability due to favorable solar irradiance and topography.
- H2: BWM produces more consistent and reliable weighting results than AHP alone.
- H3: The integration of AHP and BWM within a GIS

framework yields more accurate suitability maps compared to single-method approaches.
- H4: Sensitivity analysis will show that minor changes in GHI and slope weights significantly affect suitability classifications.

The innovations and contributions of this study are fourfold:
- Methodological Integration: A novel application of AHP and BWM within a GIS-based MCDM framework tailored to Yemen.
- National-Scale Assessment: The first comprehensive solar site suitability mapping study covering Yemen's entire territory.
- Sensitivity and Validation: Robustness tested through sensitivity analysis and validation against expert feedback.
- Policy-Relevant Insights: Actionable recommendations addressing energy security, infrastructure planning, and private-sector investment.

Accordingly, the objectives of this study are to:
- Identify and prioritize the criteria influencing solar suitability.
- Derive and validate weights using AHP and BWM.
- Generate a national solar suitability map using GIS-based weighted overlay.
- Test robustness through sensitivity analysis.
- Provide practical recommendations for strategic solar energy development in Yemen.

2. METHODOLOGY

This study employed an integrated Multi-Criteria Decision-Making (MCDM) and Geographic Information System (GIS) framework to identify and evaluate suitable locations for solar energy plants in Yemen. The methodology comprised three main stages: (1) data acquisition and preprocessing, (2) criteria weighting using AHP and BWM, and (3) GIS-based spatial analysis through weighted overlay to generate the final suitability maps [32].

2.1. Data Acquisition and Preprocessing

Twelve criteria were selected to assess solar site suitability in Yemen, structured into three groups: environmental (GHI, temperature, precipitation), topographic (elevation, slope, aspect, LULC), and infrastructural/proximity (distance to roads, urban centers, airports, rivers, coastlines, and heritage sites) [8, 14, 15, 33–35].

Datasets were obtained from sources including the Global Solar Atlas, DIVA-GIS, OpenStreetMap, ASTER GDEM V2, meteorological stations, and government GIS repositories [3, 4, 9, 19, 25, 33, 34]. Vector data were converted to raster, harmonized to $3030\,m$ resolution in WGS 1984 UTM Zone 38N, and normalized using min–max scaling to ensure comparability across criteria [10, 19]. Environmental layers (e.g., GHI, temperature) captured solar energy potential, topographic datasets informed construction feasibility and solar exposure, while LULC and proximity measures accounted for land suitability, infrastructure accessibility, and ecological/cultural constraints.

2.2. Criteria Reclassification

To standardize suitability across all factors, each raster layer was reclassified on a 1–5 scale using the Reclassify tool in ArcGIS, where 1 represents least suitable and 5 represents most suitable areas. Classification thresholds were derived from established literature on solar energy site selection [8, 14, 36] and adapted to Yemen's geographic and environmental context to ensure the results were regionally applicable.

2.3. Criteria Weighting

The relative importance of each of the twelve criteria was determined using two distinct MCDM methods: AHP and BWM.

2.3.1. AHP Methodology

The Analytical Hierarchy Process (AHP) was employed to hierarchically structure the decision problem and derive the weights for each criterion. This involved performing pairwise comparisons of criteria, a process typically carried out by experts or, in this study's context, likely the authors based on their literature review and understanding of the specific context in Yemen. Saaty's 1-9 scale was used for these comparisons, where a value of 1 signifies equal importance between two criteria, and 9 indicates extreme importance of one criterion over another. Intermediate values (3, 5, 7) represented moderate, strong, and very strong importance, respectively, with reciprocal values (1/3, 1/5, etc.) used for inverse comparisons [12, 14].

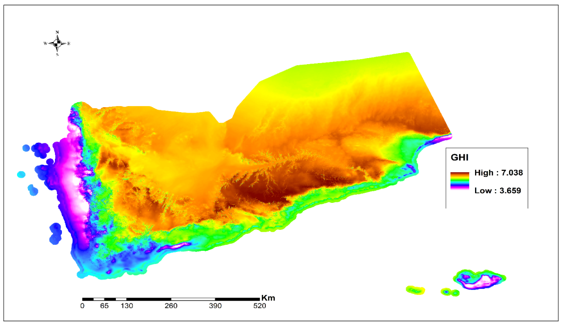
A pairwise comparison matrix (PCM) was constructed from these judgments. This matrix was then normalized by dividing each element by the sum of its respective column, as shown in Equation 1:

$$\bar{A}_{\text{norm}} = \bar{a}_{jk} = \frac{a_{jk}}{\sum_{i=1}^{n} a_{ik}}, \quad (1)$$

