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A Regional Scale Photovoltaic Site Selection Based On Geospatial Techniques

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Abstract

The current study is aimed at defining the suitable areas for establishing photovoltaic (PV) farms in Jordan utilizing geospatial techniques, remote sensing and GIS data. The methodology includes a GIS-based multi-criteria evaluation which converts and integrates geospatial data in the form of map criteria and decision-makers' preferences to define the most suitable sites for the photovoltaic site selection. The study consists of four major components: (1) identifying the potential regions for the PV farms, (2) determining the score values and relative weights of nine spatial criteria, (3) synthesizing the nine criteria according to the fuzzy-AHP method, and (4) evaluating the suitability of the potential sites for PV farms. The results show that the major contributing factors in defining the suitable PV sites are the solar radiation, aspect, and distance from a major electricity network (with relative weights of 30%, 22% and 15%, respectively). The percentage of potential regions in Jordan for PV sites was found to be 58.4%; however, the percentage of suitable regions represented 68.4% of the potential areas which were divided into four groups: "suitable" (8.3%), "slightly more suitable" (14.6%), "moderately suitable" (18.1%), and "highly suitable" (27.4%). The statistical results at the administrative-unit level (governorate) show that 11.2% of the "highly suitable" areas are located in the Ma'an governorate in the southern part of the country. Thus, utilizing the "highly suitable" areas for PV farms can generate much more electricity than the current demand in Jordan.

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Keywords: Remote sensing, GIS, topography, renewable energy, solar radiation, environment

1. Introduction

Responding to the global calls to reduce fossil fuel emissions, the world is witnessing remarkable steps being taken towards improving the production of renewable energy, storage, usage, and planning strategies. The necessity for these efforts is enforced by two major revelations: (1) climate change occurring as a result of fossil fuel burning, and (2) increased energy-safety feelings and policies [1]. In general, renewable energy is defined as the energy generated from natural and sustainable resources, which include solar radiation, wind, waves and tides, rivers and reservoirs, and geothermal heat [2]. Among these resources, solar energy is receiving increased attention worldwide due to the enormous amount of the solar radiation the Earth receives, and the remarkable advances in photovoltaic (PV) panels and concentrated solar power (CSP) technologies [3]. However, the contribution of solar energy as a source of power generation is still minimal compared to other conventional resources. The World Energy Council (WEC) estimated the total amount of power generated by PV panels as being 227 gigawatts, which was only 1% of world power production by the end of 2016 [4]. According to the WEC, major solar installations exist in regions with relatively fewer solar resources (e.g., Europe and China), whereas the potentially high solar resource regions (e.g., Africa and Middle East) remain undeveloped. China leads in new solar exploration followed by Japan, Germany, the United States, and Italy [4].

Furthermore, the incorporation of geospatial technologies, including remote sensing and geographical information systems (GIS), in solar energy capacities has significantly increased. These technologies are providing continuous, large spatial coverage, cost-effective data, and useful analysis tools for the assessment of solar energy potentials, and the selection of suitable sites for solar energy farms. Of these two issues, the selection of suitable sites is more challenging for the following reasons: (1) the amount of required spatial and non-spatial datasets, (2) the need for suitable integration models for data having different formats, (3) the potential costs, (4) environmental impacts, (5) public and community acceptance, and (6) the need to consider the future demand, which may be unpredictable in some cases [3,5–7]. However, under the framework of decision support systems (DSS), GIS-based multi criteria evaluation (GIS-MCE) has emerged in the spatial selection, planning, and management of suitable locations [8]. The GIS-MCE process converts and integrates geospatial data (i.e., in the form of map criteria) and decision-makers' preferences to define the most suitable sites [9–11]. To date, several GIS-MCE methods have been developed and used in renewable energy studies, such as the weighted sum method (WSM), the analytical hierarchy process (AHP), the technique for order preference by similarity to ideal solutions

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(TOPSIS), fuzzy overlay analysis (FOA), and fuzzy AHP (FAHP). Wang et al.[10], Pohekar and Ramachandran [9], and Ishizaka [12] conducted critical reviews and comparisons of MCE methods concluding that the methods which combine the AHP and fuzzy logic methods produced the most comprehensive evaluation tool for subjective and consistent results in sustainable energy decision-making. In solar energy projects, this approach requires mathematical simulations and optimizations of several criteria (e.g., climate variables, topographic variables, and human variables) [13]. In the present study presented, the potential regions for PV sites in Jordan were identified, and the suitable regions for PV farms were allocated utilizing a FAHP approach.

2. Description of the Study Area and the Status of Solar Energy Sector

In this study, the whole land area of Jordan (~ 88788km^2) was selected as the study area. Jordan is a developing country located in a semi-arid hot zone in the Middle East (between 29^o and 32^{o}north and 35^o and 39^{o}east) (see Figure 1). Jordan's population amounts to 9.5 million and experienced a relatively high growth rate of 4.2% at the end of 2015 [14]. Its Mediterranean climate provides hot dry summers and wet cold winters, and the average annual temperature varies with the topography, and is typically predicted as 16-18C^o in mountainous areas, 24C^o in the Jordan valley, and 18C^o in Badia. There are growing concerns about Jordan's energy demands, including rising energy prices, the security of energy supplies, the effects of industrial and population growth, environmental sustainability, and the national security. These reasons prompted both the governmental and private sectors to consider the renewable energy technologies as the main workable alternatives, above all, the PV industry.

