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Developing a GIS-based Fuzzy AHP Model for Selecting Solar Energy Sites in Shodirwan Region in Iran

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Abstract

The objective of this study is to use a Fuzzy Analytic Hierarchy Process (Fuzzy AHP) and geographical mapping models using Geographical Information System (GIS) to locate the most appropriate sites for solar energy farms in Shodirwan region in Iran. GIS interpolation showed that annual solar insolation in Shodirwan is very good and can be used for potential solar farm locations. The average of solar insolation in the region is 5.12 kWh/m2/day annually. Results showed that 18.25% of the Shodirwan area is exploitable as solar farms. With a conversion efficiency of 10% and area factor of 70%, annual electricity production for the exploitable area is roughly 16100 GWh. Land suitability analysis for solar farms implementation was carried out and overlay results obtained from the analysis of the resultant maps showed that 13.98% and 3.79% of the total land area demonstrate high and good suitability levels, respectively. The total electricity generation potential from both highly and good suitability levels in Shodirwan region was about 15,690 GWh annually.

Keywords: *Fuzzy AHP, GIS, Site selection, Solar energy, Solar radiation, Spatial analysis*

1. Introduction

The interest on renewable energies is growing day by day, as fossil fuels become more expensive and difficult to find than before. Furthermore, the latest environmental disasters caused by the oil drilling and transportation, have further focused the attention of the entire world on the risks connected to fossil fuels [1]. The utilization of non-renewable energy sources in the developing countries with low levels of technological knowledge not only results in environmental pollution but also confronts us with the dilemma of a rapid rate of depletion of such invaluable resources [2, 3]. Moreover, life of oil reserves are limited and the share of next generation must be considered so that they may have better options to utilize these badly treated treasures [2, 4, 5]. New and renewable energies will, therefore, become the world's main alternative energy sources. It is expected that 60% of world energy will come from renewable energy sources by the year 2070 [6, 7].

Iran is the second Middle Eastern country with respect to enjoying various energy resources. Iran not only enjoys vast and valuable deposits of fossil fuels and natural gas which contribute to her national economy and export earnings in a major way but also is a rich country in terms of renewable energy resources such as solar, wind, geothermal, hydro, *etc.,* where scientists and researchers have made special efforts in finding and developing renewable energy sources as well as adopting related technical

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knowledge in processing them. One of the most interesting, among the renewable energy resources in Iran, is the solar energy. Solar energy is not only inexhaustible but also clean. As on-site sources of clean power, solar energy systems can reduce greenhouse gas (GHG) emissions and air pollution, increasing energy security and creating local jobs. It can be safely converted to other forms of energy without emitting carbon dioxide gas, thereby avoiding any greenhouse effect. The utilization of the solar radiations has a wide range of applications; nevertheless the interest of solar engineering is mainly focused on thermal processes and photovoltaic (PV) applications. During the last two decades, the rhythm of the implementation of solar farms using PV panels or Concentrated Solar Power (CSP) technologies has accelerated in the countries situated in the solar energy belt, despite their prohibitive costs. Solar electricity systems also have the potential to generate power when it is needed most—on hot summer days—thereby relieving strain on the electricity system and reducing the risk of blackouts [1, 8, 9].

During the last decade, the use of the Geographical Information System (GIS) has accelerated in field of renewable energy in several regions of the world. GIS are computer-based systems that store and process (*e.g.*, manipulate, analysis, model, *etc.*,) spatially referenced data at different points in time and visualize the results [10]. A variety of renewable energy applications have been undertaken using GIS techniques [11-19]. The GIS-based decision support systems has reached a high level of maturity and emerged as a powerful tool to build solar energy strategies and to integrate large amounts of PV into flexible, efficient and smart grid. GIS is capable of handling, processing and analyzing large quantities of spatial data and valuable in underpinning decision making for the spatial deployment of PV. Using GIS and Multi-Criteria Decision Analysis (MCDA) together will provide a fine lens for the optimal site selection for plants. GIS-based MCDA is commonly used to solve the conflicts of location suitability and harmonizing the tradeoffs and risks related to various experts' judgment engaged in the implementation of different applications [9, 20-22]. The Analytic Hierarchy Process (AHP) is a useful systematic tool for handling MCDA. AHP is a decision-aided method which decomposes a complex multi-factor problem into a hierarchical structure, and each level is composed of specific elements [23-26].

