

Geospatial Suitability Mapping for Sustainable Energy Site Selection in Iraq

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ABSTRACT

This study aims to identify the best sites for establishing solar and wind energy farms in Iraq through a Multi-Criteria Evaluation (MCE) paired with a Geographic Information System (GIS) technology. Various environmental and infrastructural factors were assessed, including solar radiation intensity, wind speed, terrain slope, proximity to power lines, distance from major roads, and distance from bodies of water. The layers were standardized, weighted, and combined to create a comprehensive suitability map. The findings indicated that approximately 31% of the research area is highly suitable for Renewable Energy (RE) development, 30% is moderately suitable, and 39% is unsuitable due to environmental or logistical constraints. The most advantageous regions were identified in southeastern Iraq and small parts of the western area. The research provides a scientific foundation for energy planners and decision-makers to formulate sustainable energy policies. It supports the national efforts to diversify the energy portfolio, reduce the dependence on fossil fuels, and achieve long-term sustainable development goals. The findings underscore the importance of GIS-based Multi-Criteria Analysis (MCA) in improving land use planning for RE infrastructure.

Keywords-remote sensing; MCE; solar radiation; wind speed; Iraq electricity; sustainable energy

I. INTRODUCTION

To meet the growing demand for energy and support the achievement of sustainable development goals, sustainable energy has become an important energy source [1]. Due to their purity, availability, power factor, and construction costs relative to other clean energy options, solar and wind power systems rank among the most advanced and widely researched green energy sources [2]. The increased utilization of RE is necessary for smarter, more sustainable cities of the future [3]. Because of the challenges in finding large areas of land for these types of investment, along with the temporal and spatial variability of wind and solar resources, planners have started to concentrate on hybrid RE systems [4]. By combining the strengths of two systems, such hybridization compensates for the weaknesses of one. Besides the reliability of the power source, hybrid solar systems provide lower development costs, which encompass labor, operation, and maintenance expenses, the number of storage units, and site acquisition or leasing fees [5]. Systems powered by a combination of solar and wind

energy are more efficient than those relying on a single source [6]. The constraints define the acceptable areas in which factors compete, while factors assess the acceptability of candidates [7]. The appropriateness of wind energy locations through GIS-based MCE has been investigated [8]. This decision-making approach assists in identifying the optimal choice by evaluating various, frequently conflicting criteria. The use of remote sensing techniques and GIS has become a key component of site suitability assessment, assisting in the identification and evaluation of locations, and enabling informed decision-making by authorities and policymakers [9]. Different MCA methods, such as the Analytic Hierarchy Process (AHP) [4], are used to rank alternatives and assess criteria. In Iraq, the AHP method has also been applied in various spatial planning contexts, such as assessing ecotourism and picnic site suitability in the Sulaimani region, showcasing the flexibility of GIS-based decision-making approaches [10].

One key reason for combining multivariate analysis with GIS is the clear advantages that GIS provides in editing,

analyzing, and visualizing extensive spatial databases. Therefore, spatial suitability studies can be performed at the regional level instead of being limited to just a few alternatives [11]. GIS-MCA solutions have been widely used in evaluating the spatial applicability of RE systems [4, 12]. A thorough evaluation of the suitability of solar and wind farms across India was conducted using the GIS-AHP technology [4]. The criteria weights were established using AHP, and the criteria layers were subsequently combined in the GIS environment employing the Weighted Linear Combination (WLC) method [12]. Meanwhile, a study conducted in Mauritius utilized geography, climatology, and sociology to develop a fuzzy logic conceptual framework for evaluating the spatial suitability of wind-solar hybrid power plants [13]. Iraq's energy strategy has recently begun to prioritize investments in the solar energy sector. As a result, there is limited prior research in this area [14]. In [15], AHP and GIS were employed to evaluate the land's suitability for solar farm construction in Iraq, considering economic, environmental, and climatic factors. The findings indicated that approximately 19% of the land is suitable for solar farms, primarily in the southern and southeastern regions. The approach enables modifications for future planning. In [16], GIS-based MCA was used to identify the optimal locations for wind energy in Iraq. Factors, such as the land use, infrastructure, wind speed, and terrain were considered. According to the results, Southeast Iraq has the most significant potential, with 5.3% of the region regarded as extremely suitable for establishing wind farms. GIS was utilized in [17] to assess the wind energy potential in northern Iraq areas of high suitability, contributing to a reduction of nearly 16 million tons of CO₂ emissions. The AHP method was used to identify regions in Iraq that are suitable for groundwater potential or rainwater harvesting [18].