Being a semi-arid (hot) country, Jordan is a potential source of abundant solar energy. With an average of 300 sunny days annually, and an average daily sunshine of approximately 8.7 hours, its average direct normal irradiation (DNI) is approximately 6.3 KWh/m^2/day (i.e., ~ 2,400 KWh/m^2/year)[15,16]. As for the electricity sector, the volume of electricity generated by different sources reached 18,911 GWh in 2015, which reflected a 1% growth compared to the previous year. Electricity consumption has increased in all sectors, and reached 5% in 2015 compared to 2014 [15]. Therefore, many action plans have been advanced to meet this demand, including inviting global companies to explore potential oil and gas sources, the direct burning of oil shale to generate electricity, and investing in the renewable energy.

Jordan's achievements in renewable energy in 2015 included three finished PV projects (one project in the Mafraq governorate with a capacity of 10 MW, and two projects in the Azraq area with a capacity of 2 MW and 3 MW, and 12 projects with a capacity of 200 MW in the Ma'an governorate). Another four projects are planned for the coming five years with an expected total capacity of 200 MW (50 MW each) in the northern, central, and eastern areas of Jordan and one project with a capacity of 103 MW in the Qweirah/Aqaba area [15].

In addition, under the instructions of the Energy and Minerals Regulatory Commission, the Jordan government has begun to allow domestic entities (e.g., households, universities, commercial and industrial enterprises, hospitals, farms, etc.) to secure their electricity needs using renewable energy and sell the excess (if any) to the electricity grid by installing small-scale renewable energy systems. By the end of 2015, 35 MW additional capacities were provided in a grid-connected PV system from such small-scale projects [15]. The Jordanian strategic plan of energy has set the ambitious goal of generating 8% of its total electricity capacity using the solar energy technology by the year 2023 [15].

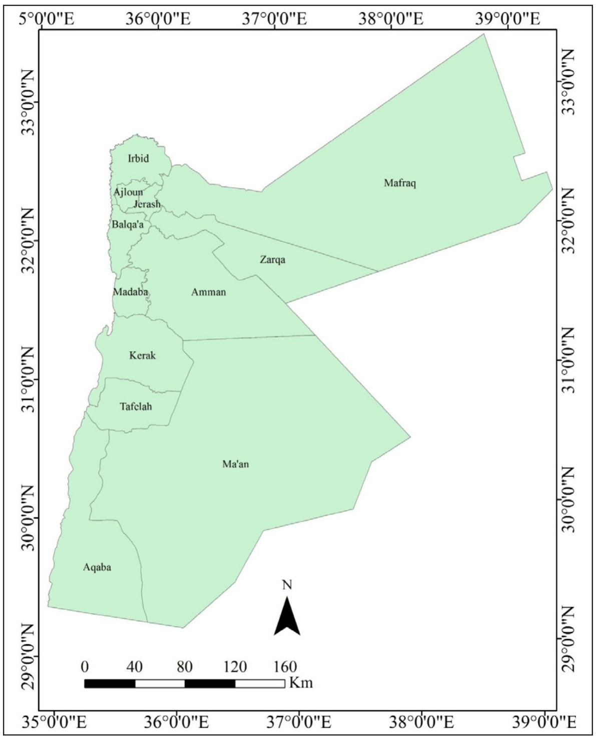

Figure 1. Study area representing the whole geographic extant of Jordan.

3. Materials and Methods

3.1. Defining the Criteria for Potential Suitable Sites for PV Farms

There are no clear-cut rules for PV site selection. However, the process of site selection must take in consideration several constraints that may impact the cost of the electricity generated from that site [17]. To identify and evaluate the potential suitable sites for PV farms in Jordan, nine criteria were determined and grouped into three categories according to their relevance: solar radiation, topographic criteria, and human-related criteria. The criteria were defined by considering the economic, technical, social, environmental, and other constraints [17] based on the past literature and experts' opinions (the Delphi method [18]). The criteria are summarized in Table 1.

Table 1. Description of criteria used in this study for identifying suitable PV sites.