In most of the real-world problems, some of the decision data can be precisely assessed while others cannot. Fuzzy AHP is a synthetic extension of AHP method when the fuzziness of the decision makers is considered. In this study, Chang’s extent analysis [27] on fuzzy AHP is formulated for a selection problem. In this study, we apply Fuzzy AHP and GIS-based mapping models to locate the most appropriate sites for solar energy in Shodirwan region in Iran.

2. Methods and Materials

2.1. Fuzzy Set Theory

In reality, it is very hard to extract precise decision data related to measurement indicators by human judgments. Decision makers and policy makers also prefer natural language expressions rather than crisp numbers. Zadeh (1965) introduced the fuzzy theory, and its first utilization for decision making problems was presented by Bellman and Zadeh’s work. Fuzzy set theory has made a major contribution to representing vague and incomplete data [29] when its capability to provide a methodology for computing directly with words is considered. Fuzzy theory is composed of three key factors, which are fuzzy set, membership function, and fuzzy number to change vague data into useful data efficiently. Fuzzy numbers are in fact natural generalizations of ordinary numbers. Triangular and trapezoidal fuzzy numbers are usually used to capture the vagueness of the parameters which are related to selecting the alternatives [26, 30-32]. In this research, we used triangular and trapezoidal to prioritize suitability of land for solar energy sites. Triangular and trapezoidal fuzzy numbers are expressed with boundaries instead of crisp numbers for reflecting the fuzziness as decision makers select the alternatives or pairwise comparisons matrix.

A fuzzy number M on R is called a triangular fuzzy number (TFN) if its membership function is given by [26, 27]:

$$\mu_{\ddot{a}}(x) = R \rightarrow [o,1]$$
$$\mu_{\ddot{a}}(x) = \begin{cases} \frac{x}{m-l} - \frac{l}{m-l} & x \in [l,m] \\ \frac{x}{m-u} - \frac{u}{m-u} & x \in [m,u] \\ 0 & Otherwise \end{cases} \tag{1}$$

and we define a fuzzy number M on R to be a trapezoidal fuzzy number if its membership function is:

$$\mu_{\ddot{a}}(x) = R \rightarrow [o,1]$$
$$\mu_{\ddot{a}}(x) = \begin{cases} \frac{x}{n-l} - \frac{l}{n-l} & x \in [l,n] \\ 1 & x \in [n,m] \\ \frac{x}{m-u} - \frac{u}{m-u} & x \in [m,u] \\ 0 & Otherwise \end{cases} \tag{2}$$

Consider two TFNs M_1 and M_2, $M_1= (l_1, m_1, u_1)$ and $M_2= (l_2, m_2, u_2)$. Their operations laws are as follows [32, 33]:

$$(l_1, m_1, u_1) + (l_2, m_2, u_2) = (l_1+l_2, m_1+m_2, u_1+u_2) \tag{3}$$

$$(l_1, m_1, u_1) \times (l_2, m_2, u_2) = (l_1 \times l_2, m_1 \times m_2, u_1 \times u_2) \tag{4}$$