Iraq must consider the long-term effects of implementing sustainable energy technology. This is a calculated step toward achieving global climate objectives, reducing the greenhouse gas emissions from fossil fuel consumption, and supporting sustainable development [19]. The present study establishes a basis for strategic planning and informed decision-making in the energy sector by evaluating the country's sustainable energy potential deploying an MCA-GIS. It emphasizes the potential of sustainable energy to tackle the country's energy challenges, along with the technological feasibility of utilizing the nation's abundant sustainable resources, as well as the associated social and economic benefits. The study contributes to the global sustainable development and the adoption of sustainable energy by demonstrating the effectiveness and utility of GIS-based MCA in assessing sustainable energy potential. Thus, a replicable procedure has been developed that can be adapted and applied in other contexts. In [20], MCA based on GIS was utilized to identify the most suitable locations for solar energy harvesting in Iraq, employing six key criteria, including solar radiation, infrastructure, and topography. The results indicated that the southern region of Iraq has the highest concentration of suitable areas. This research serves as a reference for the present study, but the best location for distributing hybrid plants will be determined by the latter. Iraq's efforts to shape a sustainable and low-carbon energy future rely heavily on this study. Its main aim is to

identify the most suitable sites for hybrid solar-wind energy plants in Iraq using GIS-based MCA. It also seeks to support efforts against climate change and foster a resilient, sustainable future based on the strategic insights and thorough analysis provided.

II. STUDY AREA

The region under study is Iraq, covering a surface area of 437,072 km² [21]. It is situated between latitudes of 29°00' to 37°20' north and longitudes of 38°45' to 48°45' east. The nation's diverse climate is shaped by its four distinct seasons and various landscapes [22]. According to [14], Iraq is known for its hot, dry summers and cold, rainy winters. Its terrain is diverse, featuring deserts in the west and south, and mountains in the north. There is a significant variation in elevations; the highest peak, Mount Cheekha Dar, rises to 3,611 m above the sea level, while the lowest point is found at the Arab Gulf [23]. Iraq's position in the global sunbelt, along with its continuous sunshine, presents significant opportunities for solar energy. Additionally, the strong winds at high altitudes in the northern Zagros Mountains may provide a viable source of wind energy.

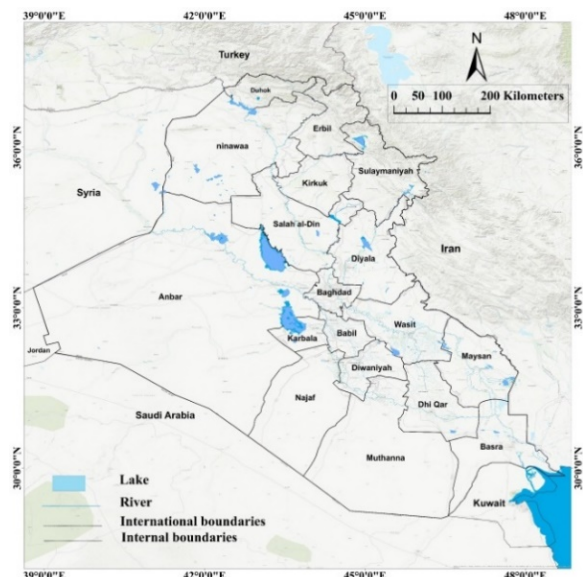


Fig. 1. Location map of the study area, Iraq.