Criterion	Data source	Rule and reasoning
Solar radiation	Remote sensing-derived (i.e., Metosat data, 2.5 km resolution)	- Major criterion represents the source of energy for PV panels. In general, the higher the solar irradiance the better the location for establishing PV farms.
Elevation	Remote sensing-derived (i.e., ASTER-GDEM data, 30m resolution)	- Elevation affects atmospheric depth. Generally, higher elevation regions are having thinner atmosphere. Therefore, less interaction between incident radiation and atmospheric components happen. Thus, these regions receive greater solar radiation. The higher the elevation the better the location for PV farms.
Slope	==	Flat or slightly gradient slope makes installation simpler and reduces the cost of technical modifications of ground adjustment [17].
Aspect	==	Generally, south-facing slope in the northern hemisphere is more appropriate. Such aspect ensures more irradiance and reduces the cost of technical modifications to adjust the ground [17].
Streams	==	Closer site to stream network might be more vulnerable to electrical equipment damage due to potential for flooding. Also, it might increase the risk of erosion of the soil structure and PV foundations [17].
Land use/cover	Remote sensing-derived (i.e., Landsat-8 data, 30m resolution)	In general, open and vacant areas are highly preferable for sites selection due to economic reasons. Forests, archeological, and protected areas are considered as restricted areas for potential PV sites.
Residential areas	Delineated from dense road network map, and Landsat-8 images	The major utilization of electricity demand in Jordan is for residential purposes. Therefore, residential areas were considered apart from other land use types. On the other side, the potential growth should be taken in consideration.
Electricity transmission lines	Ministry of Power	PV-generated electricity is distributed through local electricity transmission network. Thus, this network should be considered in PV site selection. Generally, PV sites should be close to the electricity transmission lines to increase the economic and efficiency potential.
Main road network	Royal Jordanian Geographic Center	PV sites should be served by good road networks for instruments supply and accessibility. The closer the sites are to a road network, the higher the cost reduction and availability of technical support for PV farms.

3.2. Data Preparation

3.2.1. Preparing a Solar Radiation Map

Solar radiation in this study was calculated as the global horizontal irradiance (GHI) (Figure 2a), which was obtained from the Solar Atlas for the Mediterranean (http://www.solar-med-atlas.org/solarmed-atlas/about.htm) in raster format. The data were provided by Solar Energy Mining (SOLEMI) and the Heliosat method [19], which is mainly based on Meteosat images (i.e., spatial resolution of 2.5 km and half-hourly temporal resolution). The Heliosat method was conducted in two steps:(1) the cloud index was derived from the Meteosat images, and (2) the derived cloud index was correlated to the clear-sky index, which relates the actual ground irradiance to the irradiance of the cloud-free case. These data have been validated in several studies [20–22]. The GHI map was re-projected to the Jordan Transfers Mercator (JTM) coordinate system, and then was subset to the Jordanian boundary. The GHI pixel values are in KWh/m^2/year ranging between 1,648 and 2,950. It is important to note that solar radiation is the most important criterion in PV projects being the source of energy [23]. In general, the higher the solar radiation, the better the location is for establishing PV farms [17].

3.2.2. Preparing the Maps of Topographic Criteria

The topographic maps contained the elevation, slope, and aspect (Figures 2b–2c) and streams network (Figure 2f). All the topographic maps were derived from ASTER-GDEM data[24]. Two DEM files were obtained from NASA and mosaicked and masked within the Jordanian boundaries. After that, the mosaicked file was re-projected to the JTM coordinate system. Several pre-processing steps were taken prior to generating the topographic maps, including a quality check and filling in the missing values in the DEM, to remove the small imperfections of the data. The elevation, slope, and aspect maps were, then, derived using the appropriate spatial analysis tools. The stream network map was derived in accordance with the protocols of the ArcHydro tools [25]. Steps to delineate the stream order network were followed in the required sequential order, and they included calculating the functions of flow direction, flow accumulation, stream definition, and stream order identification. Finally, the streams that were level (order) 5 and greater were extracted and used for further analysis.

3.2.3. Preparing the Maps of Human-related Criteria

The human-related criteria included land use types, main electricity transmission lines, and major roads (see Figures 2e and 2f). The map of major transmission lines was obtained as an image file (**.jpg) from the National Electric Power Company, which then was georeferenced to the JTM coordinate system and was digitized accordingly. The map of major roads was obtained from the Royal Jordanian Geographic Center, and was visually checked by overlaying it on the Google Earth base imagery. Residential areas were delineated based on the road density analysis of a detailed road network map combined with a classification procedure for Landsat-8 images. The land use map was identified through a supervised process utilizing a vegetation index-based classification technique for eleven Landsat-8 images covering the geographic extent of Jordan. Accordingly, seven land-use/ cover type classes were identified, namely, residential areas, open area, quarries, agriculture, chert plain, forest, and water bodies. Each image was exclusively classified, then the eleven maps were combined into one land-use map. The average overall accuracy and Kappa coefficient values of the classified maps of the eleven images were 89.3 % and 82.7 %, respectively. Table 2 shows statistical measures of average user's and producer's accuracies for the eleven classified maps. All the datasets were clipped within the Jordan boundaries and projected to the JTM coordinates.