$$(l_1, m_1, u_1)^{-1} = (\frac{1}{u1}, \frac{1}{m1}, \frac{1}{l1}) \tag{5}$$

2.2. Fuzzy AHP

AHP is one of the well-known multicriteria decision making (MCDM) method invented by Saaty in 1970s [34]. It is the powerful and useful MCDM approach tool. Saaty suggested the AHP as a decision making tool to resolve unstructured problems. AHP is based on pairwise comparisons. In this method, decision-maker forms a hierarchical decision tree and determines its indices and options. Although the AHP method is to capture the expert's knowledge by perception or preference, AHP still cannot reflect the human thoughts totally with crisp numbers as compared to fuzzy AHP method due to its interval values instead of simple crisp numbers. Therefore, the fuzzy AHP, which is a fuzzy extension of AHP, is applied to solve the hierarchical fuzzy MCDM problems. There are numerous cases for employing fuzzy AHP. The extend analysis method (EA) was presented in 1996 by Chang [27]. TFN is used in this model.

Let $M_i= (l_{ij}, m_{ij}, u_{ij})$ be a TFN. The stages of extent analysis approach can be summarized as follows:

Letting $C_j=\{C_1,C_2,.,C_n\}$ be a criteria set, extent analysis values for each criterion can be obtained as follows [27, 32]:

$$S_i = \sum_{j=1}^{m} M_{ij} \times \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{ij}\right]^{-1}$$
$$s.t \sum_{j=1}^{m} M_{ij} = \left(\sum_{j=1}^{m} l_{ij}, \sum_{j=1}^{m} m_{ij}, \sum_{j=1}^{m} u_{ij}\right) \; for\; i = 1,2,\ldots,n$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{ij} = \left(\sum_{i=1}^{n}\sum_{j=1}^{m} l_{ij}, \sum_{i=1}^{n}\sum_{j=1}^{m} m_{ij}, \sum_{i=1}^{n}\sum_{j=1}^{m} u_{ij}\right) \quad (6)$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{ij}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} u_{ij}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} m_{ij}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} l_{ij}}\right)$$

As $S_j=(l_j, m_j, u_j)$ and $S_i=(l_i, m_i, u_i)$ are two triangular fuzzy numbers, the degree of possibility of $S_j=(l_j, m_j, u_j) \geq S_i=(l_i, m_i, u_i)$ is defined as:

$$V(S_j \geq S_i) = height\,(S_i \cap S_j) = u_{S_j}(d) = \begin{cases} 1 & if\ m_j \geq m_i \\ 0 & if\ l_i \geq u_j \\ \frac{l_i - u_j}{(m_j - u_j) - (m_i - l_i)} & Otherwise \end{cases} \quad (7)$$

where d is the ordinate of the highest inter section point between u_{Si} and u_{Sj}. We need to compare both the values of V ($S_j \geq S_i$) and V ($S_i \geq S_j$) with S_i and S_j.

The degree possibility for a convex fuzzy number to be greater than k convex fuzzy Mi (i = 1,2, ...,k) numbers can be defined by:

$V(S \geq S_1, S_2, \ldots, S_k) = V[(S \geq S_1)$ and $(S \geq S_2)$ and….and $(S \geq S_k)] = \text{Min } V(S \geq S_i)$, i=1,2,3,…,k

Assume that $d(A_i) = \min V(S_i \geq S_k)$ for k =1, 2, ... ,n. Then the weight vector is given by:

$$W' = (d'(A_1), d'(A_2), \ldots, d'(A_n))^T \quad (8)$$

where A_i(i=1,2,..,n) are the n elements.

Via normalization, the normalized weight vectors are:

$$W = (d(A_1), d(A_2), \ldots, d(A_n))^T \quad (9)$$

where W is a non-fuzzy number.

2.3. Study Area and Data

The study was carried out for Shodirwan region in Khuzestan province, Iran. This region is peninsula between Karun and Dez rivers and is the one of the important agriculture crop areas in Iran and most of it is a rural area. Imam Khomeini agro-Industry with about 15000 hectares located in the middle of Shodirwan that sugarcane is cultivated in it.

