USING A GIS-MCDM APPROACH TO WIND AND SOLAR SITE SELECTION IN TUNISIA

Wedyan. G. nassif[1,2] Dalila Elhmaidi[1] Yaseen. K. Al-timimi[2]
Researcher Prof. Prof.
[1]Dept. Physics Sci. Coll. of Sci. Université Tunis El Manar-Tunisia
[2]Dept. Atmospheric Sci. Coll. of Sci. Mustansiriyah University
wedyan.atmsc@uomustansiriyah.edu.iq, yaseen.altimimi.atmsc@uomustansiriyah.edu.iq

ABSTRACT

This study was aimed to investigate a comprehensive methodology and its ensuing results for identifying potential sites for wind power plants (WPPs) and solar photovoltaic plants (SPVPs) across Tunisia, a crucial step given the significant long-term investment these plants entail. Using Geographic Information Systems (GIS) integrated with Multi-Criteria Decision-Making (MCDM) and underpinned by the Analytical Hierarchy Process (AHP), this research meticulously weighs and maps various site-specific criteria essential for site suitability assessment. The results indicate that approximately 1183 km² (1.8% of Tunisia's total area) and 2533 km² (3.7%) are optimally suited for large-scale SPVPs and WPPs, respectively. the prime locations for wind energy are predominantly in the northwest, southwest, southeast, and parts of the north, while the central and southern regions harbor the most potential for solar energy development due to favorable solar irradiance.

Keyword: Suitability index - hybrid sites - renewable energy – Tunisia -AHP- spvps and wpps
Part of Ph.D. Dissertation of the 1st author

استعمال منهجية GIS-MCDM لاختيار مواقع طاقة الرياح والطاقة الشمسية في تونس

وديان غالب نصيف دليلة الحمايدي الوسلاتي ياسين كاظم التميمي
باحث استاذ استاذ
قسم الفيزياء – كلية العلوم – جامعة تونس المنار– تونس
قسم علوم الجو – كلية العلوم – الجامعة المستنصرية

المستخلص

توضح هذه الدراسة منهجية شاملة ونتائجها اللاحقة لتحديد المواقع المحتملة لمحطات توليد الطاقة من الرياح (WPPs) ومحطات الطاقة الشمسية الكهروضوئية (SPVPs) في تونس، وهي خطوة حاسمة بالنظر إلى الاستثمار طويل الأمد الذي تتطلبه هذه المحطات. من خلال استخدام نظم المعلومات الجغرافية (GIS) المدمجة مع صنع القرار متعدد المعايير (MCDM) والمدعومة بعملية التحليل الهرمي (AHP). تشير النتائج إلى أن ما يقرب من 1183 كم² (1.8% من إجمالي مساحة تونس) و 2533 كم² (3.7%) ملائمة بشكل مثالي لمحطات SPVPs و WPPs على نطاق واسع، على التوالي. يُلاحظ أن المواقع الرئيسية لطاقة الرياح تقع بشكل أساسي في الشمال الغربي، الجنوب الغربي، الجنوب الشرقي، وأجزاء من الشمال، بينما تحتضن المناطق الوسطى والجنوبية معظم الإمكانيات لتطوير الطاقة الشمسية نظرًا للإشعاع الشمسي المناسب.

الكلمات الافتتاحية: مؤشر الملائمة، المواقع الهجينة، الطاقة المتجددة، عملية التسلسل الهرمي التحليلي، محطات الطاقة الشمسية والرياح.
جزء من اطروحة دكتوراه للباحث الاول