III. METHODOLOGY

This study employed a thorough method based on various criteria to identify potential sites for wind turbines and solar panels. The slope is a key attribute that offers insights into the topography of a specific region. The slope criterion layer was established using Digital Elevation Model (DEM) data from the Shuttle Radar Topography Mission (SRTM) [24]. To effectively implement solar and wind energy collection, a phase of data gathering and analysis is necessary. To complete this process and extend its application to more complex studies, raw data need to be produced, while weights need to be established to incorporate the criterion layers. The weights for this experiment were determined using AHP, which considers the assigned weights for each dataset. Taking into account

several important geographic factors that affect the feasibility of installation generation, the following analysis was conducted. This study utilized various datasets, including DEM, shapefiles, and statistical information on roads and power lines sourced from the Ministry of Planning. The average annual wind speed and solar radiation data for the years 2000–2024 were acquired from the NASA website [25]. Data processing and analysis were performed using ArcGIS 10.8.2, which was also used to generate the final site suitability map. The slope degree map was generated utilizing DEM data, with Euclidean distance showing how each cell relates to one or more sources through a straight line distance. After preparing the six criterion layers (solar radiation, wind speed, slope, electricity, roads, and water) each layer received a rating from 1 to 5, with 1 indicating an unsatisfactory layer and 5 signifying a highly satisfactory layer. The final model includes 1 to 3 layers. The AHP method determined the weight of each layer. Then, the Weighted Overlay (WO) tool in ArcGIS integrated all these categorized layers. The main data types and sources were chosen for their accuracy, reliability, and relevance to the current geographic research analysis. Reliable sources, such as the Ministry of Planning and Infrastructure Intelligence, precise infrastructure evaluations, and international agencies, such as NASA, were utilized.

IV. SELECTION CRITERIA FOR SUITABLE WIND AND SOLAR SITES

This study uses six criteria to identify the optimal sites for wind and solar energy (Table I).

A. Solar Radiation

The amount of solar radiation significantly affects the power generation of solar panels. Data on solar radiation, encompassing direct, diffuse, and total radiation, have been collected from the NASA website [25]. To identify the areas in Iraq with high solar radiation where solar panels would be most effective, the data were interpolated using the Kriging method (Figure 2(a)).

B. Wind Speed

The energy output of wind turbines is greatly influenced by the current wind speed. Wind speed data in NetCDF format were sourced from the NASA website [25], then collected and interpolated through the Kriging method (Figure 2(b)).

C. Slope

The slope is a key factor when constructing power plants [28]. Wind energy thrives on sloped or elevated areas, while solar energy performs best in regions with moderate elevation and gentle slopes of less than 5%, as steep inclines can increase the construction costs. Therefore, both elevation and slope are critical factors [29]. Ultimately, flat and open spaces are the most suitable for energy projects [30, 24]. Figure 2(c) shows the distribution of sloped terrain in Iraq.

D. Electricity Lines - Network

For the best sites for sustainable energy projects to be selected economic factors are considered, and particularly their proximity to electricity transmission lines. The distance to these lines affects the efficiency of transmitting wind and solar

energy and reduces the construction and maintenance costs. Ideal locations are near energy transmission lines when requirements are established. An index of 0.5 to 20 km can be used for this purpose. Therefore, areas adjacent to electricity transmission lines are advantageous. Figure 2(d) depicts the distribution of the electricity transmission lines in Iraq.

TABLE I. CONSIDERED CRITERIA

Criteria	Layer Source	Spatial Resolution	Condition	Reference
Solar radiation	Remote sensing data	0.25° × 0.25°	Annual average (2000-2024)	[27]
Wind speed	Remote sensing data	0.5° × 0.625°	Annual average (2000-2024)	[27]
Slope	STRM DEM	30 m	Less than 5%	[26]
Electricity Lines	Shape file	Vector	Within 0.5 km of the main electricity grid	[28]
Transportation routes	Shape file	Vector	Within 60 m away from the main roads	[28]
Water bodies	Shape file	Vector	At least 150 m away from rivers or water bodies	[28]

E. Transportation Routes

The proximity of the power farms to transportation routes is a significant economic factor. Constructing new electrical lines to connect with power farms may incur high costs and require considerable time. It has been stated that ideal locations for power plants are situated within 60 m of existing infrastructure, such as primary and secondary roads and railways [32]. Figure 2(d) illustrates the layout of major transportation routes in Iraq.