Reliable long-term sunshine measurements are sparse and available only for regions where meteorological stations are operating. Datasets for the solar insolation was obtained from the Iran Meteorological Organization and Renewable Energy Organization of Iran. In the regions where there are no data available the insolation has been estimated using an interpolation method of measured values from meteorological stations with similar climatological conditions. For this study 21 of stations in Khuzestan province that collect the amount of solar insolation were identified. The amount of daily solar insolation for each station is averaged over the period of establishment of stations to 2009 for each station. The data provides estimates for kWh/m^2/day for each month of the year, as well as an annual average. Averaged values for each station are plotted on a map of Khuzestan province with longitude and latitude based on Universal Transverse Mercator coordinate system (UTM), and then, spatial interpolation technique, Kriging interpolation is used for predicting insolation values for un-sampled locations on ArcGIS. Then map for Shodirwan region was extracted from interpolated solar insolation map. Digital databases of land cover and land use, location of roads, transmission lines, topography, and accessibility to the grid were obtained from Jahad Agriculture Organization of Khuzestan province and Iran National Cartographic Center.

2.4. Criteria of Appropriate Solar Sites Selection

The first step is to eliminate inappropriate locations due to terrain or security reasons. One criterion applied in the determination of potential solar farm locations is the current land use. Solar farm installations require the majority of land to be utilized solely for these installations. As a result, the only barren land considered as permissible for solar energy that include of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover [18]. In Shodirwan region there isn't any area that is restricted due to conservation. Any area that does not barren was eliminated for solar energy generation.

Other criterions to select appropriate sites for solar energy are amount of insolation, transmission lines, topography and Distance to roads. Slope and aspect are topographic features that play important role in selecting solar energy site. Digital elevation model (DEM) represented as a raster format with a pixel of 10 m were obtained from Iran National Cartographic Center. The value of the pixel represents the elevation which can be used to calculate slope and aspect with ArcMap. The GIS analysis was conducted on ESRI's ArcMap 9.3 software. The value of 1 was given to any cell with slope of 0-3%, and cells with slope 3-10% were valued from 0 to 1 by:

$$S_{value} = \begin{cases} 1 & x \le 3 \\ \frac{x_{slope} - 10}{-7} & 3 \le x \le 10 \\ 0 & Otherwise \end{cases} \tag{10}$$

where S is any sell in slope map of Shodirwan region and x_{slope} is slope of x cell (%). Any cell that has slope greater than 10% was assigned value of 0.

Locations with south-facing aspects are good locations for solar farms due to the southern exposure. Aspect raster map were valued by:

$$A_{value} = \begin{cases} \frac{x_{degree} - 112.5}{33.5} & 112.5 \le x_{degree} \le 146 \\ 1 & 146 \le x_{degree} \le 214 \\ \frac{x_{degree} - 247.5}{-33.5} & 214 \le x_{degree} \le 247.5 \end{cases} \tag{11}$$

where A_{value} is value that gives any cell in aspect raster map and x_{degree} is aspect of any x cell in degree.

Road adjacency is desirable criterion in the determination of potential solar farm locations and minimum distance from road is objective. Also minimum distance from transmission lines is objective. The closeness to the transmission lines means less loss of electricity when transferring electricity through transmission lines and easier establishes grid-connected PV utility there. The straight-line distance tool of ArcGIS is used to measure distances from each location to the closest road and transmission lines and then road adjacency and grid accessibility raster maps were valued by valued by:

$$D_{value} = \begin{cases} 1 & x_d \le 1000 \\ \frac{x_d - 1000}{39000} & 1000 \le x_d \le 40000 \\ 0 & Otherwise \end{cases} \tag{12}$$