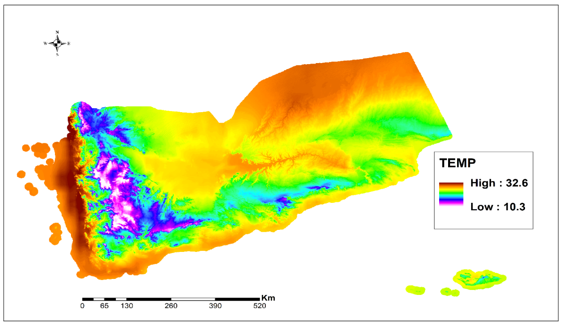
where a_{jk} represents the judgment comparing criterion j to criterion k. The criterion weight vector (W) was subsequently obtained by averaging the rows of the normalized matrix, as presented in Equation 2:

$$W_j = \frac{\sum_{k=1}^{n} \bar{a}_{jk}}{n}, \quad (2)$$

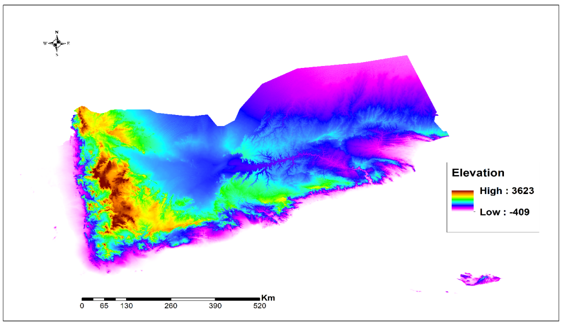
where n is the number of criteria. The consistency of the



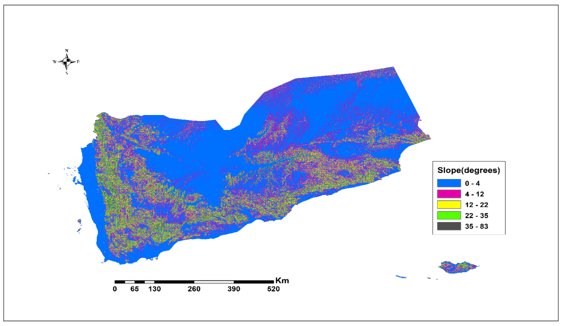
(a) Global horizontal irradiance of Yemen.(Source: Global Solar Atlas)



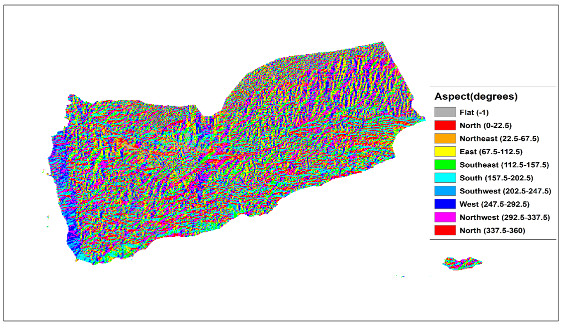
(b) Annual average temperatures in Yemen. (Source: Global Solar Atlas)



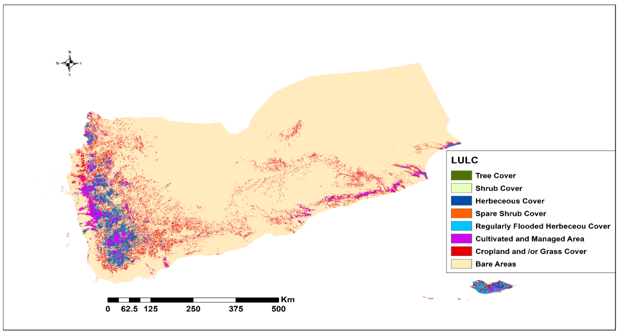
(c) Elevation in metres.