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INTRODUCTION

Renewable energy is regenerated by nature. which included Solar, wind, geothermal, biomass, and hydropower energy (33). Renewable and pollution-free, these resources help the environment (29). The main global challenges to sustainable development are rising energy use and environmental degradation (16). Population increases and technological advances are increasing worldwide dependence on fossil fuels, which cause global warming and climate change (24). It will accelerate as nations adopt renewable energy and storage technologies like solar, wind, and batteries to meet national and international greenhouse gas emission objectives (22). Renewable energy's rise is driven by environmental consciousness and its potential to create clean electricity with low air pollution (3). Solar energy is a clean, sustainable alternative to traditional power sources. Also, Agrivoltaics systems, which integrate agricultural production with solar energy generation, present a promising approach to ecological sustainability. (11,21). Solar and wind energy also improve living standards, especially in rural areas, reduce economic strains, strengthen energy security, reduce import dependency, create local jobs, and reduce environmental pollution (34). Wind energy from wind turbines boosts economic and technical growth. It helps reduce fossil fuel use, greenhouse gas emissions, and climate change (2). Geographic Information Systems (GIS) and Multi-Criteria Decision-Making (MCDM)are important tools for determining ideal renewable energy installation sites. A thorough methodology for evaluating geographical and environmental criteria is needed to find places with the greatest sustainable energy generation potential. Integrative methods have been used to find the finest wind and solar energy sites in Tunisia. Multi-Criteria Decision Making (MCDM) is a leading decision-making methodology for renewable energy site appraisal, selection, predesign, and planning due to its precision in handling difficult choices (13). This method is crucial in technical design and financial planning since it synthesizes multiple factors to get the best choice (35). The integration of GIS and MCDM has created a unified framework for spatial planning, enabling more comprehensive and informed decision-making. Many studies have used GIS-MCDM to analyze renewable energy sites (4), with a current concentration on wind and solar power generation (17). Linear regression modeling in the GIS-AHP (Analytic Hierarchy Process) framework has improved site selection for hybrid solar and wind energy projects, as shown by Saudi Arabia's large-scale power plants that meet economic, technical, and environmental standards (32). The Electricity System Sustainability Index (ESSI) has been introduced as an evaluative tool to gauge the ecological sustainability of energy systems, considering variables such as new connections, cost variability, economic productivity, energy losses, peak hour energy availability, and renewable energy generation capacity (20). The effectiveness of GIS-based MCDA in the site selection for wind farms has also been validated in Greece (6,15). This project aims to use GIS-MCDM to carefully locate solar, wind, and hybrid power plant locations. To aid renewable energy infrastructure development, this research will give policymakers a powerful tool for site selection. Using GIS technologies with such decision-making tools accelerates the process and guarantees that each decision is based on a thorough review of various and relevant criteria. This integrative approach should help deploy renewable energy and achieve energy sustainability and self-sufficiency.

MATERIALS AND METHODS

Area of study and data sources

The methodology used in this study revolves around assessing the spatial suitability of potential wind and solar farm sites in Tunisia. The primary methodologies adopted in this study are the GIS for Multi-Criteria Decision Making (GIS-MCDM) and the Analytic Hierarchy Process (AHP), reflecting a commitment to making informed, data-driven decisions for renewable energy site selection. The initial step of the research involved the collection of data. The basis of this assessment depends on seven key criteria identified through an extensive literature review and expert consultation. These standards are:

1. Global Solar Radiation (GHI): Measurement

of solar power potential.
2. Wind Speed (WS)
3. and Use: Analysis of current land utilization and potential constraints
4. Temperature: Consideration of climatic conditions affecting energy efficiency
1. Slope: Evaluation of topographical suitability for installation
2. Proximity to Power Transmission Lines: Accessibility to the grid for energy distribution
3. Distance from Roads and Cities: Assessment of logistical and infrastructural feasibility.
These data variables were sourced from meteorological stations, public databases, and other relevant platforms. After collection, the data was formatted suitably to be used in GIS software.In order to quantify the suitability of land across these diverse criteria, a weighted overlay approach was implemented. This technique allows for the assignment of relative importance to each criterion (Table 1), thereby customizing the analysis to the specific context of Tunisia's geographic and infrastructural landscape. Following the weighting procedure, the criteria were reclassified into four distinct categories, establishing a hierarchical structure that ranks the suitability from low to high. The reclassification process was facilitated by grouping raster layers according to the predefined weights, which were meticulously calculated to reflect the interplay between exclusion areas and the areas classified for potential development.

Table 1. Criteria used in wind speed and solar radiation location suitability of weight overly

NO	Criteria	Weight%	factors	Suitability
C1	Annual Wind Speed		<4.2 m/s	Unsuitable
	(at 150 m)	0.40	4.2-5.2	Low Suitable
			5.2-6.2	Moderate Suitable
			>6.2	High Suitable
			>1372.24	Unsuitable
C2	GHI (kwh/m^2)	0.40	1560.8-1749.4	Low Suitable
			1749.4-1938.04	Moderate Suitable
			1938.09-2126.8	High Suitable
C3	Slope degree		1-3 %	High Suitable
		0.20	3-7	Moderate Suitable
			7-10	Low Suitable
			10-82	Unsuitable
C4	Land cover/use		Water Bodies	Restructure
		0.10	Other	Suitable
C5	Distance from Cities		0-2 km	Unsuitable
		0.10	2-5	Low Suitable
			5-20	Moderate Suitable
			>20	High Suitable
C6	Distance from Roads	0.10	0-0.5 km	Low Suitable
			0.5-5	High Suitable
			5-20	Moderate Suitable
			>20	Unsuitable
C7	Distance from power		0-0.5 km	Low Suitable
	line	0.10	0.5-5	High Suitable
			5-20	Moderate Suitable
			>20	Unsuitable

Study area

Tunisia is located between 32° - 38° north latitude and 7◦ - 12◦ east longitude in North Africa and the Mediterranean basin. The country is bordered by the Mediterranean Sea to the north and east, Algeria to the west, and Libya to the southeast (23). (Figure1). The total area of Tunisia is 163,610 km^2, of which 8250 are covered by water (6), Tunisia has a Mediterranean climate, with mild rainy winters and hot, dry summers in the north, semi-arid conditions in the center, and arid conditions in the south (19). The major and reliable rivers in the north of the country with a few notable exceptions rise from northeastern Algeria and flow across the northern plain where adequate rainfall supports diverse vegetation and irrigated agriculture (36).