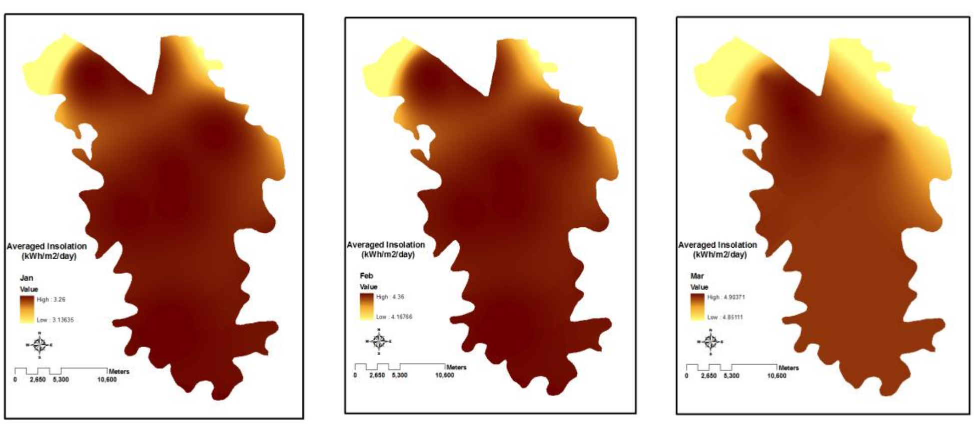
where D_{value} is value that give any cell in road adjacency and grid accessibility raster maps and x_d is distance of any x cell in meter.

To find out the most appropriate locations for solar farms in Shodirwan, slope, aspect, road adjacency and grid accessibility raster map was used in fuzzy AHP model. Pair-wise comparisons for criteria and judgment to the relative intensity of importance of one evaluation factor against another were calculated.

3. Results

The results of kriging interpolation of solar insolation for each month of the year are illustrated in Figure 1. Map of this potential will be used to prioritize the region for solar energy generation and solar site establishment. Grid cells were output at a 20 m resolution in raster format. The average of solar insolation in all the chosen region is 5.12 kWh/m^2/day annually while for each month is different. Minimum of solar insolation was related to December that ranged from 2.79 to 2.88 kWh/m^2/day. The greatest of solar insolation was in summer so that Jun and July had the maximum solar insolation in Shodirwan region. According to the results of interpolation of insolation data, the maximum insolation intensity per day is approximately 7.48 kWh/m^2/day that occur in Jun. High solar insolation and great potential of solar energy can be useful in reducing the load on the power grid and power outages in the hot summer and thereby relieving strain on the electricity system and reducing the risk of blackouts. According to solar resource potential classification by National Renewable energy Laboratory, annual solar insolation in Shodirwan is very good and can be used for potential solar farm locations [35]. Total of annual solar energy with no constraint in Shodirwan is about 1263 TWh but due to constraint and low conversion efficiency of technology only a little of this amount of energy can be used.

A constraint layer including all the unsuitable areas was created and eliminated from Shodirwan region. The region that doesn't have constraint for solar farm installation is showed in Figure 2. In this study, the current land use and land cover that was considered suitable for solar energy, were rangeland, rocky protrusions, dry farming and salty land. Due to low rainfall, dry farming isn't successful and accordingly was considered suitable for exploiting solar energy. Also the most of rangeland is medium and low dense and was considered suitable for solar energy use. It is obvious that most of the Shodirwan area is non exploitable for solar energy use and only 18.25% of it is exploitable. Non exploitable area is composed from irrigated farming, agro-industry, rivers, Shrub land, rural and urban areas and installations, marsh land with high level of surfaces water and area with slopes more than 10%, because it is not possible or not economical to build a large solar farm on buildings, marsh land or rivers.



