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Spatial modeling for the optimum site selection of solar photovoltaics power plant in the northwest coast of Egypt

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ABSTRACT

The unbalanced distribution of the Egyptian population causes serious social and economic problems. Redistributing population density to fully utilize the uninhabited areas like desert regions is very critical. This requires discovering renewable energy and water resources, to achieve an optimal goal of the sustainable national strategy. Therefore, this paper aims to define the most suitable locations for establishing the photovoltaic (PV) power plants considering the techno-economic and environmental conditions, assuring the maximum power achievement with minimizing project cost. To achieve this, the integration of Geographic Information System (GIS) tools, Remote Sensing technology (RS) with the Multi-Criteria Decision Making (MCDM) technique was performed. Among MCDM techniques, the Analytic Hierarchy Process (AHP) method has been used to determine the weights of the multi-criteria (techno-economic and environmental) as a more suitable tool to solve site selection problems. The obtained results showed that the entire region's surface receives a large amount of radiation, as the maximum and the minimum values of solar radiation for 2018 were 5.9 - 4.7 kWh/m^2/day, respectively. The Land Suitability Index (LSI) map was created to evaluate the potentiality of the sites. LSI was classified into five categories: "most suitable," "highly suitable," "moderately suitable," "marginally suitable," and "least suitable". As a result, 24.9% (261.1747 km^2) of the investigation area is more suitable and promising for deploying photovoltaic (PV) power plants.

1. Introduction

Energy plays an essential role in almost all human activities. The global demand, for sustainable energy provision, is significantly increasing and expecting to increase widely over the next years. This trend is foreseen as a result of the speedy growth of the population in developing countries (Effat, 2016). Moreover, growing awareness of climate change risks, as a result of the environmental effects of fossil fuels. Many countries encouraged to recommend strategies for replacing fossil power generation with renewable energy sources (Tahri et al., 2015).

Solar power energy has emerged as one of the most rapidly growing renewable sources in the world. Solar power generation has several environmental advantages such as the absence of toxic or greenhouse gasses emission, accelerating of reclamation of degraded land, providing job chances which lead to improvement of life quality, decrease climate change, and earn economic gains (Abdellatif, 2013; Georgiou and Skarlatos, 2016; Gherboudj and Ghedira, 2016; Asakereh et al., 2017).

Recently, several studies have concentrated on utilizing remote sensing data and GIS to identify the appropriate locations for constructing a solar energy system (Carl, 2014; Mahtta et al., 2014; Polo et al., 2015; Dawod and Mandoer, 2016; Effat and El-Zeiny, 2017; Abdelrazek, 2017; Melnikova, 2018; Tunc et al., 2019; Saadaoui et al., 2019; Gašparović and Gašparović, 2019).

ArcGIS Desktop software package includes solar analyst tools, which have come one of the most popular solar radiation modeling tools and have been widely used in solar power planning processes in several studies (Effat, 2013; Kauria, 2016; Wong et al., 2016; Al Garni and Awasthi, 2017; Mackey, 2017; Wolfs, 2017; Merrouni et al., 2018; Piirisaar, 2019).

Reviewed energy, environment and sustainability fields were ranked as the early attempts were applied using MCDM techniques to compute the weights of the multi-level hierarchical structure (Aly et al., 2017). AHP is the most method of MCDM, which was introduced by Saaty