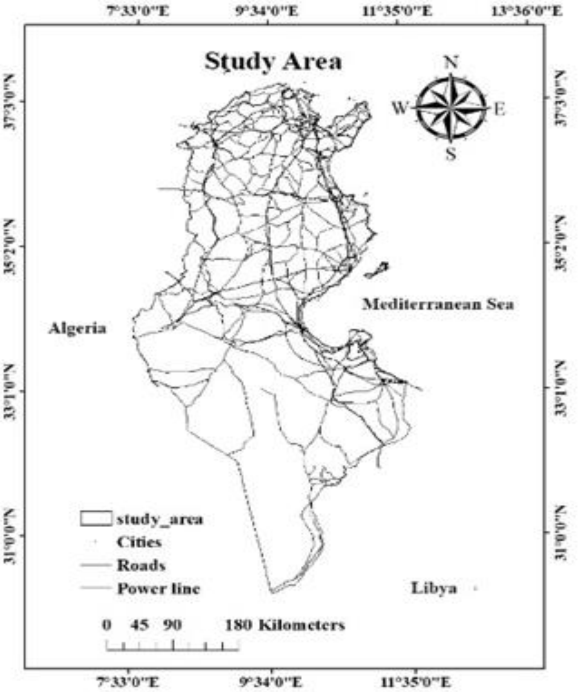


Figure 1. Location map of the study area, Tunisia

Statistical analysis

Multi-Criteria Decision Analysis and GIS (MCDA-GIS): Scientists have used GIS since the 1970s. It covers academic subjects in addition to wind and solar technology. GIS systems are created to store, retrieve, alter, analyze, and map geographical data (4). The locations where GIS technology might be used were identified using the MCDA technique. The potential of wind calculated, and solar energy based on regions while considering site circumstances and technological advancements (9). The GIS-MCDM combo creates a superb analytical tool that enables the development of a sizable typographical and cartographic database that will subsequently be employed by multi-criteria approaches to streamline problem-solving and encourage the usage of numerous criteria (27).

Weight Overlay Model (WOM)

In GIS, continuous raster data is usually divided into ranges, such as slope or Euclidean distance outputs before using it in the Weighted Overlay tool (19). Overlay analysis is a function of integrating several layers of information that reflect different topics in order to analyze or identify the relationships between each layer (31). These raters can be classified using the Reclassify tool (11). The point data were added to the weighted overlay after selecting the appropriate rating scale. Raster cells will already be configured to reflect suitability, preference, risk, or another common metric (26). By combining different attributes and geometries of data sets or entities, overlay analysis represents the composite map (14). The weighted overlay technique is one way to represent saliency. The following methodology implement of by ArcGIS using Weighted Linear Combination (WLC) model. one of the simplest and most utilized GIS-MCDA models, in which a weight is given to each point layer (28). In this research, each topic layer was sequentially combined into the ArcGIS system, creating a map with the best solar and wind energy locations. The common suitability measure is used to reclassify the values using the suitability index "SI" for cell I defined in the "equation 1" to determine each pixel's weight in the final integrated layer (20) :

$$SI = \sum_{i=1}^{n} v_i * w_i \dots\dots..(1)$$

Where:

i is indicator, and n is the number of indicators, v_i is the normalized value of indicator i, and w_i is the weight of indicator i

Figure 2 shows how Tunisia's GIS-MCDM process determines the best wind and solar energy installation sites. Optimal energy harvesting regions are identified by reclassifying important technical data on annual wind speed and sun radiation. Economic elements like terrain slope from Digital Elevation Models (DEM) are also considered for cost, ensuring that less economically burdensome terrains are favored. By using Euclidean distance analysis, closeness to power lines, roads, and metropolitan areas is reclassified to reduce ecological disruptions and improve infrastructure compatibility. Environmental criteria like land cover are carefully examined to eliminate protected areas and classify remaining areas by development potential. Temperature, precipitation, vegetation index, and soil moisture are assessed to assess prospective sites' long-term sustainability and environmental impact. Each determinant is given a significant level in a weighted overlay analysis, creating a composite suitability map. The final stage, Hybrid wind and solar energy, combines these weighted factors to identify areas with the best technical feasibility, economic viability, and environmental stewardship for wind and solar energy infrastructure deployment. An organized and planned strategy emphasizes the rigorous methodology of GIS-MCDM for renewable energy site selection (8,30).

