Land Suitability Mapping for Large-scale Solar PV Farms in Tunisia Using GIS-Based MCDM Approach

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***Abstract*—Allocating large-scale solar PV farms is a critical issue owing to the multidisciplinary data involved in the siting process. Therefore, delineating the most optimal locations is paramount. Hence, the prime aim of this paper is to highlight and assess the most suitable sites for hosting large-scale solar PV power plants on the entire territory of Tunisia. Towards this end, we integrate geographical information systems (GIS) with multi-criteria decision-making analysis (MCDM) to perform land suitability analysis of the study area.**

Based on the outcomes, the most feasible locations represented 1.11% of the total surface area and covered 1571 km2. Furthermore, it was observed that the administrative regions of Tataouine, Gabès, Gafsa, and Kassérine have shown the most potential sites that are well-suited for constructing solar PV systems. Moreover, the theoretical solar energy yield was estimated at nearly 328 TWh per year.

As a result, the adopted model was found to be a very useful tool in manipulating the selected criteria to identify the most promising locations which could assist Tunisia in achieving its energy targets by 2030.

Keywords—Solar energy, Multi-criteria Decision Making (MCDM), FAHP, Tunisia

I. Introduction

II. Being aware of the amounting challenges of the energy-environment-economy nexus, many countries have turned the focus of their policies towards the transition to renewable energy sources (RES) by setting motivating portfolios to prompt a diversified energy sector for a more sustainable, secure, and zero-carbon emission future [1]. With remarkable cost declines coupled with impressive technological advancements, renewable energy technologies, such as solar energy, wind energy, biofuel energy, etc., are rapidly gaining market share. Solar photovoltaic (PV), in particular, has taken the lead in terms of the fastest growing RES technologies worldwide due to the sharp fall in module prices as well as power generation costs [2-5]. InTunisia, a country with limited natural resources, energy sector is characterized by stagnating local supplies and steadily increasing demand. In addition, the electricity system is largely dependent on conventional fossil fuels, primarily natural gas (97%) with only a meager share of renewable energy sources (3%) [6]. In light of this context, Tunisia has considered the expansion of its power fleet by integrating 30% of RES into the energy mix by 2030 [7]. With solar resources ranging between 1800 and 2600 kwh/m2, such a strategy seems quite ambitious.

However, establishing solar PV power plants based merely on the availability of solar potential is inadequate given the various and conflicting factors involved in the construction process [9]. Moreover, placing a PV system on a well-suited site can lead to the acceleration of power generation [11]. Therefore, it is essential to screen the most optimal locations before implementing solar PV systems as it is the key component for the success of the project [8]. Consistent with this, integrating geographical information systems (GIS) with multi-criteria decision making (MCDM) techniques has been widely applied in land suitability and siting applications including solar PV power plants [9-11].

The current study combines GIS and the fuzzy analytical hierarchy process (FAHP) in order to identify the most promising sites for hosting large-scale solar PV farms in Tunisia. This combination approach would offer further insights into a variety of subjective and conflicting factors which could assist decision-makers in screening potential locations.

III. Data and Methods

To determine the land suitability of a given location, various datasets are taken into consideration in most decision-making problems.

Following an extensive literature survey and experts' feedback, a list of eight criteria has been identified for allocating suitable sites for the construction of large-scale solar PV farms in Tunisia.

The delineated criteria include global solar irradiance (GHI), landuse, temperature, slope, aspect distance from power lines, distance from major roads, and distance from urban areas. FAHP was used to assign weights to the considered criteria so that the land suitability analysis could be conducted. Then, these criteria were reclassified into five classes, brought to a common scale and then converted into raster format as illustrated in Table. I. Subsequently, each input layer was multiplied by its relative score using the raster calculator tool within Arcmap 10.8.1. Lastly, the final solar suitability map was generated.

