

An Integration of Remote Sensing and GIS Based on Multi-Criteria Decision Making for the Selection of Lands Suitable for Wind Energy Harvesting

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ABSTRACT

The renewable energy demand has increased the need to develop efficient methods for assessing suitable land for wind energy installations. This study aims to evaluate the suitability of land in Kirkuk City for wind energy projects by combining multi-criteria decision analysis with remote sensing and Geographical Information Systems (GIS). Various environmental factors, along with topographical features and infrastructure, were integrated using the Analytic Hierarchy Process (AHP) to classify the land into areas of different suitability levels. The region analyzed includes 61.77 km² of highly suitable land, 123.152 km² of moderately suitable land, and 46.807 km² of the least suitable land. The northeastern quadrant of Kirkuk City contains Site 1, with 12 km² of highly suitable land, while Site 2 at the southeastern edge of the city covers 9 km² of highly suitable land. It has been found that the wind power projects can be developed in specific regions, but sustainable development and environmental conservation remain essential. The combination of GIS and remote sensing technologies enhances the energy infrastructure development, enabling more informed decision-making.

Keywords-remote sensing; wind energy; suitability; multi-criteria decision; Kirkuk city; GIS

I. INTRODUCTION

Energy serves as the main driver of industrialization and economic growth [1]. The research into alternative energy sources has increased significantly due to the worldwide depletion of fossil fuels and growing environmental concerns. Renewable sources, such as wind and solar, have gained popularity due to the increasing demand for more affordable and environmentally friendly energy production [2]. Traditional energy sources, such as coal, oil, and natural gas, have proven highly effective in promoting the economic growth [3]. The technological innovations, manufacturing, and growing global population are increasing the energy demand.

Energy, a fundamental input in production, is essential for enhancing the societal well-being and is used in nearly every aspect of the daily life. Defined as the ability to do work, energy can take various forms, such as mechanical (potential and kinetic energy), thermal, electrical, chemical, and nuclear. It can be transformed from one form to another through suitable methods. Additionally, energy can be categorized in different ways [4]. Wind energy projects have gained popularity driven by the efforts to promote sustainable development. Using renewable energy sources supports the sustainable economic growth and enhances the export prospects in environmentally friendly countries [5]. As a result, the number of wind energy projects has grown, making the wind energy a significant component of an integrated power system [6]. Site selection is among the most critical decisions for developing the wind energy resources [7]. GIS has become a popular method for selecting locations in both onshore and offshore wind power projects. Greece, along with China, Vietnam, India, and Turkey, uses GIS techniques as its primary approach for analyzing the wind energy research [8]. GIS is a widely used decision support tool for choosing ideal locations for various projects and tasks. Multi-Criteria Analysis (MCA) is a popular GIS-based method that helps in site evaluation and land suitability assessments [9]. GIS applications have been developed for site selection across multiple research fields, including natural resource management, pollution and hazard control, spatial planning, urban development, and infrastructure management [10]. Multi-Criteria Decision-Making (MCDM) techniques have been extensively employed to evaluate and rank potential renewable energy development sites, including solar, onshore and offshore wind, wave, tidal, hydro, hydrogen, and biomass [11]. Given that the MCDM approaches aim to assess multiple factors simultaneously and identify optimal solutions, integrating GIS and MCDM provides a practical decision support system for selecting the best locations for wind farms, considering various criteria that are often difficult to manage and analyze [12]. Several levels of spatial suitability exist when selecting potential sites for power plant development using the GIS-MCDA approach [13]. In the relevant site studies, the AHP was mainly used to assign weights to specific criteria and, less frequently, to rank the decision options [14]. Some research has explored the impact of the wind energy on human life from various perspectives. Although many countries have formal programs to promote the use of renewable energy, some studies indicate that public acceptance may pose a significant barrier to achieving this goal [15].

The goal of this research is to identify suitable locations near Kirkuk City for the development of wind energy farms. The study will utilize GIS to analyze key factors, including the wind speed, along with the land use patterns, elevation, proximity to infrastructure, environmental restrictions, and socio-economic aspects. This research develops a spatial plan to enhance the wind farm placement, support renewable energy development, and promote sustainable energy standards in the region.