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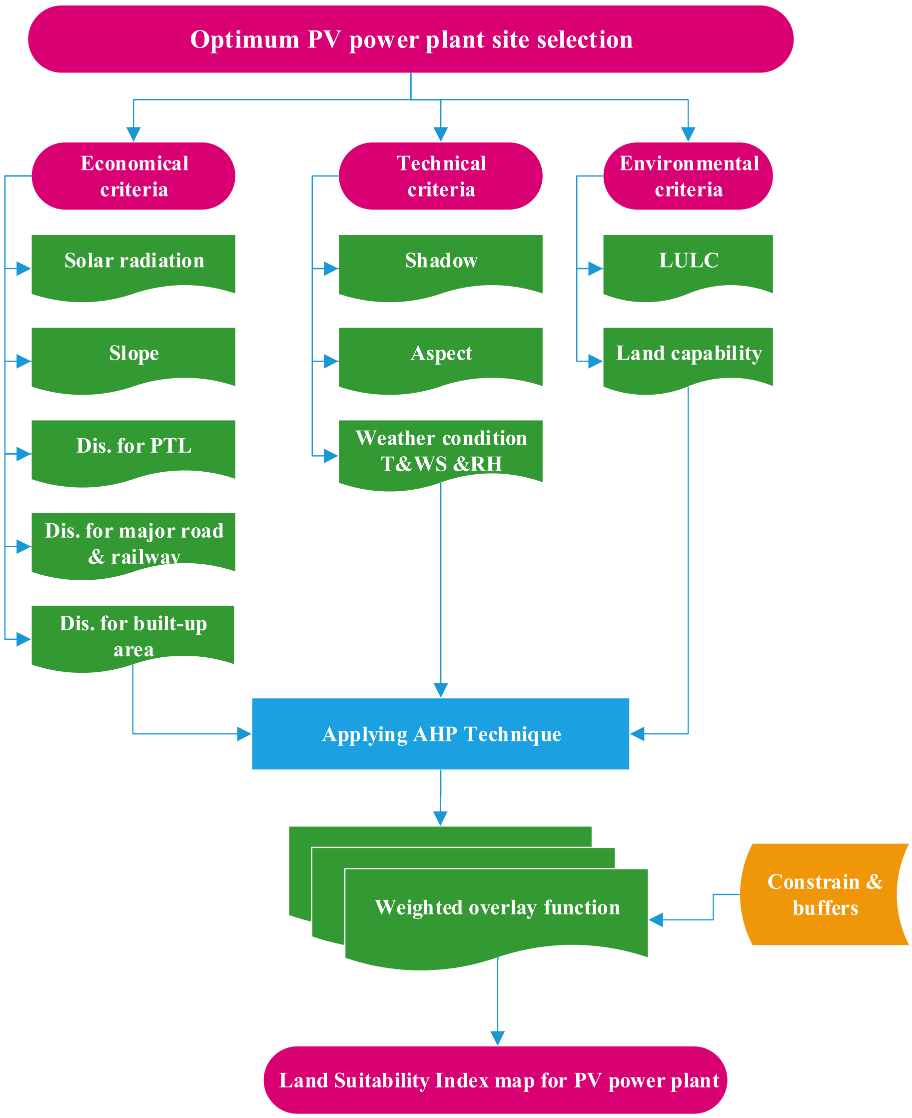

Fig. 1. The practical approach for land suitability index map (LSI) of the study area.

(1980).

PV power plant site suitability assessment is affected by different factors such as solar radiation, land value, slope, aspect, shadow, etc. These factors depend on the geographical location and techno-economic infrastructure of the investigation area, to achieve maximum energy with a desirable construction cost. These factors can be classified into three main categories technical, economical and environmental (Charabi and Gastli, 2011; Uyan, 2013; Azizkhani et al., 2017; Noorollahi et al., 2016; Georgiou and Skarlatos, 2016; Asakereh et al., 2017).

According to Phuangpornpitak and Tia (2011), solar radiation qualities were categorized into four classes including moderate (less than 4 kWh/m^2/day), good (4–5 kWh/m^2/day), very good (5–6 kWh/m^2/day) and excellent (more than 6 kWh/m^2/day). The economic generation of solar energy requires at least 4.5 kWh/m^2/day of solar radiation (Aydin et al., 2013). The suggested land for the solar plant should be protected from the change as not to be used for other purposes such as water bodies, agriculture land and urban classes (Uyan, 2013; Al Garni and Awasthi, 2017; Asakereh et al., 2017; Noorollahi et al., 2016). The ideal locations for solar projects should utilize low-value land (Piirisaar, 2019).

The land slope for the PV plant must be less than 5% to decrease the establishment cost of the PV power plant (Charabi and Gastli, 2011; Abdelrazek, 2017; Mackey, 2017; Al Garni and Awasthi, 2017). For the northern hemisphere locations, the most suitable aspect to host PV systems is where the land is flat and south-facing. Moreover, the south-facing slope is an ideal trend for solar farm sites, which receive more amount of solar radiation, while the southwest and southeast come in the second and third rank, respectively (Bartel, 2011; Tahri et al., 2015; Georgiou and Skarlatos, 2016; Al Garni and Awasthi, 2017; Azizkhani et al., 2017; Piirisaar, 2019).