F. Water Bodies

Nearby water bodies can affect the efficiency of solar panel and wind turbine installations [32]. GIS methods assessed how close water features, such as rivers and lakes, are to potential wind turbine locations in Iraq. The reclassification process requires applying the Euclidean distance criteria, given that the environmental impact of wind and solar power facilities is minimal, especially concerning the water resources. Figure 2(f) displays the distribution of major water bodies in Iraq.

V. ANALYTICAL HIERARCHY PROCESS

The GIS-based AHP-MCE method underscores the significance of decision-making. Various factors, such as solar radiation and wind speed, can be evaluated when selecting the optimal locations for specific activities [33, 34]. These elements are analyzed to determine the suitability of a site for its intended purpose [35].

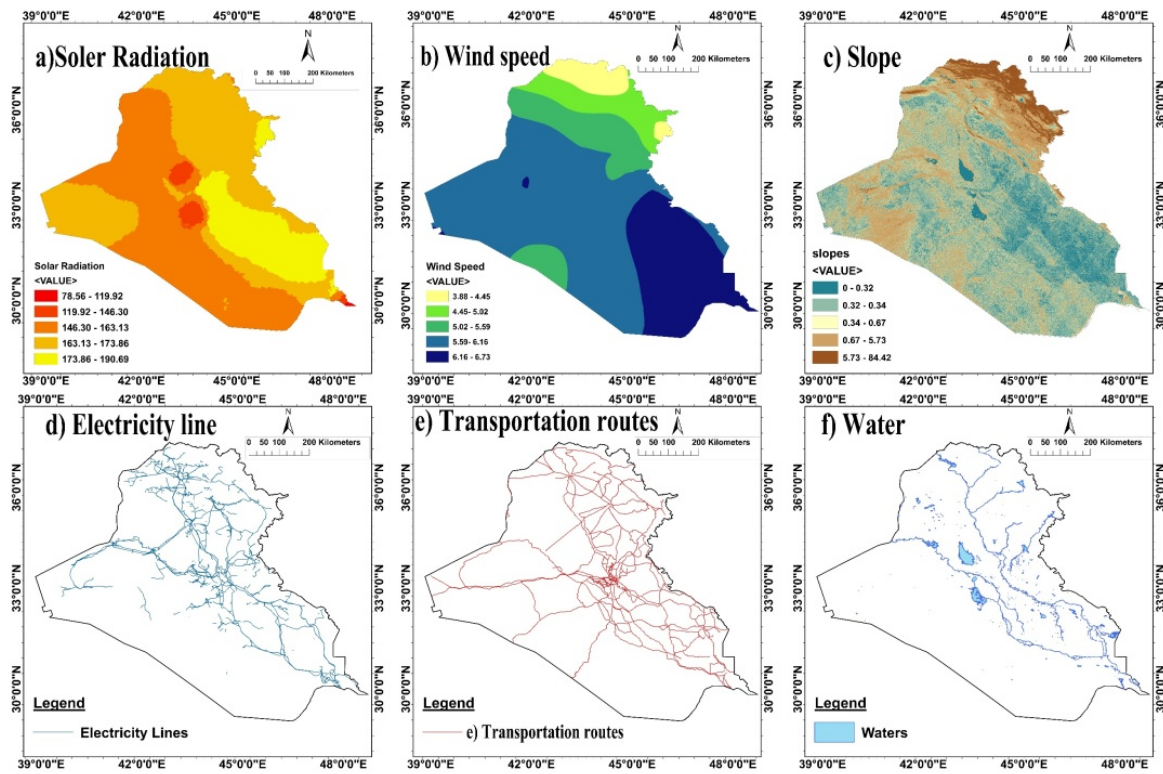


Fig. 2. Criteria of the hybrid energy model.