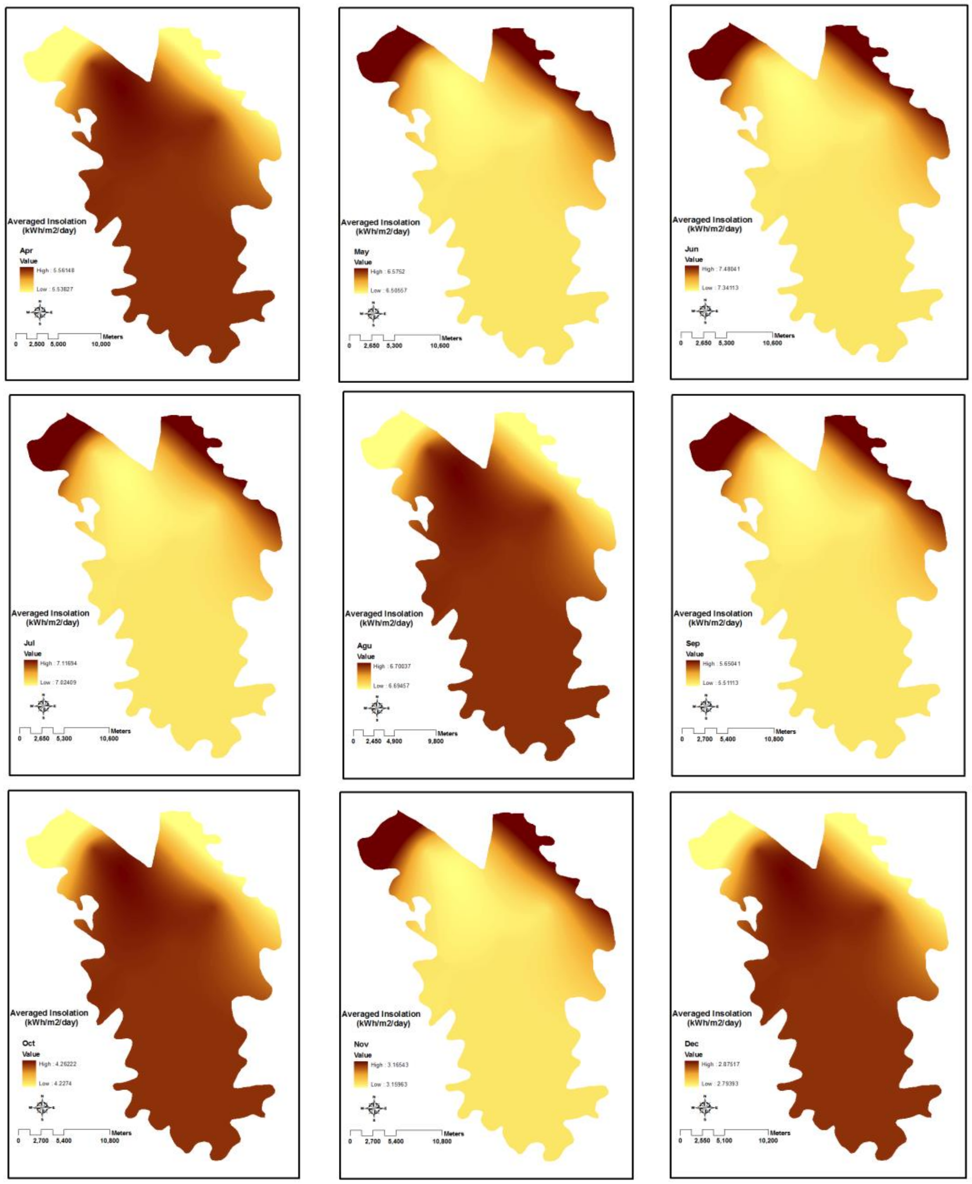


Figure 1. Monthly Solar Insolation

Annual energy that the exploitable area receives from the sun is 230 TWh that regardless of the economy, with conversion efficiency of 10% and area factor of 70%, annual electricity production for exploitable area is roughly 16100 GWh. Area factor indicates what fraction of the calculated areas can be covered by solar panels. As of 2009, the total annual net electricity consumed in agriculture sector of Khuzestan province and Iran were 695.3 and 21410.7 GWh, respectively and the total annual electricity consumed in Khuzestan province was roughly 19100 GWh [36]. In fact, if all exploitable land is used completely for solar form implementation, it can produce almost 23.3 and 0.75 times the total electricity demand in agriculture sector of Khuzestan province and Iran, respectively and 0.84 times the total electricity demand in Khuzestan province.