The appropriate distance from the power transmission networks to the solar plant is 4.8 km for safety while, regions at a distance more than 50 km from power transmission lines have been considered unsuitable areas because of the high costs of transmission energy to customers and losing energy during its transfer. Also, regions with a distance more than 50 km from the road and railway are restricted for transportation facilities of material, equipment, and labors (Noorollahi et al., 2016; Al Garni and Awasthi, 2017). On the other hand, proximity to roads causes social risks such as theft and vandalism thus, a 150 m a buffer zone around roads and railway must be used (Georgiou and Skarlatos, 2016; Noorollahi et al., 2016; Asakereh et al., 2017; Melnikova, 2018).

A solar plant at a distance less than 1.5 km around the urban must not be established, because of solar plant proximity to urban causes negative impacts on the urban growth (Uyan, 2013; Melnikova, 2018). Moreover, regions at a distance more than 50 km from populated centers are considered as unsuitable areas for solar farms establishment (Al Garni

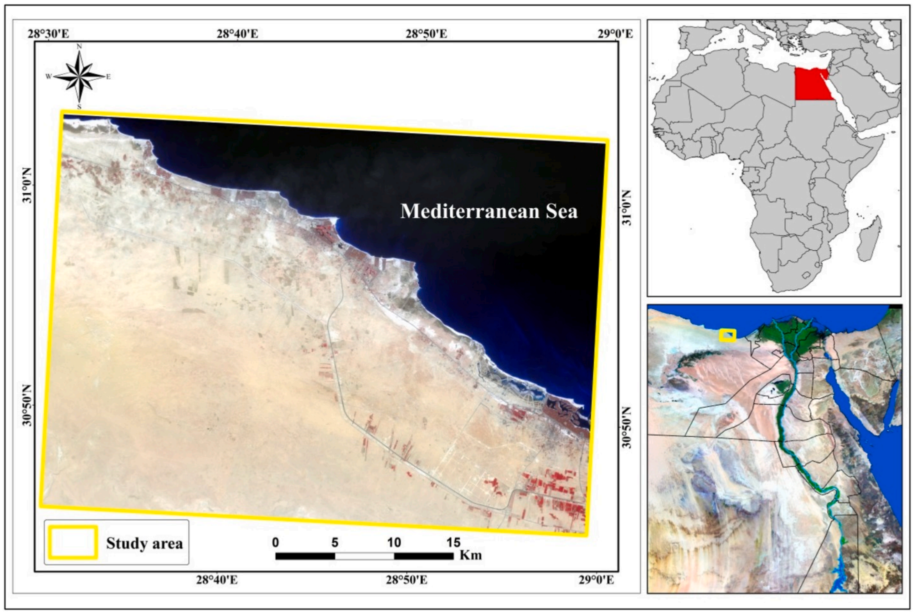

Fig. 2. Location map of the study area.