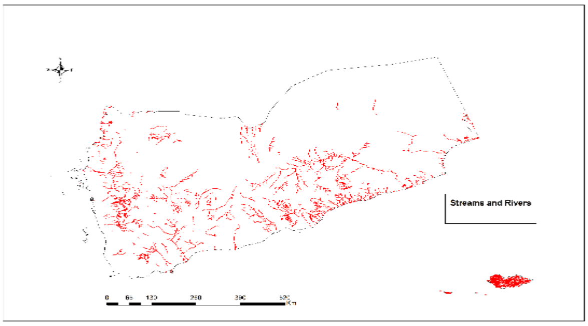
(d) Slope in degrees



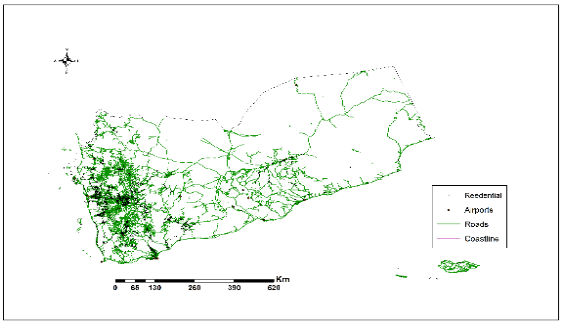
(e) Aspect in degrees



(f) Land Use/Land Cover



(g) Proximity to Infrastructure



(h) Distance to Rivers and Stream

Figure 1. The eight key criteria layers: (a) GHI, (b) annual mean temperature, (c) levation, (d) slope, (e) aspect, (f) land use and land cover, (g) infrastructure proximity, and (h) distance to rivers and streams.

judgments was evaluated using the Consistency Ratio (CR). First, the principal eigenvalue (λ_{max}) was calculated using Equation 3:

$$\lambda_{\text{max}} = \frac{\sum_{j=1}^{n} \left(\bar{A}_{\text{norm}} \cdot W\right)_j}{W_j}. \quad (3)$$

Then, the Consistency Index (CI) was calculated using Equation 4:

$$CI = \frac{\lambda_{\text{max}} - n}{n-1}. \quad (4)$$

Finally, the CR was computed by dividing the CI by the Random Index (RI), a standard value based on the matrix size (n) [12, 19]. A CR value below 0.10 (or 10%) was considered to indicate acceptable consistency in the pairwise comparisons. All AHP calculations were performed using MATLAB [37, 38].

2.3.2. BWM Methodology

The BWM, developed by Rezaei [11], was utilized as an alternative approach to determine criteria weights, offering the advantage of requiring fewer comparisons than the Analytical Hierarchy Process (AHP). In this method, the decision-maker initially identifies the best (most important) criterion (C) and the worst (least important) criterion (C_W) from the set of identified criteria. Subsequently, pairwise comparisons are performed in a structured manner: first, comparing the best criterion (C_B) against all other criteria (referred to as the Best-to-Others vector), and then, comparing all other criteria against the worst criterion (C_W) (referred to as the Others-to-Worst vector). These comparisons utilize a 1-9 scale, similar to that employed in AHP.

The optimal weights (w_1, w_2,..., w_{12}) for the twelve criteria are then derived by solving a constrained optimization problem. This problem is formulated to minimize the maximum absolute differences between the comparison ratios (established from the Best-to-Others and Others-to-Worst vectors) and the corresponding weight ratios [11, 38]. To ensure the reliability of these comparisons, a consistency ratio is also calculated for BWM. All BWM calculations in this study were performed using MATLAB [37, 38].

2.4. Weighted Overlay Analysis

The final step involved integrating the reclassified criteria layers (Section 2.2) with their corresponding weights derived from both AHP and BWM (Section 2.3) using the Weighted Overlay tool in ArcGIS 10.8 [20]. This tool combines multiple raster layers based on their assigned importance (weights) and suitability scores within each layer.

Two separate suitability maps were generated: one using the AHP-derived weights and one using the BWM-derived weights. The tool calculates a final suitability score for each cell based on the sum of the products of the reclassified suitability score and the criterion weight, typically normalized to a common scale.

$$\text{Suitability\_Score} = \sum_i (w_i \times s_i), \quad (5)$$

where w_i is the weight of criterion i and s_i is the reclassified suitability score of the cell for criterion i.

The resulting continuous suitability scores were then classified into distinct categories (e.g., optimal, highly suitable, suitable) based on defined thresholds or natural breaks in the data distribution, producing the final suitability maps (as shown conceptually in Figure 2).