The first step in the review process is that of standardization, which involves converting the criterion data into a standardized numerical format. This study employed the AHP-MCE method to determine the best locations for power plants. To accomplish this, six target layers were utilized: water bodies, power lines, transportation routes, wind speed, slope, and solar radiation. The objective layers were standardized using a common five-point rating system. Utilizing the WO method, the final fit can be achieved and the creation of the weighted hierarchy can be simplified. The primary metric for evaluating the relative importance of the AHP criteria was employed to determine the significance of each criterion in the AHP analysis [37]. This research utilized six pairwise matrices, assigning one matrix to each developed component [36]:

$$p = \begin{matrix} p_{11} & p_{12} & p_{13} \\ p_{n1} & p_{n2} & p_{nn} \end{matrix} \quad (1)$$

where p represents the matrix factors. The normalized weights for the factors are then calculated in the second step:

$$wn = \frac{GMn}{\sum_{i=1}^n GMn} \quad (2)$$

where w is the cumulative column weight of the components and GM is the average of all column weights.

The Consistency Index (CI) measures the consistency of the pairwise comparisons in the AHP:

$$CR = \frac{CI}{RI} \quad (3)$$

The eigenvalue of the judgment matrix, denoted by λ , can be calculated by:

$$CI = \frac{\lambda - n}{n - 1} \quad (4)$$

where N is the total number of strata and p is the factor weight.

The Consistency Ratio (CR) evaluates the consistency of judgments in pairwise comparisons. The CR is calculated by dividing the CI by the Random Index (RI):

$$\lambda = \frac{\sum_{i=1}^n piw}{N.w} \quad (5)$$

When the CR value is less than 0.10, it signifies contentment. The usual tables for RI were used to create the randomness index [38]. Determining the CR is essential for accurately assessing the consistency of a pairwise comparison. The AHP method facilitates the development of the Pairwise Comparison Matrix, which is considered when selecting the weight process. The matrix formed by the individual components, presented in Table II, offers a comparative evaluation of the importance of each criterion in relation to the other criteria. During the pairwise comparison process, every criterion receives a priority or weight that indicates its importance within the overall decision-making framework. The components are ranked by importance based on historical data and expert recommendations [38]. Pairwise comparisons are evaluated for consistency using the CR. A CR of 0.1 or less is generally considered acceptable, indicating sufficient consistency in the evaluations.

TABLE II. THEMATIC LAYER PAIRWISE COMPARISON MATRIX

Criteria	Solar radiation	Wind speed	Slope	Electricity	Transportation routes	Water	Weight (%)
Solar radiation	1	1	2	3	4	5	29.5
Wind speed	1	1	2	3	4	5	29.5
Slope	1/2	1/2	1	2	3	4	18
Electricity network	1/3	1/3	1/2	1	2	3	11.2
Transportation routes	1/4	1/4	1/3	1/2	1	2	7.1
Water bodies	1/5	1/5	1/4	1/3	1/2	1	4.7

CR = 2%

VI. RESULTS AND DISCUSSION

The southern region of the research area experiences higher levels of wind and solar radiation than the northern regions (Figure 3(a)). These findings align with the global average horizontal radiation, indicating that solar farms are better suited for areas with high radiation. The research sites in the southeast experience strong winds, while the northern sites exhibit lower wind levels (Figure 3(b)). Windy areas are better for constructing wind farms. The slope map in Figure 3(c) indicates that most of the research area is suitably rated, except for the northern section, which features steep slopes. Another important issue is the distance from the electrical network. The farther a point is from the network, the more energy is lost during transmission, resulting in higher energy transfer costs. Since the locations are at least 500 m from the electrical