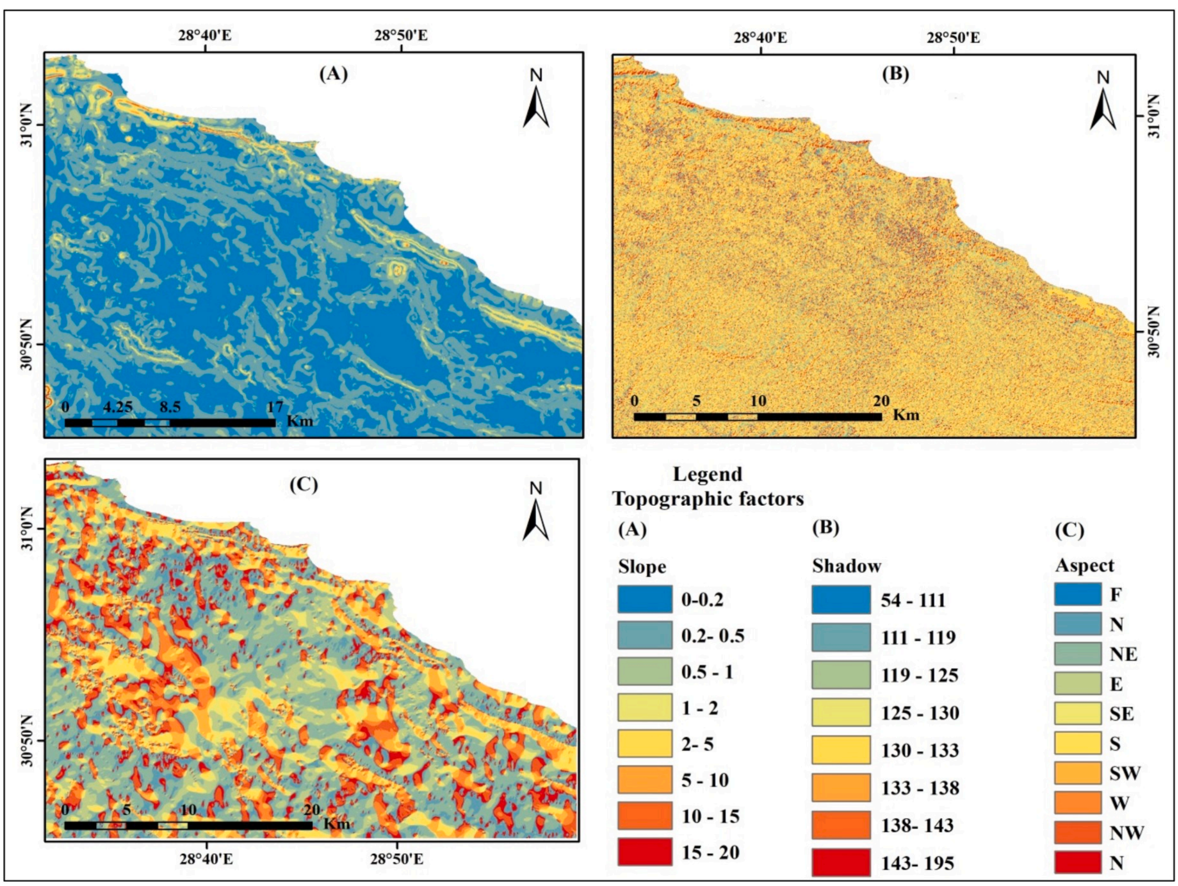

Fig. 3. Slope, aspect and shadow maps of the study area.

and Awasthi, 2017).

The impact of the relative humidity maybe 50% higher than the air temperature. The accumulated water drops can attenuate the light reaching the PV cell and can cause more dust collecting on the PV cell's surface lead to low performance of PV panel (Mekhilef et al., 2012; Gherboudj and Ghedira, 2016). Shadow effects from the surrounding topography cause a significant variation on solar radiation thus, reduce the solar electricity producing amount (Wong et al., 2016).

Mekhilef et al. (2012) stated that more heat can be removed from the PV cell surface by increasing the wind velocity, which in turn leads to better efficiency. If the wind speed in the area exceeds 25–30 mps, it can cause harm for the PV panels' surfaces (Gašparović, and Gašparović,