RESULTS AND DISCUSSION

The study presents an innovative approach by integrating GIS with Multi-Criteria Decision Making (MCDM), underscored by the Analytical Hierarchy Process (AHP), to identify suitable sites for renewable energy projects in Tunisia. The map of annual solar radiation For the period (1981-2022) (Figure 3-a) visualizes the spatial distribution of solar potential across the country. It is obvious that the southern parts of Tunisia show higher solar irradiance, making them more suitable for solar energy projects. Figure (3-b) presents the spatial distribution of annual wind speed across Tunisia at 150 meters above ground level for 43 years for the period from (1981-2022). The data depicted their process using GIS software, classifying the wind speed into several categories ranging from 3.6 to 10.2 meters per second. This classification assists in identifying potential areas with sufficient wind resources for wind power generation.

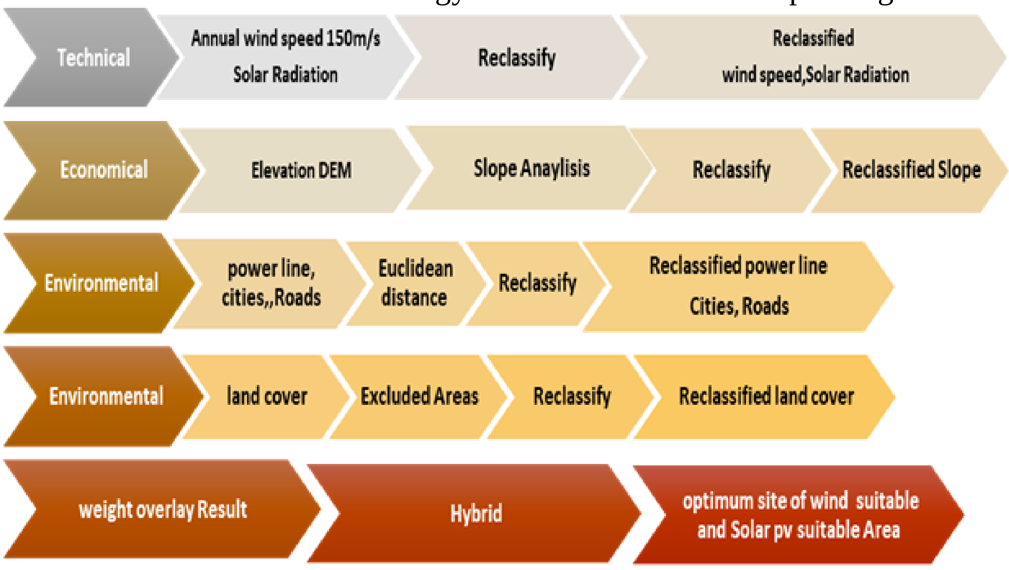
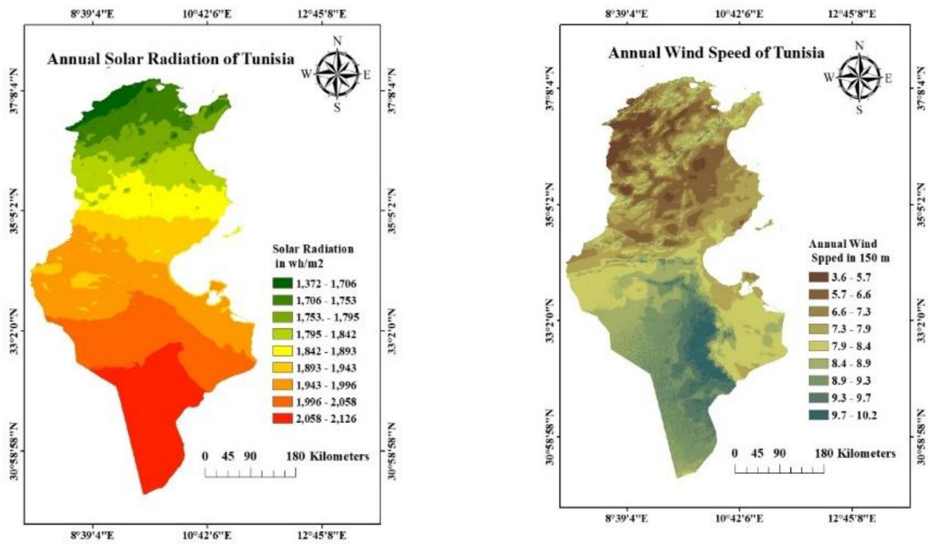
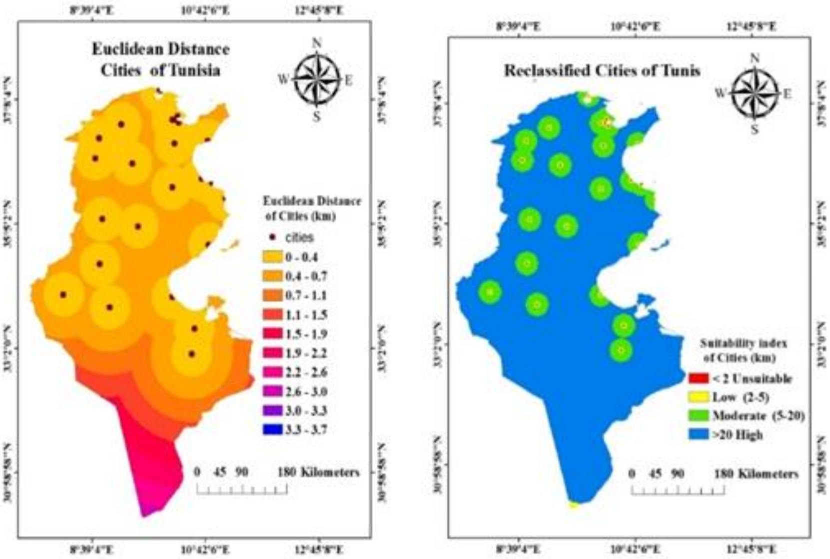