II. STUDY AREA

Kirkuk, located in northern Iraq, is the capital of Kirkuk Governorate. Kirkuk City lies between latitudes $35^{\circ}13' N$ and $36^{\circ}29' N$ and longitudes $44^{\circ}00' E$ and $44^{\circ}50' E$. The city plays an important role in Iraq's oil industry and has a population of approximately 1.2 million residents. It spans about 2,900 km². The climate is semi-arid, characterized by hot summers and mild winters, which can affect wind conditions in the area [16-17]. With the rising energy demand, the region offers a promising opportunity to develop renewable energy sources, such as wind energy, to meet the future energy needs. Figure 1 shows the study region (Kirkuk City).

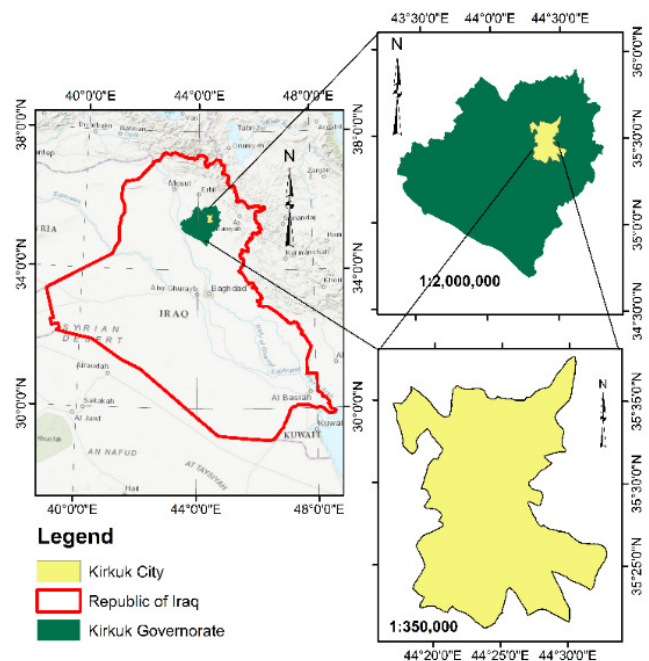


Fig. 1. The study area.

III. METHODOLOGY

The methodology for this study, as shown in the flowchart in Figure 2, follows a systematic process for selecting the suitable sites for wind energy development in Kirkuk, Iraq, using GIS and the AHP. The process is divided into several main steps:

1. The study gathered data on wind speed, DEM, Sentinel 2A satellite images, power lines, and road networks.

The Space Shuttle gathered worldwide SRTM elevation data in 2000 [18].

2. The extracted slope data and elevations from the DEM helped researchers evaluate the wind turbine sites. The AHP method determined the priority of the wind speed and slope parameters.
3. Satellite imagery processing extracted features of urban areas and water bodies. The safety, environmental, and regulatory constraints were managed by establishing buffer zones.
4. A constraint map was created by integrating buffered areas and restricted zones, such as urban regions and water bodies.
5. A GIS-based method removed the constrained areas to show the available land area.
6. Land Suitability Analysis: The remaining land was evaluated for wind energy development by integrating criteria, like wind speed, slope, proximity to power lines, elevations, and roads to find the most suitable locations.

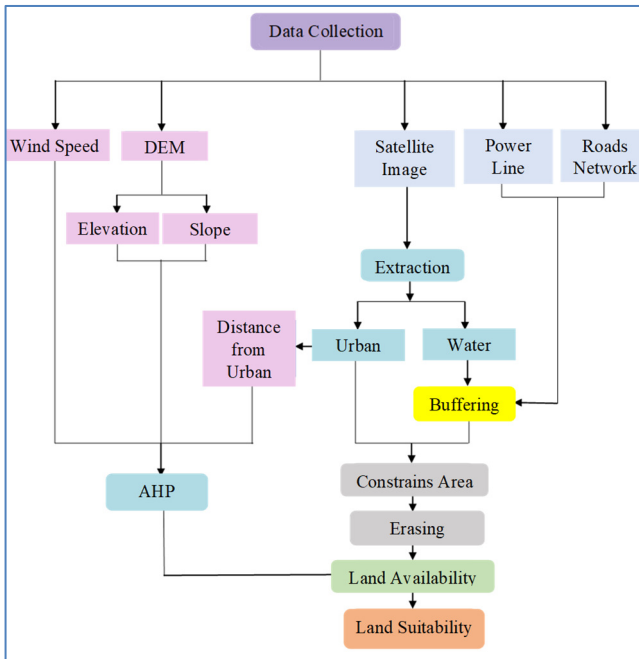


Fig. 2. Flowchart of wind energy site selection for the current study.