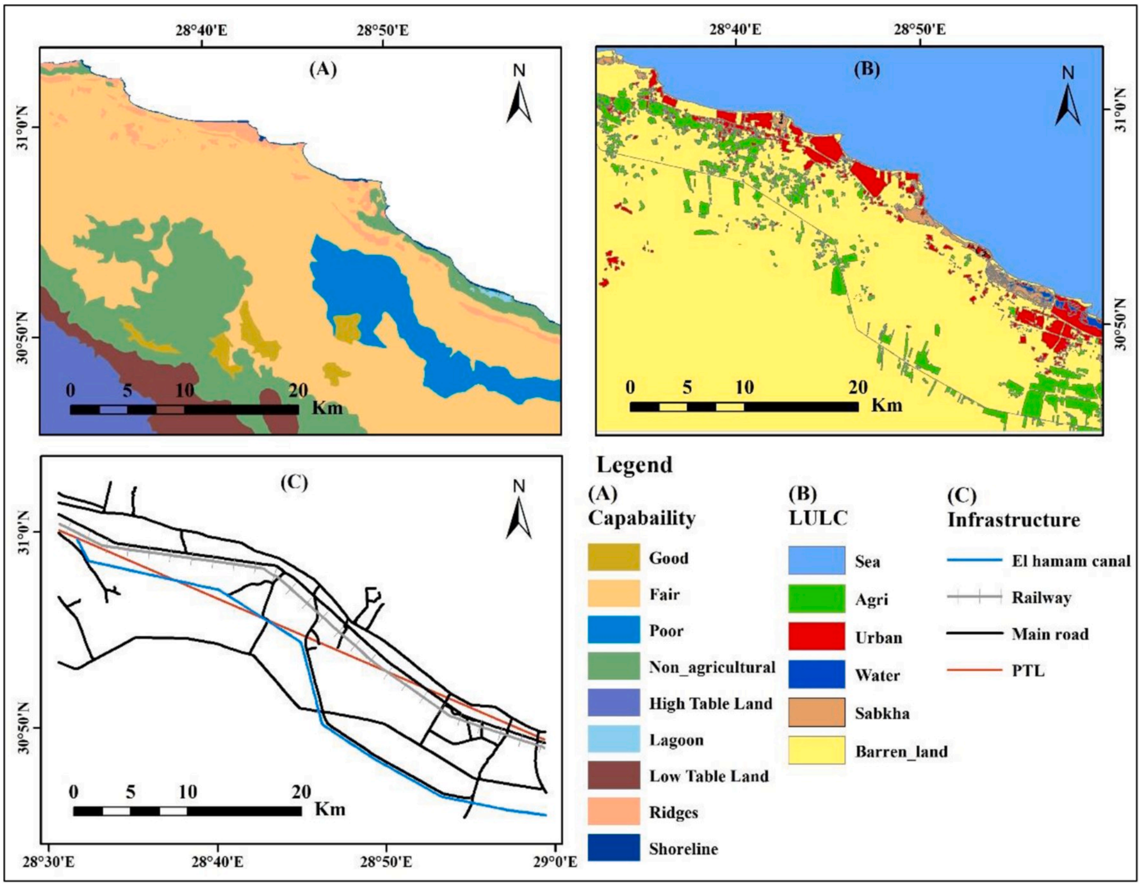

Fig. 4. LU/LC, land capability and infrastructure maps of the study area.

Table 1
Parameters used in ArcGIS solar analyst tool.

Parameter	Value	Parameter	Value
DEM	Resolution of 30 m	Slope aspect input type	From_ DEM
Latitude	30.9 (Auto)	Calculations directions	32
Sky size	200 (Default)	Zenith divisions	8
Time configuration	The whole year (2018)	Azimuth number	16
Day interval	14 Days (Default)	Diffuse model type	Standard_overcast_sky
Hour interval	0.5 (Default)	Diffuse proportion	0.316214 (Calculated)
Z factor	1	Transmissivity	0.607029 (Calculated)

2019). Moreover, Wind speed has a significant role in the accumulation of dust particles on PV cell surfaces. Gherboudj and Ghedira (2016) found that a high drop in solar cell performance during low winds because of light transmittance is higher for the covering of dust created during high winds than the covering of dust created during low winds. The optimum air temperature is 15–40 °C, as it is one of the most essential factors which affect the efficiency of PV solar panels and the period of its operation (Kereush and Perovych, 2017).

The unbalanced distribution of the population in Egypt causes serious social and economic problems. It is very critical to redistribute the population density and to fully utilize the uninhabited areas like desert regions and re-planning of land-use. This issue requires discovering renewable energy and water resources, to achieve an optimal goal of the sustainable national strategy.

Solar energy can afford a great opportunity for sustainable development and population redistribution in the wide deserts of Egypt. However, there is a gap in understanding the solar potential for the investigation area, due to the lack of climate stations and their high cost. This encouraged many researchers to begin evaluating solar radiation based on satellite images to overcome the scarcity of measured solar radiation data. The selection of the optimum site for a photovoltaic (PV) power plant is considered the first stage to develop a solar energy industry. Therefore, the main objectives of this study are calculating solar energy of the western desert of Egypt by using RS and GIS techniques in addition to, creating an improved and applicable GIS model based on multi-criteria analyses for selecting the optimum sites for the PV power plant and estimating the PV technical potential for each the selected sites.

2. Material and methods

To identify the suitable regions for establishing a PV power plant in the north-western coastal zone of Egypt, the proposed framework is presented in Fig. 1 and can be summarized in the following phases:

- Identification of the technical, economical and environmental criteria (multi-criteria) for hosting PV plants.
- Preparation of the multi-criteria for the land suitability index (LSI) modeling.
- Applying the AHP technique for determining the criteria weights, based on the relative importance of each one.
- Evaluating the multi-criteria for PV optimum site selection
- Modeling LSI areas for PV power plants.
- Estimating the technical potentiality of the PV power plant.