2.5. Sensitivity Analysis

A sensitivity analysis was performed to assess the impact of variations in criteria weights on the final suitability classification. This involved systematically adjusting the weights of key criteria (specifically GHI and slope) and observing the resulting changes in the spatial distribution and extent of the suitability categories. This analysis helps understand the robustness of the results and identifies criteria to which the model is particularly sensitive.

3. RESULTS

3.1. Criteria Weights from AHP and BWM

The relative importance of the twelve selected criteria for solar energy plant site suitability in Yemen was quantified using both the Analytical Hierarchy Process (AHP) and the Best-Worst Method (BWM). AHP involved constructing pairwise comparison matrices following Saaty's scale, with consistency verified through the Consistency Ratio (CR) [12, 18]. BWM required identification of the best and worst criteria and subsequent pairwise comparisons relative to them, optimizing weights using a constrained minimization approach [11, 16].

The normalized weights derived from both methods are presented in Table 1. Both AHP and BWM consistently identified Global Horizontal Irradiance (GHI) as the most influential factor, followed by elevation and distance to main roads, underscoring the significance of climatic and topographic variables in determining solar site suitability. Intermediate importance was assigned to criteria such as temperature, distance to cities, aspect, land use/land cover (LULC), and slope, while spatial constraints such as distance to coastline, rivers/streams, airports, and archaeological sites received comparatively lower weights [8, 10, 18].

The calculated Consistency Ratio (CR = 0.002551) for the AHP comparisons is well below the 0.10 threshold, indicating excellent consistency and reliability in the expert judgments. The close alignment between AHP and BWM weights further strengthens confidence in the robustness of the criteria weighting, providing a solid foundation for subsequent GIS-based site suitability analysis [8, 9, 11].

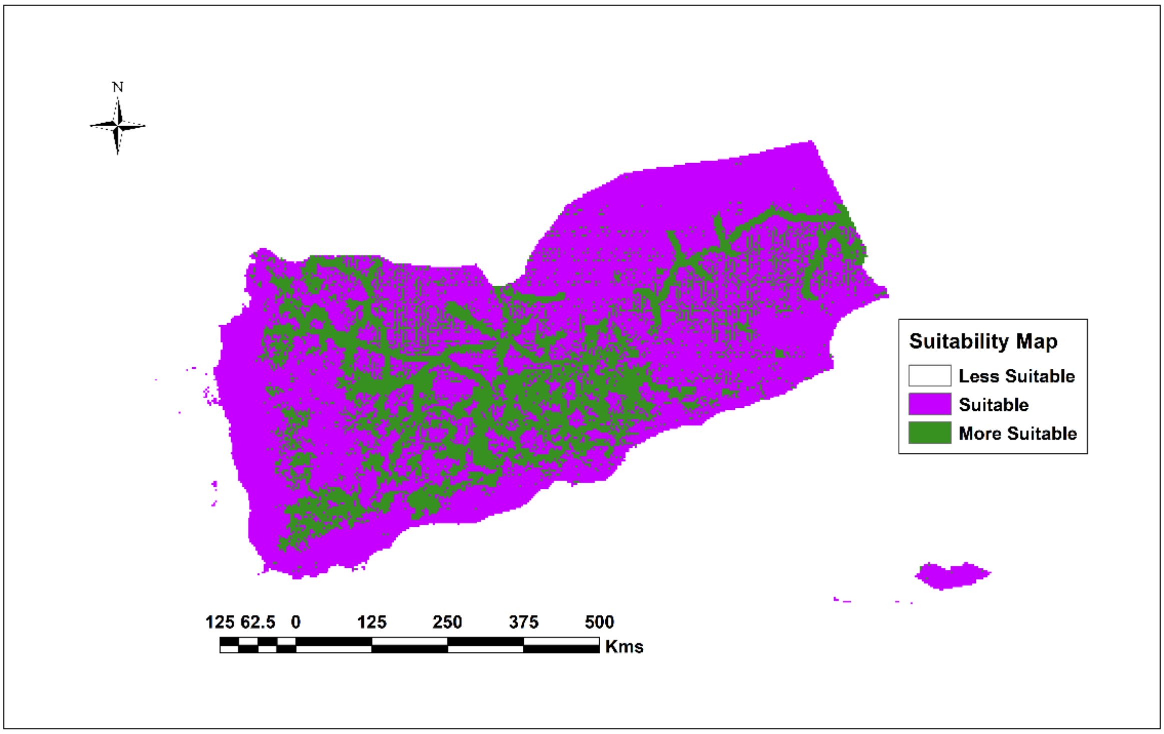


Figure 2. Suitability map

Table 1. Normalized Weights of Criteria Derived from AHP and BWM.