Figure 2. Overview of site suitability for wind and solar



(a) **(b)**

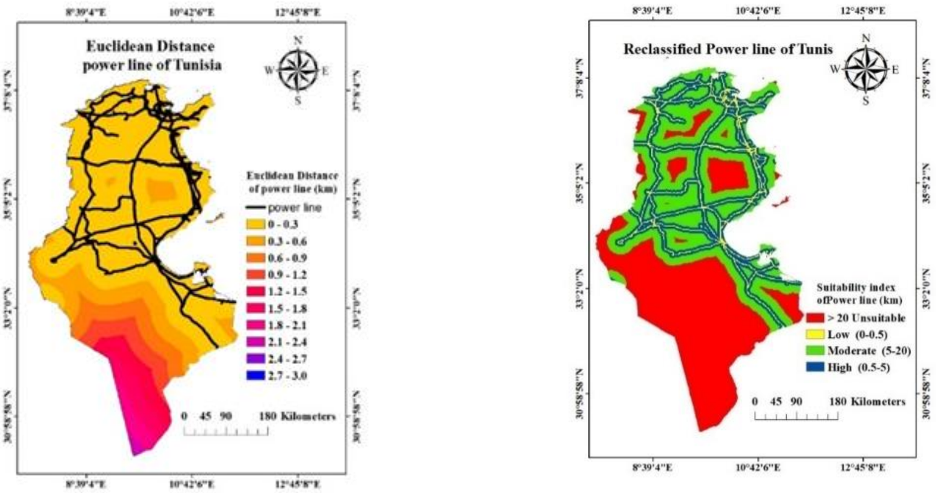
Figure 3. a. Annual Solar Radiation of Tunisia b) Annual Wind Speed of Tunisia



(a) (b)

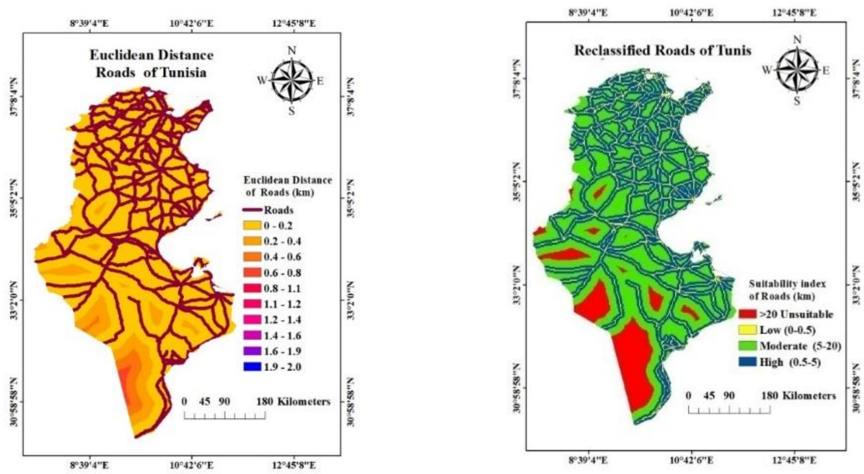
Figure 4. a. Euclidean distances of the cities b) Reclassified cities of Tunisia based on suitability Index