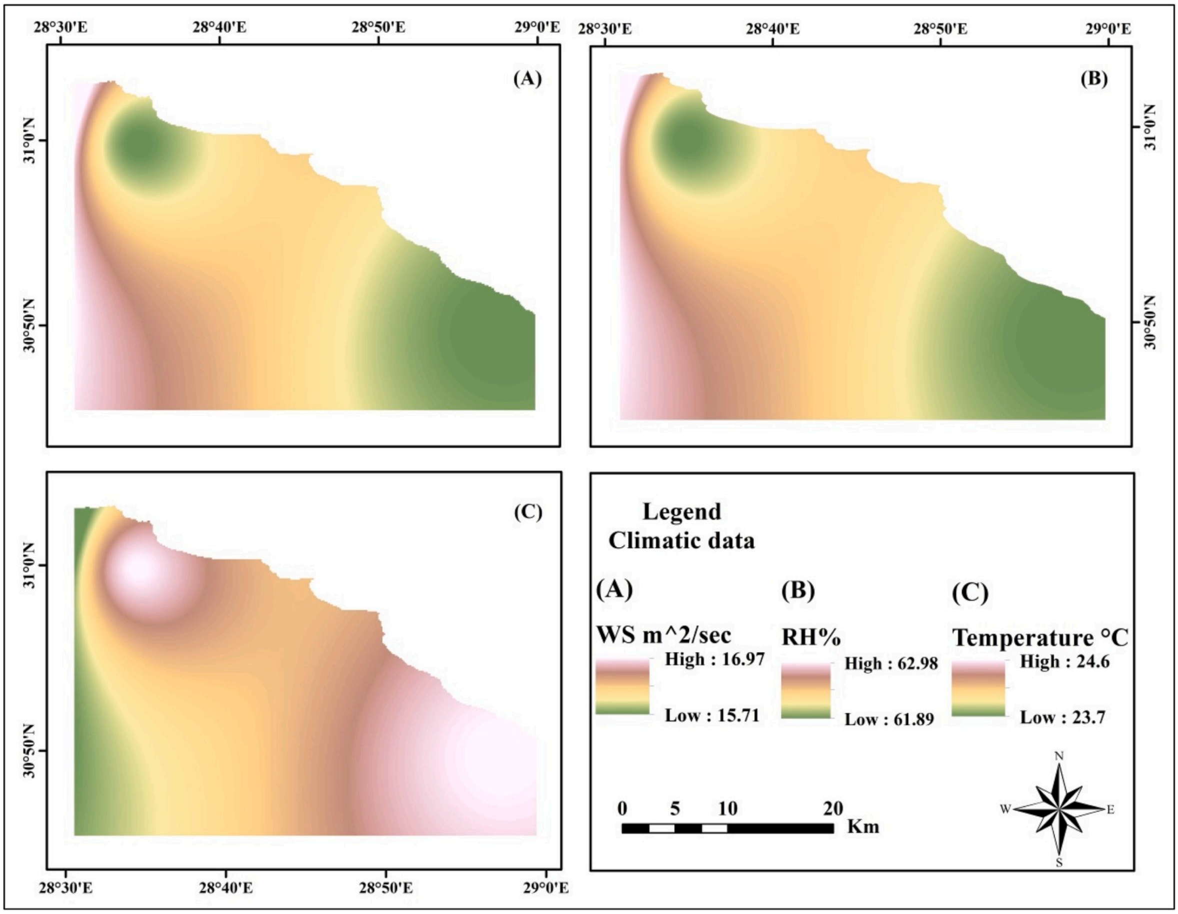

Fig. 5. Climatic maps of the study area.

2.1. Description of the study area

Northwest Coast of Egypt is one of the promising areas for development and providing a solar energy source as one of the essential requirements. The study area is located at the northern extent of the Egyptian western desert, in the north-western coastal zone. It extends from westwards El Alamein to near El-Dubai area. The study area is bounded between longitudes 28° 30′ E & 29° 00′ E and Latitudes 30° 45′N &31° 05′ N, with a total area about 1061.9 km^2 as shown in Fig. 2.