A. GIS Analysis and MCDA

Given their complementary nature and their ability to blend policy makers' views with experts' opinions, GIS and MCDM models have become increasingly popular for land suitability and spatial analyses including RES siting [12]. In the literature, the analytical hierarchy process (AHP) has

TABLE. I. SUITABILITY RATING FOR CRITERIA

C1	C2	C3	C4	C5	C6	C7	C8	C9	Suitability Rate
> 2100	> 8	< 20	0 - 2	S	Bare land	0.3 - 1	0.5 - 1	2- 5	5
2000 - 2100	7 – 8	20 – 21	2 - 5	SE, SW	Grass land & Sparse vegetation	1 - 5	1 - 5	5 - 10	4
1900 - 2000	6 – 7	21 – 22	5 - 8	E, W	shrubs	5 - 10	5 - 10	10 - 15	3
1700 - 1900	5 - 6	22 – 23	8 - 10	N, NE, NW	Cropland and trees	10 - 15	10 - 15	15 - 20	2
< 1300	< 5	> 23	> 10	Flat	Settlements, water bodies, Forests	> 15	> 15	20 – 25	1

appeared to be the most frequently used MCDM technique owing to its advantageous features. It is simple, applicable to quantitative as well as qualitative data, and flexible in handling unstructured and multi-attribute issues [9]. Nonetheless, in real-life situations, this technique falls short as uncertainties are generally associated with decision-making problems given the dynamic nature of the parameters involved [13]. As such, FAHP can be applied to overcome this weakness. It has been proven that FAHP produces more accurate and comprehensive assessments as it uses fuzzy judgments instead of exact crisp ones [14]. As an extension of conventional AHP combined with fuzzy logic, FAHP is considered one of the most effective tools for site selection [15]. In this model, the degree of membership is determined using linguistic variables. Then, the AHP values are transformed into the TFN scale as depicted in Table I. Refs. [16, 17] give a detailed explanation of the implementation of FAHP. The main steps included in the FAHP model are presented as follows:

Step 1: Construct the fuzzy matrix according to Table I:

$$\tilde{A} = \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & \tilde{a}_{22} & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & \tilde{a}_{nn} \end{bmatrix} \quad (1)$$

Step 2: compute the geometric mean of the fuzzy comparisons for criteria

$$\tilde{r}_i = \left(\prod_{i=1}^{n} \tilde{a}_{ij} \right)^{1/n}, i = 1,2,\ldots n \quad (2)$$

Step 3: calculate the fuzzy weights

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_i \oplus \tilde{r}_i \oplus \ldots \oplus \tilde{r}_i)^{-1} \quad (3)$$

Step 4: defuzzify the obtained using the central area method

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \quad (4)$$

Step 5: compute the normalized weights

$$N_i = \frac{lw_i + mw_i + uw_i}{\sum_{i=1}^{n} M_i} \quad (5)$$

B. *Decision criteria and constraints*

Placing a solar PV farm is a challenging task given the multifaceted data used in the process. In this paper, the relevant criteria were classified into three main groups: climate, topography, and accessibility. Such criteria were finalized based on similar research works, with a specific focus on solar PV, and experts' feedback. The details of these criteria are shown in Table II. A brief description of the criteria used is presented below.

Table II. TFN and Linguistic variables

Saaty Scale	Definition	TFN Scale
1	equally important	(1,1,1)
3	moderately more important	(2,3,4)
5	strongly more important	(4,5,6)
7	very strongly more important	(6,7,8)
9	extremely more important	(9,9,9)
2	Intermediate values between two adjacent scales	(1,2,3)
4		(3,4,5)
6		(5,6,7)
8		(7,8,9)

- *Climate Criteria*

When constructing a solar PV system, solar radiation is the most influential factor. As it is the principal source of energy for solar cells. Hence, locations with higher insolation are the most preferred [10]. It has been noted that an amount of 1300 KWh/m2/year is required for a PV system to be economically feasible [18]. In contrast, the ambient temperature is considered a major limiting factor. Higher temperatures deteriorate the system's performance as well as its durability [10]. Fig 1. depicts these criteria.