A. Main Criteria

A suitable site was selected on the outskirts of Kirkuk city for wind turbine installation, considering several criteria: being at least 500 m away from power transmission lines, 150 m from main roads, 300 m from water bodies, and being close to urban zones (Figure 3). Buffer zones were created to define these distances from the roads, power lines, and water bodies. Additionally, the Support Vector Machine (SVM) classification

method was employed in Kirkuk City to distinguish between the urban areas and water bodies.

B. Buffering in GIS

A buffer is a proximity function that represents an equidistant line around a feature. The buffer operations always result in polygons, regardless of the input feature class. The buffer zones serve as important spatial tools for analyzing how the features interact with their surroundings [19]. The buffering process was used in two stages in this study: the first stage was utilized to prepare the water bodies and road factors at 300 m and 150 m, respectively, and the second to prepare the distance criterion from the urban areas.

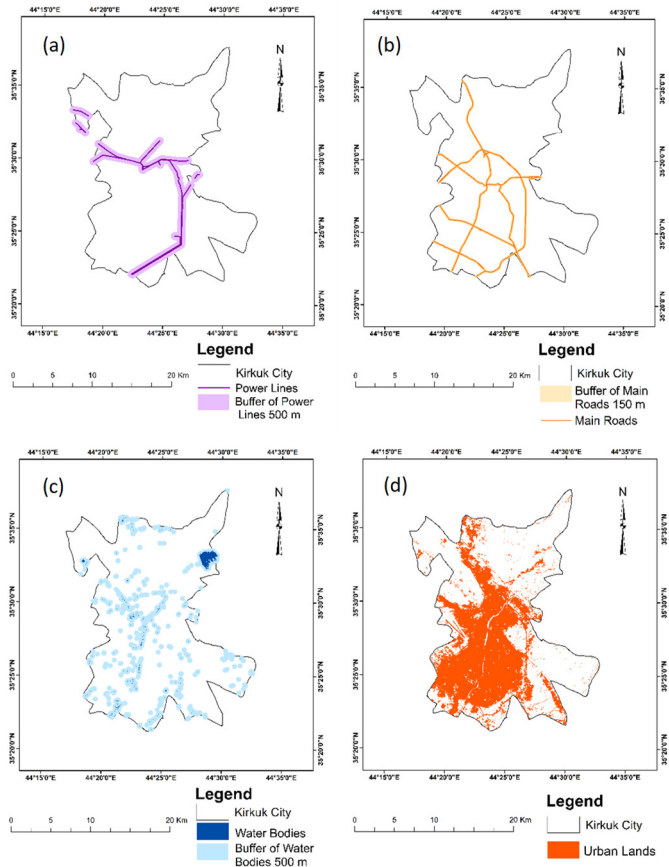


Fig. 3. Main criteria for land availability identification: (a) power lines with buffer 500 m, (b) main roads with buffer 150 m, (c) water bodies with buffer 300 m, (d) urban lands.

C. Maximum Likelihood Classification

The Maximum Likelihood (ML) method was employed to determine the required land cover classes (Figure 4). As one of the most common techniques in remote sensing, ML offers a strong theoretical probability advantage, but several factors should be considered when implementing it [20]. Its definition is provided in:

$$L_k(X) = \frac{n^{-1}}{(2\pi)^2 |\Sigma k|^{1/2}} \text{EXP} \left[\frac{1}{2} (X - \mu k) \Sigma k (X - \mu k)^t \right] \quad (1)$$