The reclassification of the cities Figure (4-a), based on the Euclidean distance from major urban centers, illustrates the accessibility and potential connectivity of energy projects to existing urban infrastructure. Cities with close proximity to high-suitability areas for solar and wind energy, may benefit more from renewable energy projects due to lower transmission costs and losses. The reclassified Cities of Tunis map in Figure (4-b) based on the suitability index for renewable energy development presents a clear demarcation of urban areas with varying degrees of potential. In the analysis, cities like Tunis, Sfax, Sousse, and Bizerte emerge as areas with moderate suitability, which could be attributed to a balanced combination of wind and solar potentials, coupled with the availability of existing infrastructure and accessibility. The assessment further stratifies the cities, indicating a handful of highly suitable regions. These zones are particularly noteworthy, as they present a compelling case for the concentrated development of renewable energy facilities due to factors such as optimal solar irradiance, robust wind profiles, and potentially favorable logistical conditions. ====Figure (5-a) further refines this analysis by quantifying the Euclidean distances from power lines, a metric that significantly influences site selection. Shorter distances suggest reduced transmission costs and enhanced feasibility for connection to the national grid, thus increasing the site's suitability for development. The reclassification of the power line map for Tunisia (Figure 5-b) represents a crucial analytical step in the GIS-MCDM framework, providing insights into the suitability of various regions for renewable energy connectivity. In this detailed reclassification, the proximity of power lines is quantified, rendering areas immediately adjacent to the existing grid as highly suitable. This indicates a lower logistical burden for connecting future renewable energy sites to the national grid, which is a significant factor in the economic feasibility of such projects. These classifications are grounded in precise geospatial analysis, where the distance from power lines is inversely proportional to the suitability score-regions further away from power lines are marked with lower suitability, signaling increased infrastructural challenges and potential cost increments for grid expansion. The Euclidean distance Figure(6-a) further refines our understanding by quantifying the proximity of land areas to the nearest roads. Zones within a closer range to the roads, particularly those enveloped by the extensive network in the north, are more suitable for the development of energy projects due to the lower costs and higher feasibility associated with transporting materials. Figure (6-b) takes this analysis further by presenting the reclassification of Tunisia’s roads based on suitability indices accentuates the potential logistic efficiency for renewable energy projects. Regions with higher road suitability, such as those surrounding the capital Tunis and the coastal city of Sfax, could be optimal candidates for renewable energy projects given their enhanced infrastructure. This contrasts with the southern interior and some coastal regions where the suitability is lower, likely due to limited infrastructure, suggesting a need for investment to improve accessibility before large-scale energy projects can be developed. Figure(7-a) outlines the topographical and slope reclassification analysis for Tunisia, vital components in the site selection process for renewable energy projects within the GIS-MCDM framework. The DEM of Tunisia indicates significant variation in elevation across the country. On figure (7-b), the reclassified slope map furthers this analysis by segmenting the country into areas with different slope categories, from flat (0-1% slope) to steep (>6% slope). The flat areas are identified as highly suitable for renewable energy projects due to lower installation and maintenance costs. These are likely found in the central and southern plains, which may also correspond to the areas of high solar irradiance. Conversely, regions with steeper slopes are marked as unsuitable, which aligns with the northern mountainous terrain.



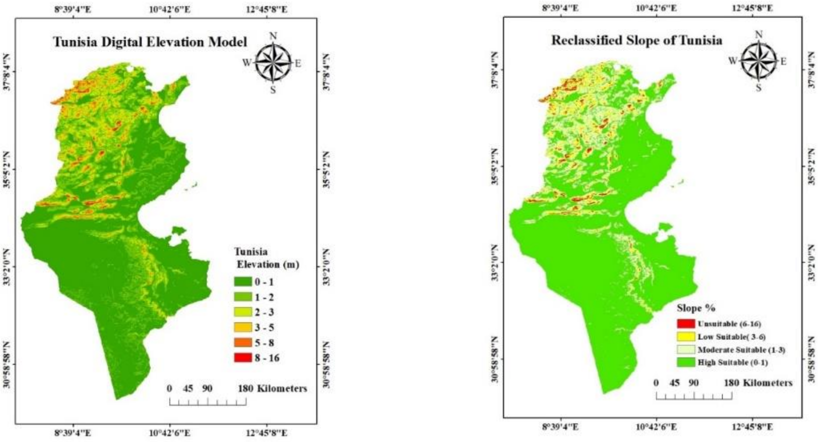
(a) **(b)**

Figure 5. a. Euclidean distance power line b) Reclassified power lines of Tunisia based on suitability index.



(a) **(b)**

Figure 6. a. Euclidean distance Road b) Reclassified Road of Tunisia based on suitability index.



(a) **(b)**

Figure 7. a. Tunisia digital elevation model b) the reclassified slope

Figure (8) presents the land cover of Tunisia delineates the varied topographical and ecological zones across the country, each presenting distinct prospects and challenges for renewable energy development. The northern part of Tunisia, traditionally marked by greater vegetation density, might offer opportunities for biomass energy projects. However, this area's complex ecosystem and agricultural value could limit the large-scale deployment of wind and solar farms. Moving southward, the more open and less dense areas such as the grasslands and shrublands suggest a potential suitability for wind and solar installations, with fewer ecological constraints and possibly lower land acquisition costs. The expansive open terrain in regions like Kasserine and Gafsa could be conducive to utility-scale solar farms, given the ample sunlight and land availability. The dry regions, including sandy and stony deserts, especially around areas such as Tataouine and Kebili, provide vast tracts of land that could be ideal for solar energy projects.