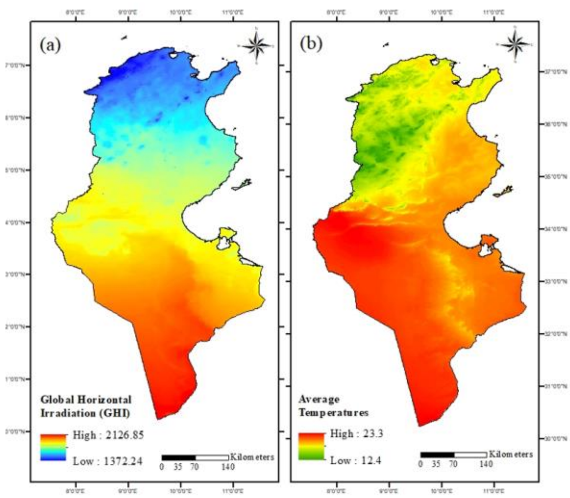

Fig. 1. Thematic maps for climate criteria Global Horizontal Irradiation (b) Annual Average Temperatures

- *Topography criteria*

Geographic features of flat terrain or low slopes are essential for minimizing ground adjustments and construction costs. Moreover, in the northern hemisphere, to ensure maximum output power and minimize the shadow effect, south-facing slopes are preferred [10]. Additionally, a solar PV power plant should be deployed on a suitable type of land, preferably barelands or medium grassy vegetation or shrublands. As a result, the study area has to be screened to eliminate undesired locations such as mountains, lakes, sand dunes, and water bodies. Fig.2. shows such criteria.

- *Accessibility criteria*

The availability of adequate transportation and grid infrastructure is crucial during the construction and operation of PV projects [10]. Furthermore, being close to residential areas minimizes power distribution over long distances; however, in some cases, this may hinder future urban development [19]. These criteria are illustrated in Fig.3.

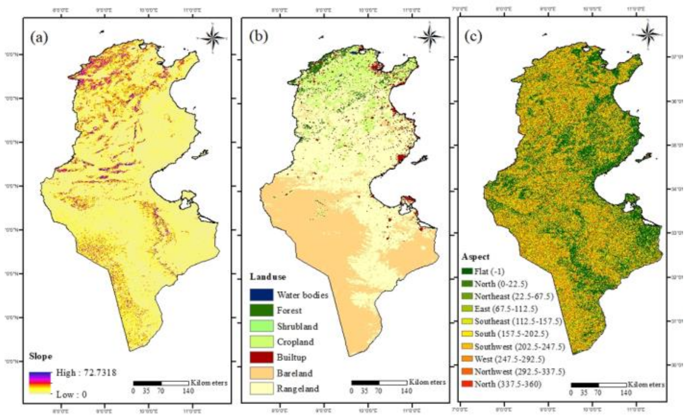

Fig. 2. Thematic maps for the topographic criteria (a) Landuse (b) Slope (c) Aspect

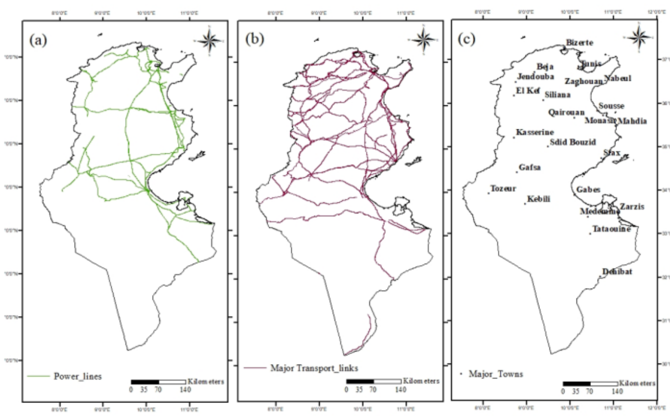

Fig. 3. Thematic maps for the topographic criteria (a) Grid network (b) Major roads (c) Major towns

C. Constraints

Logically, a PV power plant could not be established within a protected area which poses a hindrance to the deployment of such facilities. Therefore, several economic, technical, and environmental constraints have to be taken into account to limit the feasibility analysis of the siting process [10, 20]. For this reason, the use of Boolean algebra (1 and 0) within the integrated tools of ArcMap8.1 software has made it possible to exclude undesired areas. The "1" value indicates that there are no constraints and establishing PV farms is possible, whereas "0" indicates that there are constraints, and therefore, construction is not feasible. Accordingly, areas with a "zero" value must be discarded. Table 3 depicts the constraints considered in this study.