D. Multi-Criteria Decision Analysis (MCDA)

MCDA is a commonly deployed method for decision analysis in operation research [21, 22]. It addresses decision-making problems involving conflicting options assessed across multiple criteria. For example, MCDA was utilized to identify the suitable locations for wind farms in Kirkuk Governorate. Several criteria were considered, including the proximity to urban areas, wind speed, elevation, and slope, with data sourced from available spatial geographic databases. This information was transformed into a raster data format and visualized on a map to evaluate the potential for wind energy development in the region. Multiple relevant factors should be chosen and weighed based on their influence on the final decision. In geographic analysis, this is typically accomplished by creating a suitability map with multiple layers, each representing a distinct criterion. Each criterion receives a weighted suitability score categorized into various classes. These layers are then overlaid to produce a final suitability map, enabling users to identify the optimal locations and explore them further.

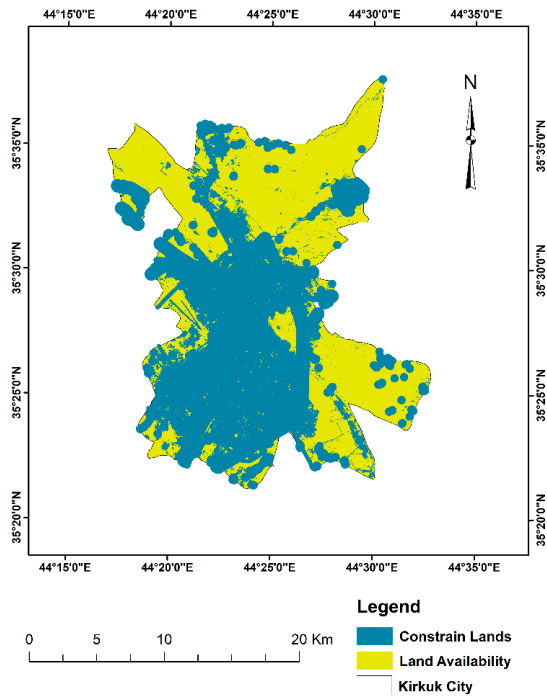


Fig. 4. Constrained lands and availability of lands.

E. Analytic Hierarchy Process

The AHP is a comprehensive, logical, and organized framework designed to assist analysts in understanding complex judgments by decomposing the problem into a hierarchy. By integrating and assessing all relevant decision factors, the decision-maker can determine the trade-offs among different objectives [23]. The hierarchical analysis method involves constructing multiple pairwise comparison matrices that evaluate each criterion against all others. These matrices compare each pair of criteria to determine which is more important [24]. A scale from 1 to 9 was used, where 1 signifies

equal importance between the criteria, and 9 indicates that the criterion being assessed is significantly more important than the others.

F. Land Suitability

Assessing the land suitability for wind farms is essential for sustainable land use planning, environmental management, and protection. The former involves a detailed and careful analysis of multiple factors. Decision-makers and land planners should develop wind energy facilities that minimize the environmental risks, address local stakeholders' concerns, and deliver economic benefits. Similarly, decision-makers need to evaluate the evolving criteria logically and simultaneously. MCDM methods have become essential for planners to navigate complex challenges, including high uncertainty, conflicting goals, diverse perspectives, and contradictory information. A GIS-based site suitability analysis, as represented in Table I, establishes the fundamental criteria and factor specifications necessary to select the optimal site location for wind energy turbines.

TABLE I. FACTORS AND CRITERIA FOR WIND ENERGY SITE SELECTION WITH THEIR SETTING

NO.	Criteria and factors	Setting
1	Wind speed (m/s)	All values are suitable but vary in importance
2	Slope (%)	0-3, 3.1 -7, 7.1-10 suitable, and 10.1-68 not suitable
3	Elevation	Elevations between (462 – 632 m) have high suitability
4	Land cover classes	Urban areas are excluded and sites must be 300 m away from water bodies
5	Distance from city (km)	1 high suitable, 2 moderate suitable, and 3 not suitable
6	Distance from roads (m)	More than 150 m is suitable
7	Distance from power line (m)	More than 500 m is suitable

All wind speed measurements are rated appropriately, though their importance varies with the actual values. Slope significantly influences the site selection; areas with less than 10% inclination are deemed suitable, whereas slopes over 10% are unsuitable for construction. Land cover excludes the urban regions from being suitable sites, and water bodies must be located more than 300 m away for a site to be considered qualified. Additionally, locations at least 150 m from roads and 500 m from power lines are preferred for safety and risk mitigation. These criteria are combined in the GIS spatial analysis to identify the optimal sites that fulfill the environmental, economic, and technical requirements.