Criterion	BWM Weight	AHP Weight
Global Horizontal Irradiance (GHI)	0.2696	0.267
Elevation	0.1643	0.166
Distance to Main Roads	0.1067	0.093
Temperature	0.0600	0.068
Distance to Cities	0.0578	0.060
Aspect	0.0578	0.060
Land Use/Land Cover (LULC)	0.0566	0.059
Slope	0.0566	0.059
Distance to Coastline	0.0538	0.052
Distance to Rivers & Streams	0.0538	0.052
Distance to Airports	0.0345	0.035
Distance to Archaeological Sites	0.0286	0.030

3.2. Site Suitability Map

Given the strong consistency between the AHP- and BWM-derived weights, the AHP weights were applied in a weighted overlay analysis using ArcGIS 10.8. This process combined the normalized weights with reclassified spatial layers for each criterion, producing a comprehensive solar energy site suitability map for Yemen .

The final suitability map classifies the study area into three categories based on composite suitability scores:

- Highly Suitable (Level 3): Areas with optimal conditions for solar plant development, meeting most criteria at high levels.
- Moderately Suitable (Level 2): Areas with substantial potential, generally fulfilling the requirements but with minor limitations.
- Less Suitable (Level 1): Areas that remain viable but face significant constraints, requiring mitigation or adaptation strategies.

The spatial analysis shows that 30.8389% of Yemen's land area is highly suitable, while 69.1589% is moderately suitable, concentrated mainly in the eastern, southern, and northern regions. Only 0.0022% falls into the less suitable category, primarily within the western highlands and mountainous areas. These patterns reflect the combined influence of Global Horizontal Irradiance (GHI), moderate temperatures, flat topography, and favorable land cover conditions.

Table 2. Distribution of Site Suitability Classifications for Solar Energy Plants in Yemen

Suitability Level	Suitability Category	Percentage of Study Area (%)
3	Highly suitable	30.8389
2	Moderately Suitable	69.1589
1	Less suitable	0.0022

3.3. Sensitivity Analysis

A one-at-a-time sensitivity analysis was conducted to assess the robustness of the site suitability results, focusing on the most influential criteria: Global Horizontal Irradiance (GHI) and slope. Weight variations of ±10% and ±20% were applied to evaluate their impact on the spatial distribution of suitability categories [8, 9, 16, 18].

Key findings include:

- GHI: Increasing the weight by 10–20% slightly expands highly suitable areas, particularly in the eastern and southern regions, highlighting its critical role in solar potential.
- Slope: Increasing the weight reduces highly suitable zones in mountainous regions, emphasizing slope's importance in photovoltaic efficiency.
- Other factors: Infrastructural and proximity-related criteria exhibited minimal influence on the spatial extent of suitability categories.

4. DISCUSSION

This study provides the first comprehensive national-scale solar energy suitability assessment for Yemen, applying an integrated MCDM–GIS framework that combines the Analytical Hierarchy Process (AHP), the Best–Worst Method (BWM), and weighted spatial overlay. The findings highlight Yemen's substantial solar energy potential while emphasizing the methodological and policy considerations required for effective implementation.

4.1. Criteria Weighting and Methodological Insights

The comparative use of AHP and BWM demonstrated high consistency in criteria weighting, with Global Horizontal Irradiance (GHI) consistently emerging as the most influential factor, followed by elevation and proximity to roads. This outcome is aligned with both the physical fundamentals of solar energy generation and previous studies across the MENA region [12, 27, 39, 40]. The strong agreement between AHP and BWM confirms the robustness of the weighting process, while the lower comparison burden of BWM highlights its practical advantage for expert-based assessments. Nonetheless, AHP's hierarchical structure remains valuable for decomposing complex decision problems.

5. SPATIAL DISTRIBUTION AND REGIONAL POTENTIAL

The suitability map confirms that nearly all of Yemen's territory is favorable for solar energy development. Specifically, 30.8389% of the country is classified as highly suitable (Level 3), while 69.1589% is moderately suitable (Level 2). Less than 0.01% is categorized as less suitable (Level 1), mainly within mountainous western zones. The most promising regions are concentrated in the east, south, and north, where high irradiance, relatively flat topography, and accessible land dominate [41].