2.2. Description of the used data

This paper aims to create a GIS model utilizing satellite image, spatial analyses and thematic layers, as input criteria. All digitization, conversion, and analysis of map processes were performed by ArcGIS for Desktop 10.2.2 and ENVI 5.1 software using geo-reference the Universal Transverse Mercator (UTM) Zone 35 North with projection WGS-84. The spatial resolution of all layers is 30 m/pixels. The data was used in the current study are described as follows:

- The Shuttle Radar Topography Mission (SRTM) is a near-global Digital Elevation Model (DEM) that is very important to develop thematic maps, which needed for the LSI model. Fig. 3 shows the created input maps (slope, aspect, and shadow), which was created by using spatial analyst toolset in ArcGIS.
- SENTINEL-2 is a multi-spectral image generated by the U.S. Geological Survey (USGS) with (GeoTIFF) file format. SENTINEL-2 image classification considered the main source for obtaining land use/land cover map. It was acquired for the study area in Feb. 2018.
- The topographic map, published by the Egyptian General Survey Authority, at scale 1:50,000 was scanned, geometrically corrected and used for extracting railway(RW) layer following on-screen digitizing technique as shown in Fig. 4.
- Google Earth provided useful data for getting roads and irrigation canal layers, was acquired by on-screen digitizing technique as shown in Fig. 4.
- Power Transmission Line (PTL) data of the study area was acquired from the following website for the year 2017 as shown in Fig. 4 https://energydata.info/dataset/egypt-electricity-transmission-network-2017.
- Land capability map of the investigation area evaluated by Jalhoum (2015). It includes eight capability indices as shown in Fig. 4.
- Climatic data, such as air temperature (T), wind speed (WS), relative humidity (RH %) and cloud coverage for the year 2018 were acquired from the following websites. https://www.worldweatheronline.com/al-alamayn-weather/matruh/eg.aspx https://www.wunderground.com/weather/eg/al-alamin-marina

2.3. Multi-criteria preparation

In order to create the LSI map for the PV power plant, each criterion was prepared as a layer in a GIS environment. These criteria were chosen based on attributes of the study area, available data and the outcome's study case, which concerning renewable energy using MCDM-GIS.

2.3.1. Land use/Land cover (LULC) map

Layer stacking and subset image were used as a preprocessing for image classification. Supervised classification (Maximum Likelihood Classifier) was used to produce the land use/land cover map. LU/LC map