Table 2. Average values of statistical measures of 11 landsat-8 classified images generated through confusion matrices

Average producer's % accuracy	Average user's % accuracy	Land use / cover type
85.3	89.3	Residential areas
82.4	90.2	Open area
94.3	93.4	Quarries
80.7	82.3	Agriculture
96.8	97.4	Chert plain
86.3	85.1	Forest
97.8	98.3	Water bodies

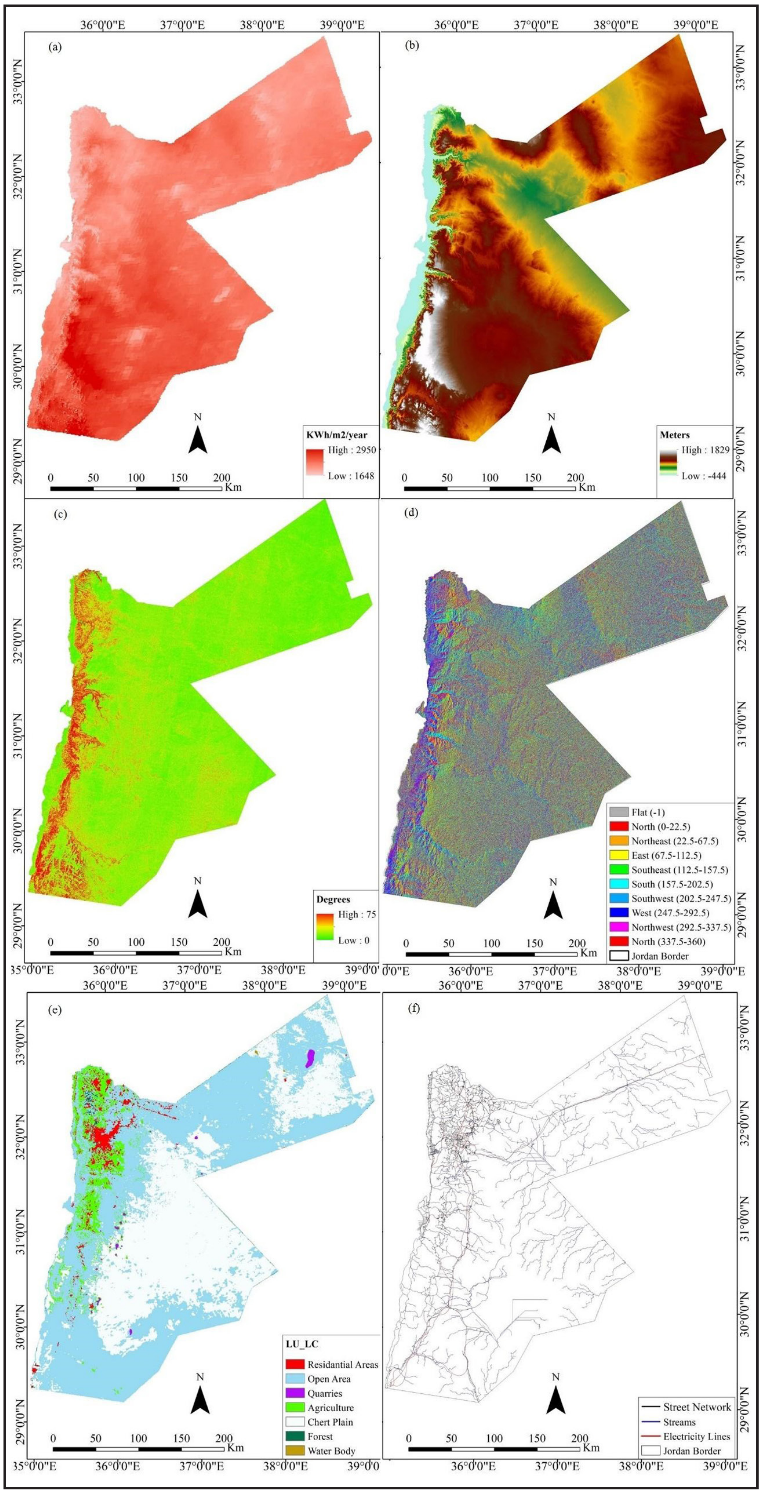

Figure 2. Maps of selected criteria used in this study for defining potential sites of photovoltaic farms: (a) solar radiation, (b) elevation, (c) slope, (d) aspect, (e) land use/cover, and (f) streets, streams, and electricity network.

3.3. Methods

Figure (3) shows a schematic diagram of the methodology, which consisted of four major components: (1) identifying potential regions for PV farms, (2) determining the score values and relative weights of each criterion, (3) synthesizing the criteria according to the GIS-MCE function, and (4) evaluating suitable sites for PV farms.