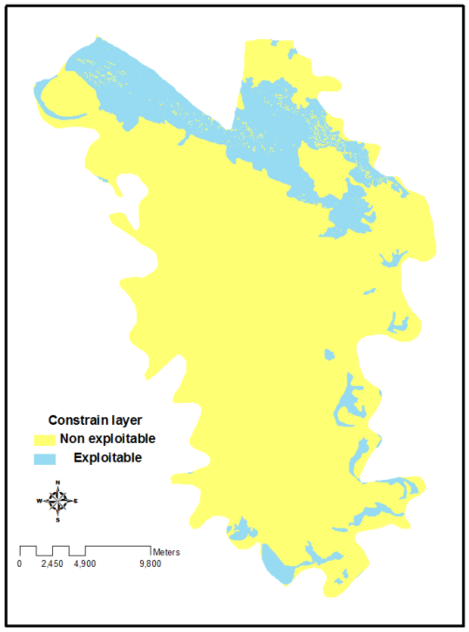
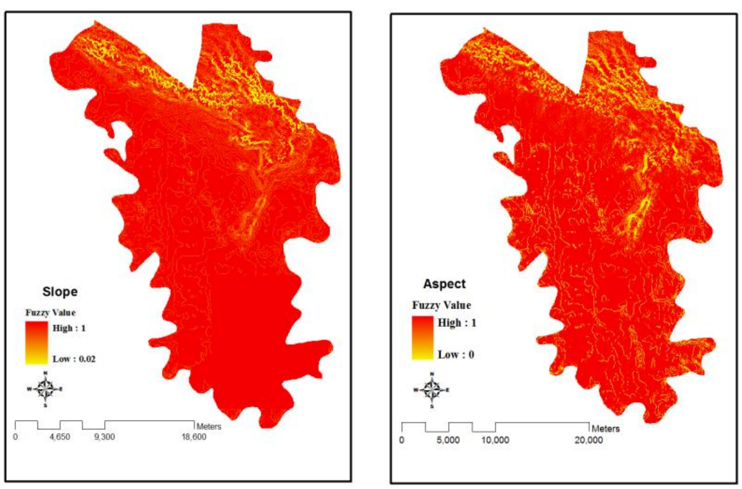


Figure 2. Constraint Layer

Fuzzy layer of criteria are illustrated in Figure 3. Road accessibility layer had values from 0.89 to 1. About 45.3% of Shodirwan area had value of 1. This range of fuzzy value showed that all of Shodirwan area has good accessibility to roads. In terms of access to power transmission lines, 16.54% of all Shodirwan area had a fuzzy value of 1. Minimum value of grid accessibility was 0.59. Most of Shodirwan region is flat so that only 0.63% of its slope is greater than 10% and about 93.22% its slope is less than 3% with fuzzy value of 1. Also, due to the flatness of the land, most areas have a fuzzy value of 1 for aspect. Aspect of fuzzy value ranged from 0 to 1.