network, the distance to the electrical distribution system is optimal (Figure 3(d)). In order to achieve the maximum potential from solar and wind energy collections, it is imperative to consider the proximity to major urban areas and road networks. Most of the research area is encircled by the road network, as illustrated in Figure 3(e). The power plants must maintain a minimum distance of 150 m from water sources, like rivers and lakes. As portrayed in Figure 3(f), most of the area was identified as marginally suitable. The finalized suitability map divided the research area into three distinct zones: high suitability, medium suitability, and unsuitability. These zones represent percentages ranging from 39% for unsuitable areas to 30% for low suitability and 31% for high suitability, illustrating that the total area of highly suitable locations in Iraq is 142,159 km², indicating the country's potential for energy harvesting (Figure 4 and Table III).

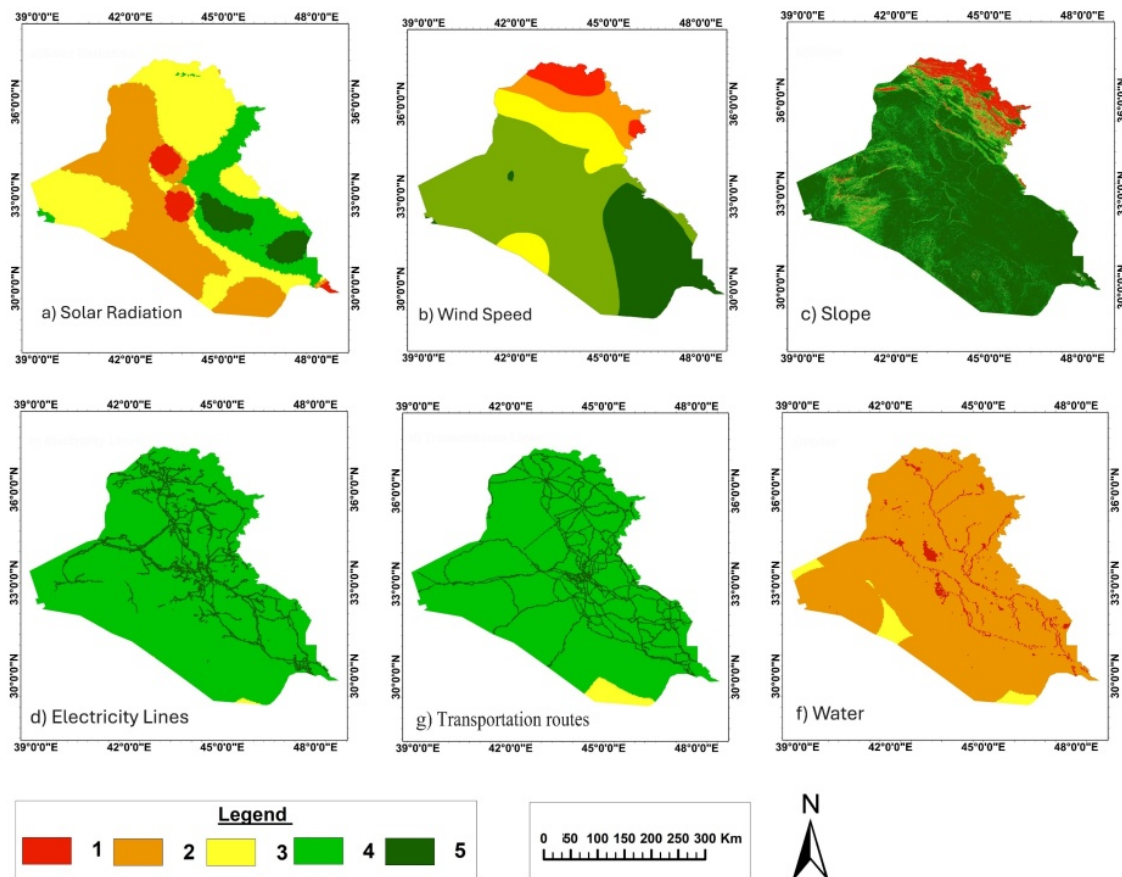


Fig. 3. The raster dataset that has been categorized. (1) Unsuitable, (2) marginally suitable, (3) moderately suitable, (4) suitable, and (5) optimal.