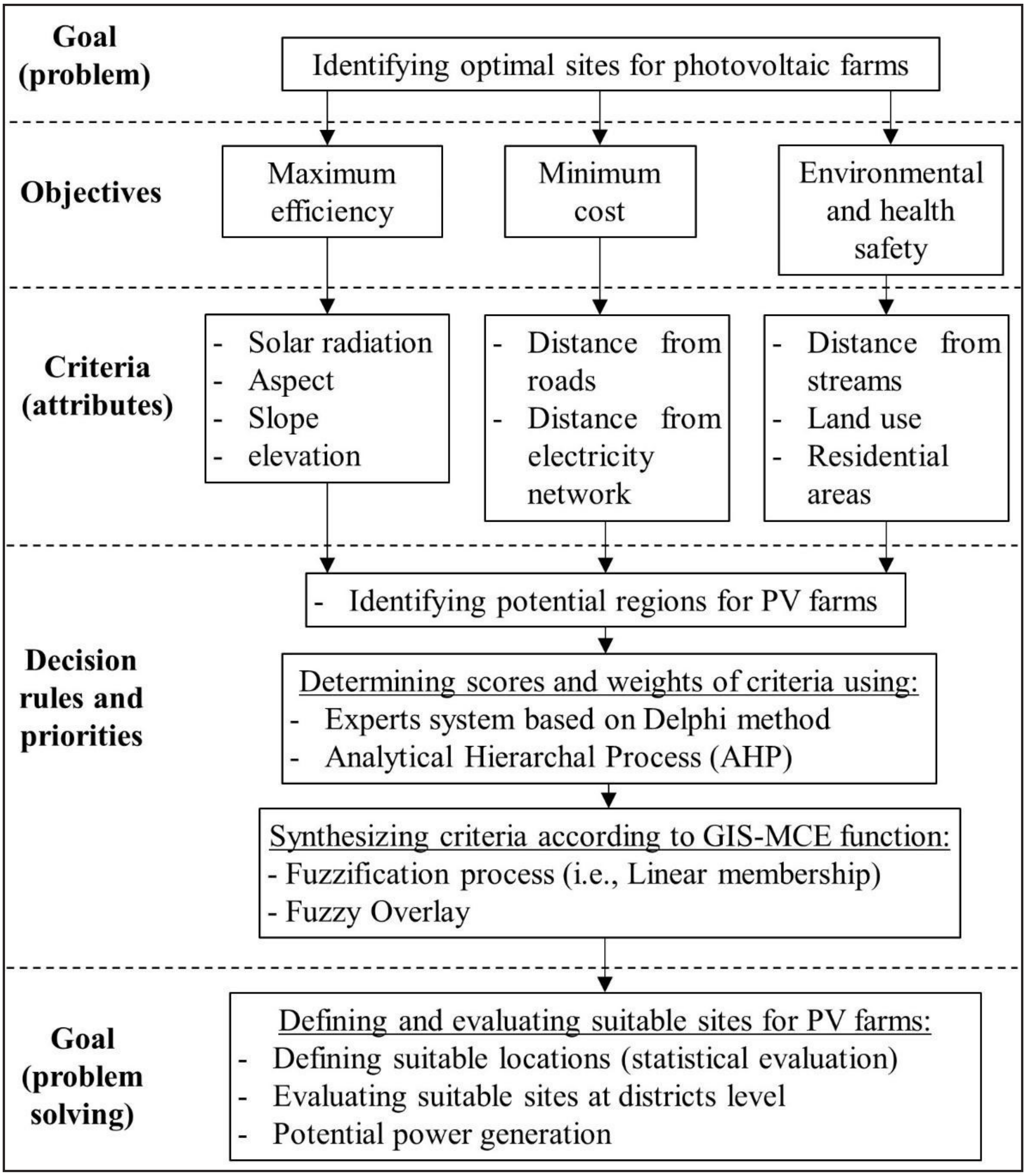

Figure 3. Schematic diagram of the proposed model for photovoltaic farms site selection; the bold terms represent the general steps of multi-criteria evaluation process.

3.3.1. Identifying Potential Regions for PV Farms

To identify potential regions for PV farms and to reduce the processing time of the MCE site selection functions, several spatial masks were applied to define the potential regions for PV farms excluding the unsuitable regions as the first step. The excluded regions were determined based on several constraints, including environmental, technical, safety/security, social and economic constraints [13]. The spatial masks included the following regions:

- Regions with less than 1,300 KWh/m^2/year of solar radiation (technical and economic constraints).
- Protected regions such as forests, national parks, wildlife conservations, lakes, and reservoirs (environmental constraints) [17].
- Regions within a buffer of 0.5km from protected regions (environmental constraints).
- Regions within a buffer of 2km from residential areas (safety, social, and environmental constraints).

- Regions at a distance greater than 50 km from roads and power transmission lines (technical and economic constraints).
- Regions with a distance less than 0.5 km from streams, and less than 0.1 km from roads (technical and safety constraints).
- Regions with a slope greater than 11% (technical and safety constraints).

3.3.2. Determining the Score Values and Relative Weights for each Criterion

The next step entailed that the potential regions determined in the first step were tested for their suitability for establishing PV farms based on the score values and the relative weights of each criterion. Based on an expert system procedure (the Delphi method), the score values for each criterion were set to define the spatial proportional importance of a tested location compared to other locations within the single criterion.