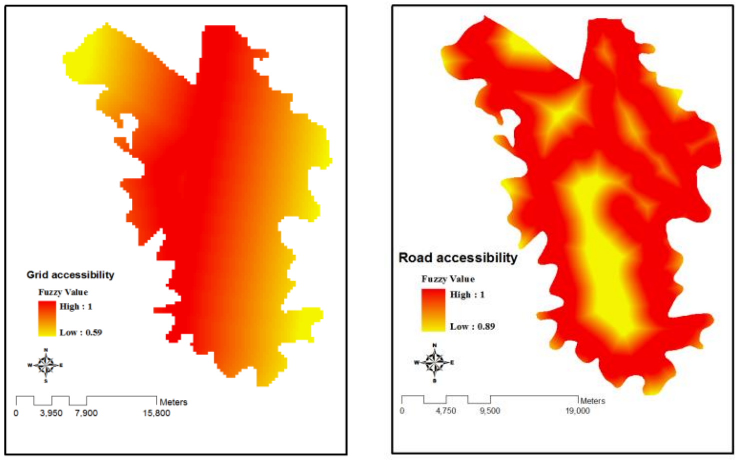


Figure 3. Fuzzy Layer of Criteria

Fuzzy value of multi criteria for exploitable area and spatial distribution of land suitability levels is illustrated in Figure 4. Based on fuzzy AHP model, exploitable area was classified into 3 classes including moderate, good and highly suitable for solar energy development (Figure 4). According to the model, it can be noticed that a big portion of exploitable area have the highly potential for solar energy development (76.58% of exploitable area). Moderate suitability level have very small portion of exploitable area with 2.68%.

Table 1. Total Generation Potential on Different Suitable Lands

Class	Area			Generation potential (GWh/year)
	(m^2)	Exploitable (%)	Shodirwan (%)	
Moderate suitable	3305430	2.68	0.49	430
Good suitable	25592380	20.75	3.79	3340
Highly suitable	94451290	76.58	13.98	12350

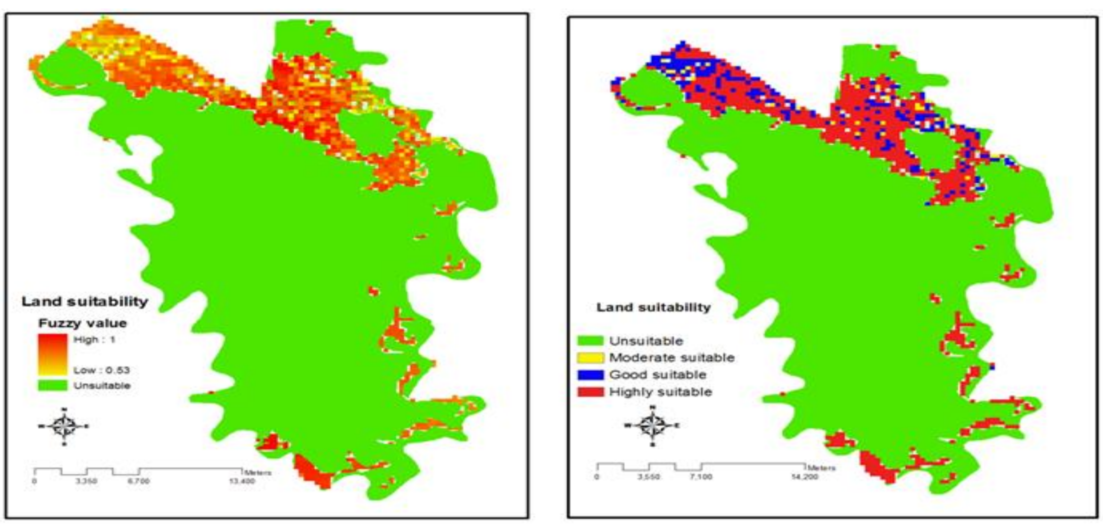


Figure 4. Spatial Distribution of Land Suitability Levels

4. Conclusion

This study has described the application of a GIS-based spatial multi-criteria evaluation approach, in terms of the Fuzzy AHP module to assess the land suitability for solar farms implementation in Shodirwan region in Iran. GIS interpolation showed that annual solar insolation in Shodirwan is very good and can be used for potential solar farm locations. The average of solar insolation in the entire chosen region is 5.12 kWh/m^2/day and GIS overlay showed that 18.25% of the Shodirwan area is exploitable. Annual electricity production for exploitable area with conversion efficiency of 10% and area factor of 70% is roughly 16100 GWh. Land suitability analysis for solar farms implementation was carried out and overlay results obtained from the analysis of the resultant maps showed that 13.98% of the total land area demonstrate a high suitability level. It was found that the region has a very high technical potential for implementing solar forms to generate power. The total annual electricity generation potential from both highly and good suitability level is roughly 15690 GWh.

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