6. SENSITIVITY AND ROBUSTNESS OF THE MODEL

Sensitivity testing showed that modest adjustments in the weights of GHI and slope substantially reshaped the distribution of suitability categories, with optimal areas decreasing by half when GHI weight was reduced. This underscores both the importance of accurate weight assignment and the inherent vulnerability of MCDM results to expert assumptions. Such findings reinforce the need for iterative validation and incorporation of local expertise when scaling this framework to project-level planning. In addition to the significance of selecting optimal sites for solar projects, the performance and efficiency of photovoltaic modules are highly influenced by local climatic conditions. A recent study in Sana'a demonstrated that polycrystalline silicon PV modules exhibited noticeable degradation rates after 8.65 years of operation under the city's weather conditions (Dahesh & Al-Matwakel, 2025) [42].

6.1. Limitations and Research Boundaries

While this study provides a robust national-scale framework, it is important to acknowledge its limitations, which also define clear boundaries for its application. First, the study is constrained by its reliance on global or national-scale datasets (e.g., DEM, satellite-derived GHI, generalized LULC), which may overlook local-scale variability. The uncertainty in our model stems from two primary sources: the inherent accuracy of these input spatial datasets and the subjectivity in the criteria weighting process. Datasets like Global Horizontal Irradiance (GHI) are derived from satellite imagery and meteorological models, not a dense network of ground stations in Yemen, and thus carry inherent model uncertainty. Similarly, the 30m resolution of the DEM can smooth out fine-scale topographical features, and data for infrastructure like roads may have positional inaccuracies or be incomplete. Errors in these inputs can propagate into the suitability classification, particularly given the model's sensitivity to highly weighted criteria like GHI.Second, the weighting process, while systematic and validated for consistency, retains an element of subjectivity based on the expert judgments that inform it.shaped by on-the-ground realities, including governance, security, and institutional stability. These "soft" factors represent a necessary next step for analysis to ensure that technical recommendations align with the socio-political landscape of Yemen. Overall, these limitations point to the importance of complementing national-scale assessments with finer-resolution, locally validated analyses and incorporating socio-political and conflict-sensitive considerations into future frameworks.

7. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

7.1. Conclusion

This study successfully developed an integrated multi-criteria decision-making framework, utilizing AHP, BWM, and GIS, for a comprehensive nationwide site suitability analysis for solar energy facilities in Yemen. The consistent criteria weights obtained through AHP and BWM validate the importance of various factors. Notably, Global Horizontal Irradiance (GHI) emerged as the foremost determinant of site suitability, closely followed by elevation and proximity to road infrastructure, emphasizing the significance of logistical considerations alongside resource availability. The GIS-based weighted overlay analysis revealed that a substantial portion of Yemen's land—approximately 100%-is either highly suitable (30.84%) or moderately suitable (69.16%) for solar development. These findings delineate promising zones concentrated in the eastern, southern, and northern regions, underscoring the country's immense solar potential. This research addresses a critical knowledge gap and offers a foundational spatial framework and strategic tool for policymakers and investors. It provides data-driven insights to support the development of Yemen's solar infrastructure and informs a national solar master plan. By identifying high-potential areas, the study facilitates targeted investments in transportation and energy infrastructure, ultimately promoting the sustainable harnessing of Yemen's significant solar resources.

7.2. Future Research Directions

Building on this work, future studies should:

- Enhance data resolution and validation by integrating high-resolution, locally sourced datasets (LULC, meteorological, grid infrastructure) and conducting on-site ground-truthing to validate the model's findings at a project scale.
- Incorporate socio-economic and governance factors such as land tenure, energy demand, political stability, and community acceptance, which are critical for determining practical feasibility and ensuring social license to operate.
- Advance environmental and climate integration by accounting for biodiversity impacts, water availability for panel cleaning, and disturbed land suitability. Crucially, future work should develop dynamic models that account for future climate change impacts. This would involve leveraging downscaled climate models (e.g., from CMIP) to project future changes in cloud cover and aerosol concentrations, which affect solar irradiance, as well as projecting future temperature increases that can decrease the operational efficiency of photovoltaic panels.
- Explore hybrid energy solutions and grid resilience, including solar–wind complementarity, energy storage systems, and micro-grid applications to ensure stable integration into Yemen's fragile energy systems.
- Strengthen participatory and policy-oriented approaches through stakeholder engagement (e.g., Delphi method, participatory GIS) and detailed policy/regulatory analysis to translate suitability maps into actionable deployment strategies. By bridging technical analysis with socio-political realities, future research can transform suitability assessments from academic exercises into operational roadmaps that advance Yemen's renewable energy transition and contribute to sustainable development under challenging conditions.