The relative weight for each criterion was defined in relation to the other criteria and was calculated using the AHP protocols. For these protocols, the AHP hierarchy was developed by defining the overall goal (the best PV sites) as well as the sub-goals (suitable site per criterion) based on the attributes assigned for each alternative (e.g., a raster cell or cluster representing a score value). Then, a pairwise comparison matrix A between the defined criteria was designed based on the Saaty scale of preferences [26] (see Table (2) for details), and calculated the relative weights following Equation (1), the consistency index [CI: Equation (2)], and the consistency ratio [CR: Equation (3)] to measure the inconsistency associated with the pairwise comparison matrix A. As a rule of thumb, CR values less than or equal to 0.1 indicate an acceptable level of consistency in matrix A and vice versa [27].

$$W_{(i)} = \frac{\sum \frac{v_{(ij)}}{s_{(j)}}}{n} \quad \text{.......(1)}$$

$$CI = \frac{\lambda_{\max} - P}{P - 1} \quad \text{.......(2)}$$

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

where is the relative weight for criterion i, is the value of criterion i in column j in matrix A is the sum of column j, and n is the number of criteria. is the largest eigenvalue that could be obtained once its associated eigenvector was determined. P is the number of columns of matrix A. RI is the random inconsistency index as defined in Table (3) [26].

Table 3. Saaty's preferences in the pairwise comparison process (matrix).

Numerical rating	**Verbal description of preference between criterion *i* and criterion *j***
1	*Ai* is equally important to *Aj*
3	*Ai* is slightly more important than *Aj*
5	*Ai* is strongly more important than *Aj*
7	*Ai* is very strongly more important than *Aj*
9	*Ai* is extremely more important than *Aj*
2, 4, 6, 8	Intermediate values
Aj has the reciprocal value when compared with criteria *Ai*	Reciprocals of above non-zero number

Random inconsistency indices (RI)*.

n criteria	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

3.3.3. Synthesizing Criteria according to the GIS-MCE Method

The combined FOA-AHP method is selected for this study to address the two main sources of inaccuracies in the attribute data that can severely affect decision-making selection, namely, the definition of the classes in a classification, and the imprecision in assigning phenomena to classes. Also, the FOA-AHP method can provide an overlay analysis closer to natural human thinking [28]. In FOA-AHP, all the input variables must be in raster format to allow for the map algebra processes.

The FOA-AHP method was conducted through two major steps: (1) the fuzzification process in which each individual raster cell in each map criterion was reclassified or assigned a value between 0 and 1 representing the possibility of that cell value being a member of a certain suitability set (i.e., 0 was not in a set, other values were at various levels of possibility), (2) a fuzzy overlay analysis in which the locations that best met all the criteria (i.e., having high likelihood of membership in all sets) were multiplied by the relative weight value of the corresponded criterion. Then, the results were totaled to assign the final relative level of suitability for each location on the final suitability index map, which is expressed below in Equation (4) [29].

$$S = \sum w_{(i)} * x_{(ij)} \quad \text{.......(4)}$$

Where S is the suitability index for each pixel in the final map, w_i is the weight of ith criterion map, and x_{ij} is the criteria score of class j in criterion i. This equation returns the highest potential membership or suitability value for each cell in all the multiple criteria simultaneously.

Finally, the suitability index map was regrouped into four different classes of suitability: "suitable" , "slightly more suitable", "moderately suitable" , and "highly suitable".

3.3.4. Evaluating Suitable Sites for PV Farms

Results for the twelve governorates were investigated and analyzed according to the Jordanian administrative system. The land suitability index of each governorate was then determined according to the four classes of suitability. In addition, the location of an already existing PV farm in Jordan (i.e., Shams Ma'an) was evaluated. Finally, the potential power generation from the selected "highly suitable" sites was calculated for different PV systems in Table 4 using Equation (5)[30,31].

$$GP = SR * CA * AF * \eta \quad \text{.......(5)}$$

Where GP is the potential power generation capacity (GWh/year); SR is the annual solar radiation (GWh/km^2/

year); CA is the total area of suitable locations (km^2); AF is the area factor (portion) of CA that can be covered by solar panels (%); and η is the efficiency with which the PV solar system converts sunlight into electricity (%) as shown in Table 4 [32].

Table 5. Efficiencies of different PV systems evaluated under standard test conditions (STC)* that manufacturers use (i.e., 1000 W/m^2) from annual data.

PV solar panel technologies	Efficiency η, (%)
Micromorph silicon (μ-Si)	7.7
Monocrystalline silicon (M-Si)	14.5
Amorphous silicon (a-Si)	6.9
Polycrystalline silicon (Poli-Si)	13.5

** STC is defined as the solar irradiation of one kilowatt (kW) per square meter, a module temperature of 25 degrees Celsius and a solar irradiation angle of 45 degrees.*

4. Results and Discussion

4.1. Potential Regions for PV Sites

After applying the appropriate spatial masks for the protected/restricted areas, the potential regions for establishing PV farms in Jordan were identified as shown in Figure 4. The total potential areas were located mainly in the southern and eastern regions (approximately 51818.6km^2), representing 58.4% of the whole country.

4.2. AHP Analysis and FOA Results

Table 5 shows the pairwise matrix generated in this study and the calculated relative weight for each criterion. Based on the above-mentioned calculations, the solar radiation, aspect, and distance from electricity network lines, variables were found to be the most important criteria with relative weights of 30%, 22%, and 15%, respectively. The slope, distance to main roads, and land-use type variables came having moderate importance with relative weights of 10 %, 9% and 6 %, respectively. The distance to streams, elevation and the distance from residential areas were found to have minimal influence on the PV site selection and the relative weights as low as 4 % and 2 %, respectively. Tarhi et al., [33], Sánchez-Lozano et al., [34], Charabi and Gastli [35], Uyan [36], and Noorollahi et al., [13] also considered solar radiation as the most important criterion. The consistency analysis of the pairwise matrix and the relative weights revealed a consistency ratio of 0.088, indicating an acceptable and consistent pairwise matrix as its value was less than 0.10. Thus, the resultant relative weights have been validated for use in further analysis.