IV. RESULTS

In this study, GIS-based FAHP approach was used to conduct land suitability for screening the most optimal sites. A set of eight criteria was identified including GHI, slope, orientation, landuse, temperature, and distance from grid network, transportation links and urban areas. Weights were assigned to the selected criteria by means of fuzzy pairwise comparison matrices technique (Table III). According to FAHP results, solar radiation was ranked first (33.6%) as it is the most influential criterion, followed by slope (17.86%). The next most important criterion came landuse with a weight of 13.3%. Proximity to grid and transportation links were yet other significant factors scoring 9.998 % and 11.4%, respectively. The remaining criteria were found to be least important according to the experts' preferences.

A. Solar feasible sites

Based on the combination of GIS-MCDM, the overlaid result map revealed that the potentially feasible areas were clustered into five categories: 1.11% (1704 km^2) 'most suitable', 10.41% 'suitable', 24.13% 'moderately suitable', 59.15% 'least suitable', and 5.20% 'unsuitable' (Fig. 4). The central and southern regions of Tunisia have shown more potential sites that are well-suited for hosting large-scale solar PV farms. This is chiefly due to the advantageous high solar insolation, mild slopes, appropriate grid and road network infrastructure as well as proximity to residential areas. From this map, it was noted that more than 74% of the most suitable locations were scattered within the regions of Tataouine, Gabès, Gafsa, and Kassérine. By comparing the most suitable sites with the ones obtained from our recent paper [21], despite being located in the same regions, FAHP approach has shown more accurate results compared to AHP technique.

B. Estimated Energy Production

From a theoretical perspective, solar power could be defined as an area with abundant solar resources that is well-suited to hosting solar PV systems using existing technology. Therefore, solar potential is determined based on the GIS-based FAHP approach by excluding all restrictive areas from the final suitability map. Accordingly, solar power was estimated as follows:

$$AEP = SR\ CA\ AF * \eta \qquad (6)$$

Where AEP is the annual generated power (TWh/year), SR is the annual solar radiation (kWh/m2/year), CA is the total area of suitable locations (km2); AF is the area factor of total CA that could be covered by solar panels (%), and η is the PV system's efficiency (%). In this paper, this output power was computed based on the technical characteristics of mono-crystalline silicon technology.

According to the results, the most suitable sites are capable of providing an estimated theoretical energy of 328 TWh/year (Table IV). If it is to take only 10% of these highly suitable locations, it would be possible to generate around 33 TWh of solar energy per annum. This represents 1.65% of the total demand in 2020 [6].

TABLE III. PAIRWISE COMPARISON MATRIX AND WEIGHTS

	C1	C2	C3	C4	C5	C6	C7	C8	Weight
C1	(1,1,1)	(2,3,4)	(4,5,6)	(3,4,5)	(6,7,8)	(3,4,5)	(2,3,4)	(4,5,6)	**33.6%**
C2		(1,1,1)	(1,2,3)	(1,1,1)	(1,1,1)	(2,3,4)	(1,2,3)	(4,5,6)	**17.86%**
C3			(1,1,1)	(1,2,3)	(1,2,3)	(2,3,4)	(1,1,1)	(3,4,5)	**13.3%**
C4				(1,1,1)	(1,1,1)	(1,2,3)	(1/4,1/3,1/2)	(2,3,4)	**5.3%**
C5					(1,1,1)	(2,3,4)	(1/4,1/3,1/2)	(2,3,4)	**5.12%**
C6						(1,1,1)	(1/3,1/2,1)	(4,5,6)	**9.98%**
C7							(1,1,1)	(3,4,5)	**11.4%**
C8								(1,1,1)	**3.44%**
λmax = 8.401			CI = 0.057			CR = 4.06%			