REFERENCES

[1] M. D. Nichols, B. McKibben, M. Z. Jacobson, *et al.*, *Proven Climate Solutions: Leading Voices on how to Accelerate Change* (Bloomsbury Publishing PLC, 2024).

[2] J. Shi and Y. Zhao, "Challenges and pathways for tripling renewable energy capacity globally by 2030," Chin. J. Urban Environ. Stud. **13**, 2550004 (2025).

[3] S. Dubey, J. N. Sarvaiya, and B. Seshadri, "Temperature dependent photovoltaic (pv) efficiency and its effect on pv production in the world–a review," Energy procedia **33**, 311–321 (2013).

[4] J. Twidell, *Renewable energy resources* (Routledge, 2021).

[5] H. Oukhija, "Climate crisis and conflict: A case study of the yemen war and its implications for peace and security," Ph.D. thesis, San Francisco State University (2024).

[6] I. Al-Wesabi, F. Zhijian, C. P. Bosah, and H. Dong, "A review of yemen's current energy situation, challenges, strategies, and prospects for using renewable energy systems," Environ. Sci. Pollut. Res. **29**, 53907–53933 (2022).

[7] S. Matallah, K. Zerigui, and A. Matallah, "Renewable energy solutions to the lack of access to electricity in conflict-ridden countries: A case study of yemen," Energy **296**, 131233 (2024).

[8] A. Koc, S. Turk, and G. Şahin, "Multi-criteria of wind-solar site selection problem using a gis-ahp-based approach with an application in igdir province/turkey," Environ. Sci. Pollut. Res. **26**, 32298–32310 (2019).

[9] M. Uyan, "Gis-based solar farms site selection using analytic hierarchy process (ahp) in karapinar region, konya/turkey," Renew. Sustain. Energy Rev. **28**, 11–17 (2013).

[10] B. Feizizadeh and T. Blaschke, "An uncertainty and sensitivity analysis approach for gis-based multicriteria landslide susceptibility mapping," Int. J. Geogr. Inf. Sci. **28**, 610–638 (2014).

[11] J. Rezaei, "Best-worst multi-criteria decision-making method," Omega **53**, 49–57 (2015).

[12] T. Saaty, *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*, Analytic hierarchy process series (RWS Publications, 1990).

[13] S. Saraswat, A. K. Digalwar, S. Yadav, and G. Kumar, "Mcdm and gis based modelling technique for assessment of solar and wind farm locations in india," Renew. Energy **169**, 865–884 (2021).

[14] O. Jbaihi, F.-z. Ouchani, A. A. Merrouni, *et al.*, "An ahp-gis based site suitability analysis for integrating large-scale hybrid csp+ pv plants in morocco: An approach to address the intermittency of solar energy," J. Clean. Prod. **369**, 133250 (2022).

[15] S. Ali, J. Taweekun, K. Techato, *et al.*, "Gis based site suitability assessment for wind and solar farms in songkhla, thailand," Renew. Energy **132**, 1360–1372 (2019).

[16] P. Majumder, V. E. Balas, A. Paul, and D. Baidya, "Application of improved fuzzy best worst analytic hierarchy process on renewable energy," PeerJ Comput. Sci. **7**, e453 (2021).

[17] P. Trivedi, J. Shah, R. Čep, *et al.*, "A hybrid best-worst method (bwm)—technique for order of preference by similarity to ideal solution (topsis) approach for prioritizing road safety improvements," IEEe Access **12**, 30054–30065 (2024).

[18] D. Pamučar, F. Ecer, G. Cirovic, and M. A. Arlasheedi, "Application of improved best worst method (bwm) in real-world problems," Mathematics **8**, 1342 (2020).

[19] A. Almasad, G. Pavlak, T. Alquthami, and S. Kumara, "Site suitability analysis for implementing solar pv power plants using gis and fuzzy mcdm based approach," Sol. Energy **249**, 642–650 (2023).

[20] K. Calvert and W. Mabee, "More solar farms or more bioenergy crops? mapping and assessing potential land-use conflicts among renewable energy technologies in eastern ontario, canada," Appl. Geogr. **56**, 209–221 (2015).