IV. RESULTS AND DISCUSSION

A. AHP Outcomes

A weighted evaluation model, based on criteria (factors) and sub-criteria, is presented in Table II for evaluating the engineering site suitability. The analysis includes four main criteria: slope, wind speed, distance from urban areas, and elevation. Each main criterion receives a weighting based on its effect on the site suitability.

TABLE II. FINAL WEIGHTS OF CRITERIA AND SUB-CRITERIA BASED ON AHP

Main criteria	Sub-criteria	Weights of sub-criteria	Weights of main criteria	Final weights
Slope	0-3	0.7318	0.2309	0.1690
	3 to 7	0.1896	0.2309	0.0437
	7 to 10	0.0785	0.2309	0.0181
Wind speed	4 - 4.5718	0.5714	0.3486	0.1992
	2 to 4	0.2857	0.3486	0.0996
	1.7332 - 2	0.1428	0.3486	0.0498
Distance from urban areas	0-1	0.5389	0.1893	0.1020
	1 to 2	0.2972	0.1893	0.0562
	2 to 3	0.1637	0.1893	0.0310
Elevation	462 - 632	0.6318	0.2309	0.1459
	370 - 462	0.2088	0.2309	0.0482
	275 - 370	0.1593	0.2309	0.0367
Sum				1

Every main criterion contains sub-criteria that decision-makers weigh in terms of importance by assigning specific numerical weights. Each sub-criterion receives its final weight through multiplication of the main criterion weight by its sub-criterion weight. The site selection primarily depends on the wind speed, which is the main factor, with a value of 0.3487. The most influential sub-criterion of the wind speed ranges from 4 to 4.57 m/s, as demonstrated by its final weight value of 0.1992. The lower slope, ranging between 0-3%, together with the elevated areas from 462 to 632 m, represents the most beneficial conditions. The suitability scores increase for the sites located near urban centers (0-1 km), as the urban distance proves to be a moderate influence factor. A balanced multi-criteria evaluation results when the sum of all final weights equals 1. The method enables a practical and unbiased site suitability assessment by first identifying the geographic areas that best match the engineering project's requirements.

B. Land Suitability

The study area is categorized into three wind energy land suitability zones: high, moderate, and low (Figure 5). The high-suitability zone encompasses 61.77 km², mostly in the northern and northeastern parts of the exploration area. The central and southern parts cover 123.152 km² of moderately suitable land, which needs careful planning and terrain mitigation to address the development challenges. The low-suitability zones, totaling 46.807 km², are mainly in the western and southeastern parts of the region, where the steep terrain, proximity to cities, and accessibility issues pose significant development constraints.

C. Best Suitable Sites

Kirkuk City's suitability zones are classified into three categories: low, medium, and high (Figure 6). Low-suitability areas are marked in red, medium-suitability areas in yellow, and high-suitability areas in blue. The assessment likely considers four main factors: soil quality, land slope, water resources, and environmental conditions. According to [22], the land suitability evaluation for Kirkuk identified specific locations with high development potential and areas with agricultural needs. In the northeastern part of Kirkuk, Site 1 covers approximately 12 km², making it an optimal location for wind energy development. The area features highly favorable land qualities, offering significant potential for urban growth and agriculture. The southeastern region, including Site 2,

spans about 9 km² and is also highly suitable. Although smaller than Site 1, it still presents a strong potential for wind energy development due to its favorable environmental conditions and easy access to critical infrastructure.