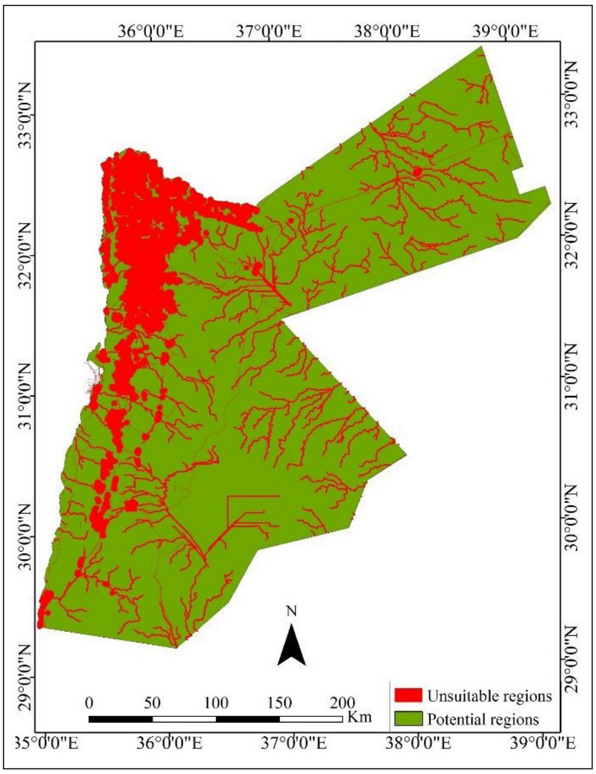

Figure 4. Potential regions for photovoltaic farms in Jordan, the unsuitable regions show the restricted areas according to specific spatial masks discussed in Section 3.2.1.

Table 5. Pairwise comparison matrix of multiple criteria for PV site selection and its calculated relative weights based AHP analysis. Values in the crossed cells represent the scale of importance for comparison pair in row i and column j as defined in Table (2) or its replicable.

Criteria*	SR	E	S	A	LU	DR	DE	DS	DRA	W (%)
SR	1.00	7.00	5.00	3.00	5.00	5.00	3.00	5.00	7.00	30
E	0.14	1.00	0.20	0.14	0.20	0.20	0.20	0.33	1.00	2
S	0.20	5.00	1.00	0.20	3.00	3.00	0.33	3.00	5.00	10
A	0.33	7.14	5.00	1.00	5.00	3.00	3.00	5.00	7.00	22
LU	0.20	5.00	0.33	0.20	1.00	0.33	0.20	3.00	3.00	6
DR	0.20	5.00	0.33	0.33	3.03	1.00	0.33	3.00	5.00	9
DE	0.33	5.00	3.03	0.33	5.00	3.00	1.00	5.00	5.00	15
DS	0.20	3.03	0.33	0.20	0.33	0.33	0.20	1.00	3.00	4
DRA	0.14	1.00	0.20	0.14	0.33	0.20	0.20	0.33	1.00	2

** SR = solar radiation, E = elevation above sea level, S = slope degree, A = aspect, LU = land use, DR = distance from roads, DE = distance from electricity network lines, DS = distance from stream network, DRA = distance from residential areas, W = relative weight.*

The results for the total suitable areas shown in Figure 5 were found to be approximately 35468 km^2 (~ 68.4% of the potential area for PV). These areas were reclassified into four levels of suitability: "suitable" (suitability index less than 0.4), "slightly more suitable" (0.4 > suitability index < 0.5), "moderately suitable" (0.5 > suitability index < 0.6), and "highly suitable" (suitability index < 0.6). As can be seen in Figure 5, most of the "highly suitable" sites were located in the open land use areas having flat south-oriented topographies and higher solar radiation exposure and were closer to power sources and road networks.

The land use and distance from streams or residential areas were found less important in the PV farms-site selection. The statistical measurements showed that the "suitable," "slightly more suitable," "moderately suitable," and "highly suitable" areas represented approximately 8.3%, 14.6%, 18.1%, and 27.4% of the potential areas, respectively. The statistical results for the administrative units (i.e., governorates) showed that 11.2% of the "highly suitable" areas were located in the Ma'an governorate in the southern part of the country. In contrast, the less suitable areas were identified in the districts of the Jordan Valley in the western part of the country because although they have high potential for solar radiation, these areas have low land-terrain topographies.