Solar PV: The spatial distribution of global horizontal irradiance is depicted in the reclassified solar radiation map, identified as Figure (9-a). This map has been categorized into segments ranging from unsuitable areas, marked by irradiance values below 1372.24 Wh/m^2, to regions of high suitability, where irradiance exceeds 1938.04 Wh/m^2 The map reflecting solar radiation suitability is critical in identifying regions where solar PV projects The southern parts of Tunisia, notably in areas such as Kebili and Tataouine, are marked as highly suitable due to their abundant solar resources. Figure (9-b) shows Potential Sites for Solar PV. The solar PV potential sites map further refines our understanding of where solar energy projects can be feasibly developed. It not only captures the solar irradiance but also integrates other geographical and infrastructural factors, providing a composite view of solar energy viability. The highlighted areas with high suitability in the south, such as near the Sahara Desert's fringes, indicate regions where large-scale solar projects could thrive, leveraging the exceptional solar resources.

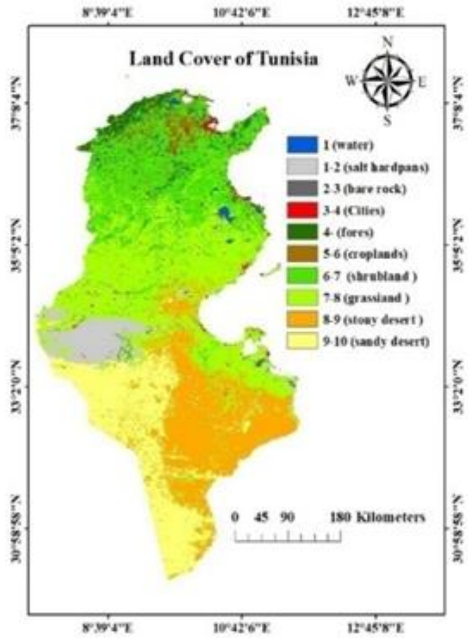
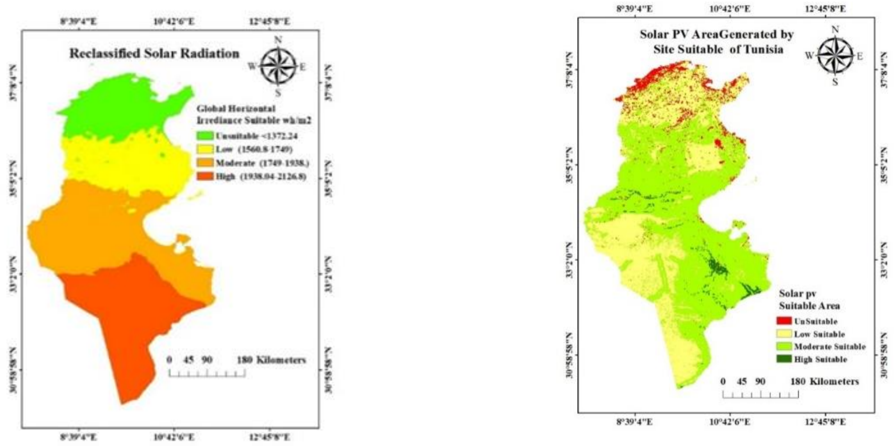


Figure 8. Land cover of Tunisia

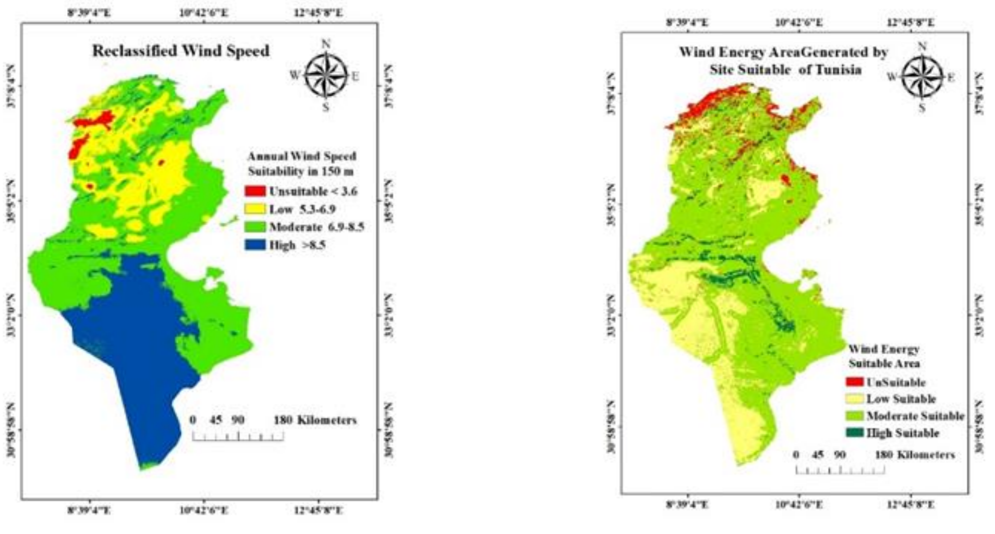


(a) **(b)**

Figure 9. a. Reclassification of the Solar Radiation b) Solar PV Suitable sites potentials in Tunisia