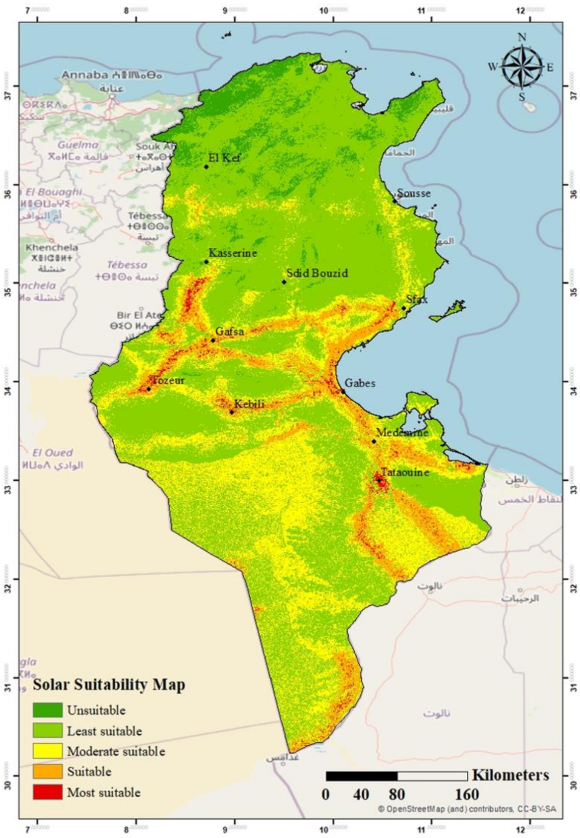

Fig. 4 Final suitability map for potential solar sites.

TABLE IV. ANNUAL ENERGY PRODUCTION (TWH)

Region	**Annual Energy Production**
Gabès	48.975
Gafsa	45.405
Kassérine	31.554
Kebili	18.436
Le Kef	0.317
Médenine	14.747
Sfax	18.899
Sidi Bou Zid	2.694
Sousse	0.320
Tataouine	118.954
Tozeur	27.723
Total	**328.030**

V. CONCLUSION

It has become evident that solar energy is a viable option for electricity generation that can contribute to a sustainable, secure, and environmentally friendly future. Nonetheless, installing large-scale solar PV farms is a challenging task given the various conflicting factors involved. Thus, identifying the optimal locations before constructing such facilities is deemed essential as it saves a great deal of time and cost. In this study, the GIS-based FAHP methodology was employed to assess land suitability for deploying large-scale solar PV power plants in Tunisia. This approach has

proved to be a very useful tool in manipulating the selected criteria as well as the geospatial data. The criteria used in the spatial analysis were determined based on an extensive literature survey and experts' feedback according to the peculiarities of the Tunisian power system.

Thus, identifying the optimal locations before constructing such facilities is deemed essential as it saves a great deal of time and cost. In this study, the GIS-based FAHP methodology was employed to assess land suitability for deploying large-scale solar PV power plants in Tunisia. This approach has proved to be a very useful tool in manipulating the selected criteria as well as the geospatial data. The criteria used in the spatial analysis were determined based on an extensive literature survey and experts' feedback according to the peculiarities of the Tunisian power system. The perusal of the final suitability map revealed that Tunisia enjoys significant solar potential. It was observed that the most feasible sites covered an area of 1571 km^2 and were scattered mainly around the central and southern parts of the country.

The administrative regions of Tataouine, Gabès, Gafsa, and Kassérine were by far the most suitable locations for constructing solar PV systems as they represented nearly 74% of the areas of most suitability. Additionally, the theoretical annual solar energy was estimated at 328 TWh. Accordingly, we conclude that the present findings are very Encouraging for policy-makers and investors with regard to Tunisia's efforts to improve its energy system, reduce its heavy dependence on conventional fuels, and demonstrate the economic viability of developing solar farms .

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