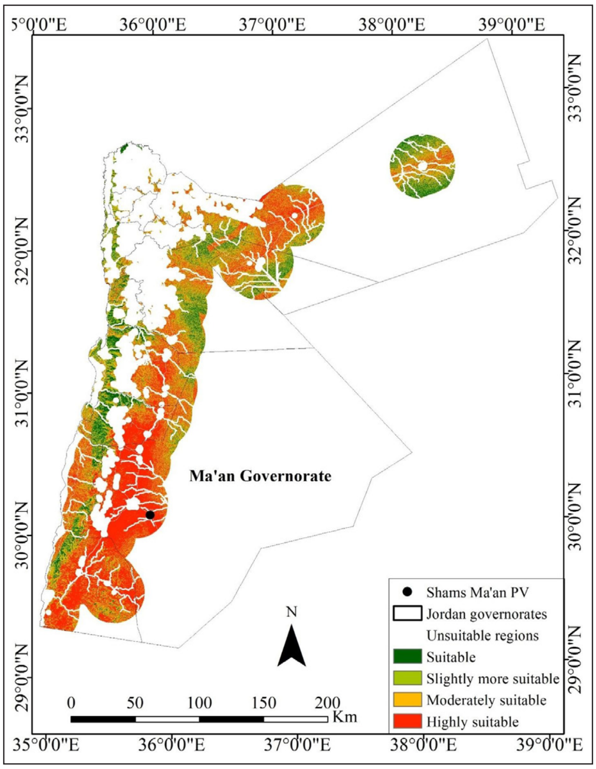

Figure 5. Suitable areas for photovoltaic sites in Jordan as calculated by Fuzzy-AHP method.

4.3. Evaluation of Suitable Sites for PV Farms

Our evaluation of the existing PV project [i.e., Shams Ma'an (2km^2) in the governorate of Ma'an showed that it was in a "highly suitable" area (see Figure5). The advantages of this site include the excellent environmental economic and safety factors for allocating the PV farms. Our assessment results confirmed that the region of Ma'an is indeed highly suitable for PV projects. The solar radiation high potential, the distance from electricity networks, the south-facing orientation, and the large open areas are unsurprisingly key factors that increase the suitability indexing of this area. In comparison to other areas in the Mediterranean region, Ma'an offers competitive opportunities. For example, the percentage of "highly suitable" areas was 3% in Cartegena, Spain [37], 5% in Granada, Spain [38], 14% in Karapinar, Turkey [7], 23% in Ouarzazate, Morocco [33], 4% in Oman [35], 14.7% in Iran (e.g., 38.4% in Kerman province)[13], and 20% in Lake Nasser Region, Egypt [39].

The evaluation of potential power generation for the highly suitable areas (see Equation 4) for the four PV technologies is presented in Table 6. Note that an AF of 70% was used based on the maximum land occupancy and distance between PV panels, which ensured a minimal shading effect [40]. Dolara et al., [41] and Altarawneh et al., [16] addressed the shading effect on the potential power generation of a PV system, and demonstrated that 50% shading of a PV single cell may result in reducing the PV potential of power generation by more than 30%. The efficiency η percentage of each PV system was considered in this study for typical high temperatures and low solar-radiation region applications. Table 6 shows that all the tested PV systems could produce huge amounts of electricity. For instance, if monocrystalline silicon (M-Si) system was selected for installing PV farms in "highly suitable" areas, it has a power generation potential of 104,886,738 GWh/year for various electricity demand sources in Jordan. Note that in 2015, the total annual electricity production in Jordan was 18,911 GWh. Thus, utilizing "highly suitable" areas for PV farms would generate many multiples of the current demand for electricity in Jordan. It is worthwhile to mention that such large projects require highly trained professionals and can be costly. Therefore, collaboration with other interested parties in the world is necessary. It is important to note that in this study, only the potential use of PV technology was considered, while other technologies, such as CSP were not investigated because, compared to PV systems, they require large amounts of water for the purposes of cooling and mirror washing. Therefore, for arid and semi-arid countries with scarce water resources, as is the case for Jordan [42], PV technologies would be the best choice, since PV technologies are more environment-friendly, economical, flexible, and faster to be implemented and connected to electric grids than CSP technologies [30].

Table 6. The potential power generation for the highly suitable areas for the four PV technologies.

PV solar panel technologies	Potential power generation (GWh/y)
Micromorph silicon (μ-Si)	55,698,474
Monocrystalline silicon (M-Si)	104,886,738
Amorphous silicon (a-Si)	49,911,620
Polycrystalline silicon (Poli-Si)	97,653,170

Concluding remarks

This study applied the geospatial-based fuzzy multi-criteria approach in the evaluation of the suitability of land areas for installing PV farms in Jordan. The evaluation module of this approach incorporated expert opinions on the criteria and their weights, and applied a fuzzification process to identify the suitable sites based on several environmental, human, and topographic variables. The results show that approximately 16.1% of the country contains highly suitable locations for PV farm implementation with the governorate of Ma'an leading the list of the most suitable sites among all the other governorates of Jordan. In addition, we evaluated the potential electricity generation for four different PV technologies for highly suitable areas, and found that PV could produce surplus electricity that exceeds the current power demand of Jordan. It should be noted that for the successful implementation of the PV technology, long-term strategies must be developed and followed.

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