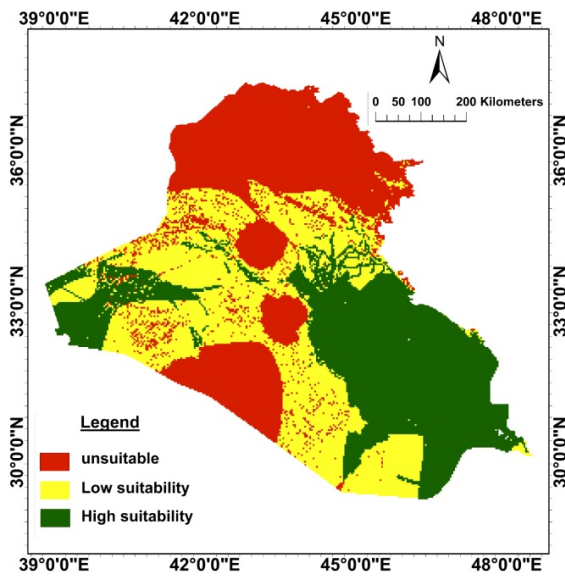


Fig. 4. Final suitability model.

The results may assist sustainable development planners and policymakers. In accordance with the global trends, arid and semi-arid regions experience an increase in sunlight due to reduced cloud cover and lower. Southern Iraq appears to be a promising location for solar energy development in the Middle East. The findings of this study are consistent with those of previous research conducted in Iraq, which suggested that the southern and southeastern regions are particularly conducive to the development of solar and wind energy initiatives. The results in [15, 16], support these findings and underscore the potential for RE in these locations by identifying them for solar and wind farm installations. The slope analysis indicates that the high northern terrain may render the expansion of RE infrastructure costly and challenging. These results support the findings of studies conducted in topographically analogous regions, such as Iran and Turkey, where steep slopes similarly posed limitations on project feasibility [38, 39]. Factors, such as traffic, location in the urban center, and proximity to the electric network, enhance the cost-effectiveness of the proposed sites. Moreover, 31% of the research area shows strong applicability, indicating significant potential. These regions meet technical standards and align with Iraq's RE strategy, which seeks to diversify the energy mix and decrease the dependence on fossil fuels. This research can improve the land use planning and promote investment in hybrid solar-wind systems.

TABLE III. THE AREA OF EACH SUITABILITY CLASS

Class	Area km ²	Area %
Unsuitable	144,622.5	39%
Low suitability	145,561.5	30%
High suitability	14,2159	31%
Total area	432,343	100%

VII. CONCLUSION

Iraq has a considerable Renewable Energy (RE) potential, especially in its southern and southeastern regions, which

benefit from the high levels of solar radiation and wind speeds. The performed analysis highlighted key factors influencing the feasibility of RE projects, including the terrain slope, closeness to vital infrastructure, like roads and power networks, and compliance with the environmental protection regulations related to urban development and natural water bodies. Approximately 31% of the study area has been classified as highly suitable, mainly due to its flatter terrain and favorable accessibility conditions, which promote the economic and operational efficiency. Nevertheless, approximately 39% of the area was found unsuitable due to difficult topography or conflicts, with environmental and land-use considerations underscoring the need for detailed site assessments. To enhance the robustness and precision of future site selections, subsequent research should consider additional environmental factors, including seasonal variations, the impact of frequent dust storms, and potential short-term decreases in the solar energy output due to fluctuations in weather conditions. Comprehensive climate data and ongoing monitoring would enhance reliability assessments throughout the year. These insights establish a robust basis for strategic planning and focused investment choices, greatly supporting Iraq's long-term goals for sustainable energy and environmental conservation.

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