Wind renewable energy

In Figure (10-a), the reclassified wind speed map indicates significant variability in wind energy potential across Tunisia. The northern regions, including the area around Bizerte and extending through the Cap Bon Peninsula, show high suitability with robust wind speeds. These areas, with their favorable wind conditions, are optimal locations for wind energy projects, capable of harnessing the strong Mediterranean Sea breezes that could drive the turbines for substantial parts of the year. Figure (10-b) shows the wind energy suitable areas, the suitability map for wind energy areas emphasizes the spatial dimensions of wind resource availability for energy generation. The northern coastline, with its extensive areas of high and moderate suitability, represents a significant potential for wind farm development. These regions are likely to be the focal points of Tunisia's wind energy expansion, with the capacity to contribute a substantial share of the country's renewable energy supply.



(a) **(b)**

Figure 10. a. Reclassified wind speed b) Wind Energy Suitable areas

Hybrid Sites of solar and wind in Tunisia: Represents a significant outcome of this research, illustrating regions within Tunisia where conditions are simultaneously favorable for both solar and wind energy production. This hybrid map integrates the identified potential of solar and wind energy layers, effectively highlighting specific locales that offer an optimal blend of geographic and climatic attributes conducive to the dual harnessing of these renewable resources. The analysis of the hybrid solar and wind energy potential map in identifies key southern governorates, particularly Kebili and

Tataouine, as prime locations for renewable energy due to ample sunlight and consistent winds, ideal for simultaneous solar and wind installations. Tataouine offers excellent solar conditions and effective wind farming due to its open spaces and low cloud cover.

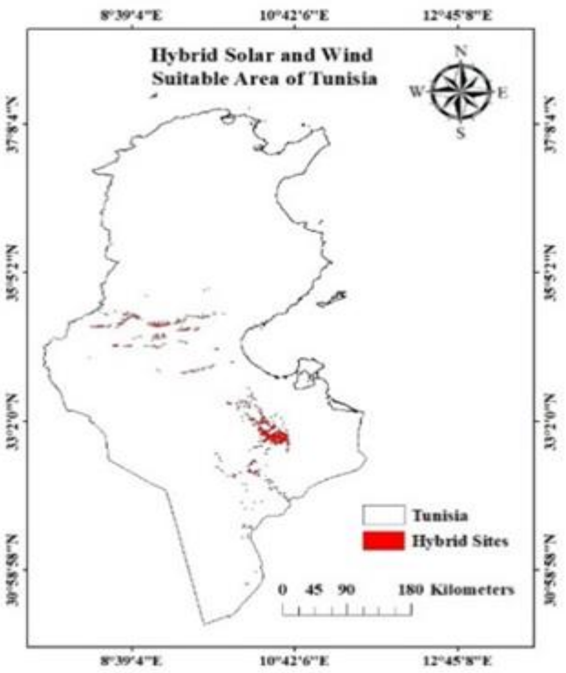


Figure 11 . Hybrid Solar and Wind Suitable Area of Tunisia

CONCLUSION

1. The conclusion of this study demonstrates the efficacy of GIS-MCDM techniques in selecting strategic sites for renewable energy projects in Tunisia.
2. This research combines geospatial and environmental data through AHP-weighted GIS analysis to identify optimal locations for wind and solar farms.
3. The climatic and geographic conditions in these areas are conducive to both high solar gain and strong wind speeds, making them ideal candidates for hybrid solar and wind energy projects.
4. The southern governorates of Kebili and Tataouine, as revealed by the hybrid suitability map, stand out as epicenters of dual renewable prowess. Their selection is not arbitrary; it is underpinned by a set of stringent criteria that consider land use, proximity to power lines, roads, and urban centers—factors that are pivotal for the logistical feasibility and economic viability of renewable energy projects.
5. The evaluation of the locations of wind energy resources is: 3.7%(2533,45km2) . The total available area was classified as "high suitable", with 65.1% (43,995 km2) falling under the "moderate suitable" , the low suitable at 26.1% (25140 km2), and unsuitable at 5.1% (3,474 km2), As for solar energy resources on an area of only 1183 km2 with (1.8% of the available area), followed by 55.9% (37,903 km2), 37% (25,140 km2), and 5.1% (3,484 km2) within the "moderate suitable" categories. "Low suitability to unsuitability"

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