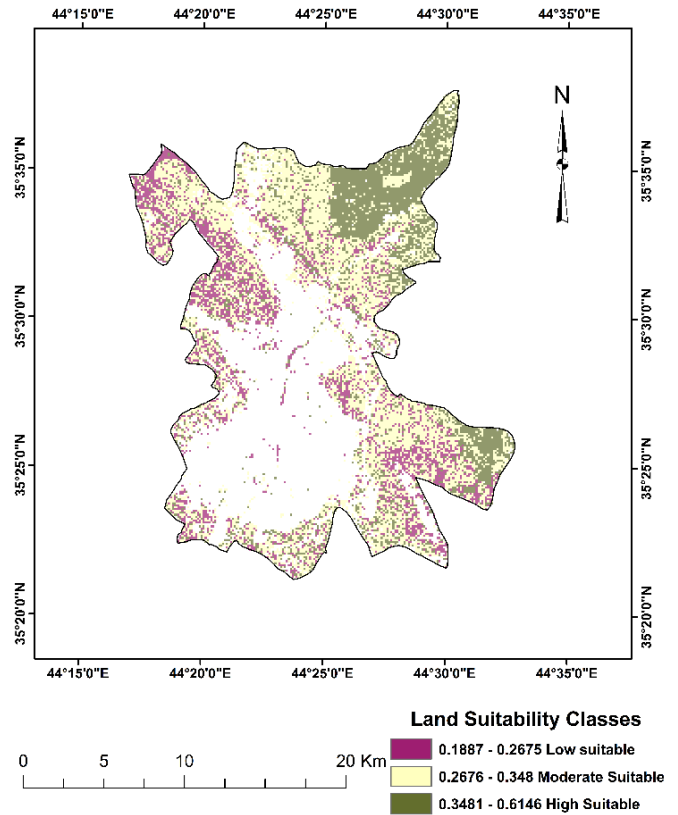


Fig. 5. Land suitability classes of wind energy site selection.

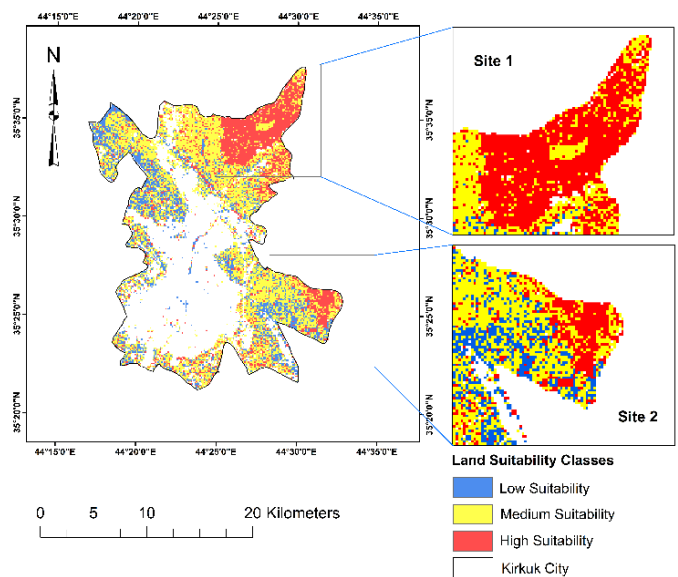


Fig. 6. Best suitability sites for wind energy site selection.

V. CONCLUSION

This study utilized a GIS-based Multi-Criteria Decision-Making (MCDM) approach, specifically the Analytic Hierarchy Process (AHP), to identify the optimal sites for wind energy projects. The findings revealed 61.77 km² of highly suitable land, mainly in the northern and northeastern regions. An additional 123.152 km² of land was classified as moderately suitable, needing further assessment for optimal placement. Conversely, 46.807 km² was deemed unsuitable due to the urban restrictions, challenging terrain, and limited wind resources. Site 1, located in the northeast, encompasses 12 km² of highly suitable land, benefiting from favorable natural features, such as topography, soil quality, and resource accessibility. Site 2, in the southeast, includes 9 km² of highly suitable land, slightly smaller but still promising. The benefits of these sites' suitability are also highlighted. Compared to other research, this study confirms that GIS, combined with AHP, effectively supports the wind site selection. The high suitability ratings and spatial precision observed in Kirkuk illustrate the success of the integrated spatial methods in pinpointing viable wind zones elsewhere. Overall, the research highlights the importance of the environmental sustainability and proximity to infrastructure in site selection.

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