[21] M. Al-Saidi, E. L. Roach, and B. A. H. Al-Saeedi, "Conflict resilience of water and energy supply infrastructure: Insights from yemen," Water **12**, 3269 (2020).

[22] Y. M. Khaldi and M. Sunikka-Blank, "Governing renewable energy transition in conflict contexts: investigating the institutional context in palestine," Energy Transitions **4**, 69–90 (2020).

[23] V. Khare, S. Nema, and P. Baredar, "Solar–wind hybrid renewable energy system: A review," Renew. Sustain. Energy Rev. **58**, 23–33 (2016).

[24] T. Huld, "Pvmaps: Software tools and data for the estimation of solar radiation and photovoltaic module performance over large geographical areas," Sol. Energy **142**, 171–181 (2017).

[25] A. Q. Al-Shetwi, M. Hannan, M. A. Abdullah, *et al.*, "Utilization of renewable energy for power sector in yemen: current status and potential capabilities," IEEE Access **9**, 79278–79292 (2021).

[26] A. S. Rawea and S. Urooj, "Strategies, current status, problems of energy and perspectives of yemen's renewable energy solutions," Renew. Sustain. Energy Rev. **82**, 1655–1663 (2018).

[27] A. Aghahosseini, D. Bogdanov, and C. Breyer, "The mena super grid towards 100% renewable energy power supply by 2030," in *Proceedings of the 11th International Energy Conference, Tehran, Iran,* (2016), pp. 30–31.

[28] M. Jahangiri, R. Ghaderi, A. Haghani, and O. Nematollahi, "Finding the best locations for establishment of solar-wind power stations in middle-east using gis: A review," Renew. Sustain. Energy Rev. **66**, 38–52 (2016).

[29] S. Matallah, K. Zerigui, and A. Matallah, "Renewable energy solutions to the lack of access to electricity in conflict-ridden countries: A case study of yemen," Energy **296**, 131233 (2024).

[30] N. Narjabadifam, J. Fouladvand, and M. Gül, "Critical review on community-shared solar-advantages, challenges, and future directions," Energies **16**, 3412 (2023).

[31] M. M. Aklan and H. Lackner, "Solar-powered irrigation in yemen: opportunities, challenges and policies," Rethink. Yemen's Econ. **22**, 1–25 (2021).

[32] D. C. Jordan, J. H. Wohlgemuth, and S. R. Kurtz, "Technology and climate trends in pv module degradation," Tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States) (2012).

[33] J. Macknick, C. Lee, G. Mosey, and J. Melius, "Solar development on contaminated and disturbed lands," Tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States) (2013).

[34] OpenStreetMap Contributors, "Openstreetmap," [Online] (2023). Available: https://www.openstreetmap.org.

[35] Y. Zatsarinnaya, A. Logacheva, and D. Amirov, "Contamination of solar panels as factor in selecting location for construction and operation of solar power plants in russia," in *2019 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM),* (IEEE, 2019), pp. 1–5.

[36] P. Romero-Lankao, D. M. Gnatz, O. Wilhelmi, and M. Hayden, "Urban sustainability and resilience: From theory to practice," Sustainability **8**, 1224 (2016).

[37] Esri, "Arcgis desktop 10.8," [Online] (2019). Available: https://desktop.arcgis.com.

[38] MathWorks, "Matlab r2018a," [Online] (2018). Available: https://www.mathworks.com.

[39] S. E. Phillips and B. L. Cypher, "Solar energy development and endangered species in the san joaquin valley, california: Identification of conflict zones," West. Wildl. **6**, 29–44 (2019).

[40] D.-J. Van de Ven, I. Capellan-Peréz, I. Arto, *et al.*, "The potential land requirements and related land use change emissions of solar energy," Sci. reports **11**, 2907 (2021).

[41] C. Cader, S. Pelz, A. Radu, and P. Blechinger, "Overcoming data scarcity for energy access planning with open data-the example of tanzania," The Int. Arch. Photogramm. Remote. Sens. Spatial Inf. Sci. **42**, 23–26 (2018).

[42] M. Dahesh and M. Al-Matwakel, "Degradation analysis of 8.65-year-old polycrystalline silicon pv modules under the weather conditions of sana'a-yemen," Sana'a Univ. J. Appl. Sci. Technol. **3**, 628–633 (2025).