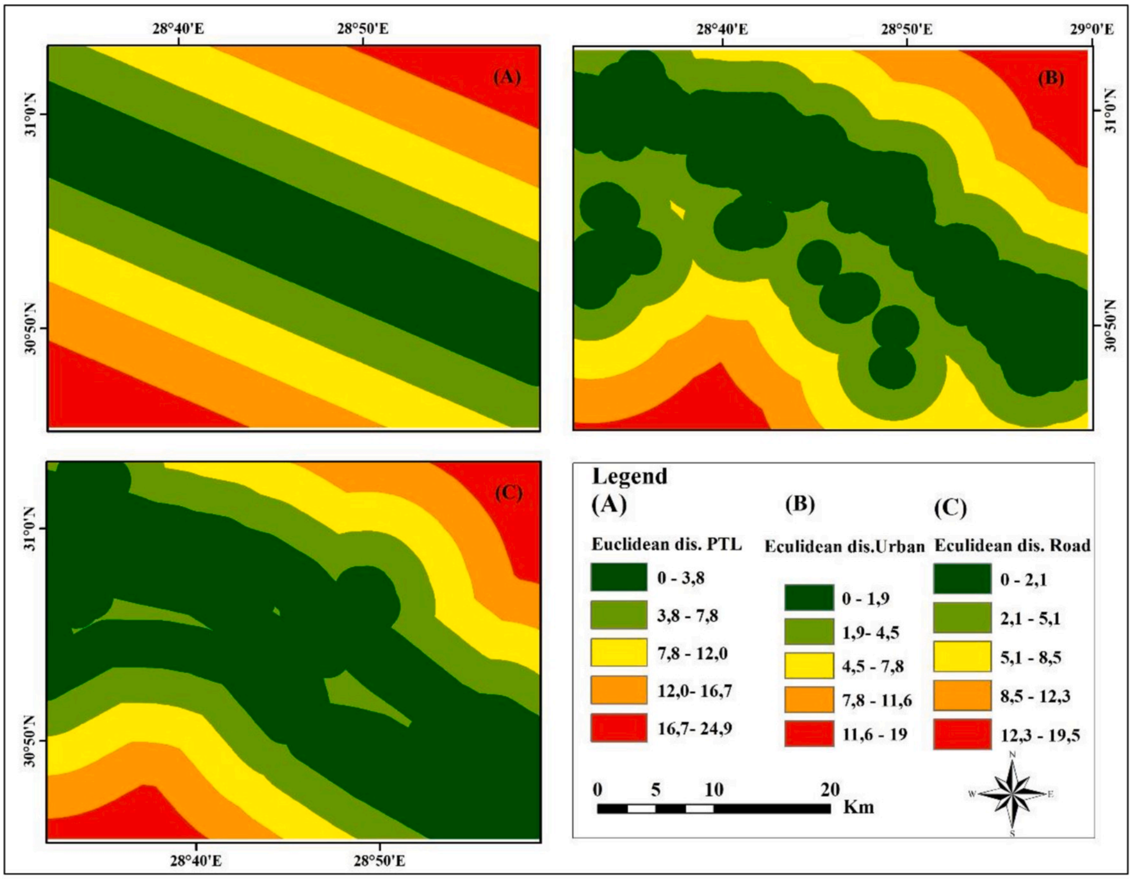

Fig. 6. Proximity maps for urban, power transmission line, and major roads of the study area.

was classified into 6 classes, which has a large unused area (barren land and sabkha land) equivalent to 61.3% (932.5 km^2) of the total area as shown in Fig. 4.

2.3.2. Solar radiation map

The solar analyst tool uses DEM as input, which was used to generate slope, shadow, and land aspects layers internally as topographic parameters for calculating the solar irradiation. Also, to create a solar map with the solar analyst tool there are other climatic parameters such as the diffuse proportion of irradiation (D) and transmissivity (T). These parameters are very important for the calculation of global solar radiation and should be calculated because using the default value will be reduced insolation value against true value. Since no direct measurements of these values are available for the study area, the formulae presented in equations (1) and (2) can be applied by using the cloud coverage data.

$$T = 0.7 \text{ P clear sky} + 0.5 \text{ P partial cloudy} + 0.3 \text{ P cloudy} \tag{1}$$

$$D = 0.2 \text{ P clear sky} + 0.45 \text{ P partial cloudy} + 0.7 \text{ P cloudy} \tag{2}$$

Where: P clear is the proportion of clear days, P partial cloudy is the proportion of partly cloudy days and P cloudy is the proportion of cloudy days (Wong et al., 2016). The parameters applied in the solar analyst tool for creating the solar radiation map are presented in Table 1. The value of the output insolation map for the year 2018 was validated with NASA power weather data, which acquired from the following website: https://power.larc.nasa.gov/data-access-viewer/. The NASA insolation data unite is (kWh/m^2/day) and its spatial resolution (0.5*0.5) degree.

2.3.3. Air temperature, WS and RH maps

Inverse Distance Weighted (IDW) function was employed to create raster maps for climatic factors (air temperature, wind speed and relative humidity) as shown in Fig. 5. IDW predicts unknown values for surface grid cells by averaging the values of a limited number of geographic data points in the neighborhood of each cell.

2.3.4. Proximity maps

The Euclidean distance function was used to get the proximity maps as shown in Fig. 6. It calculated from the center of the source cell (urban, power line transmission, railway, and roads) to the center of each of the surrounding cells based on the straight-line distance. To be able to manage accessibility data more easily, one single roads network file was created by merging roads and railway layers.

2.4. Application MCDM process for PV power plant

AHP is considered an effective method for dealing with complex decision-making problems and may help the decision-maker to predict priorities and make the optimum decision which needs a high degree of flexibility and reliability (Carrión et al., 2008).

Previous studies integrated MCDM techniques and GIS tools to solve site selection problems. In this study, the AHP technique is applied to analyze the PV site selection by generating useful alternative solutions and then evaluating these alternatives. Thus, it decreases the influence of any error that may reside in the multi-criteria. The fundamental concept of AHP can be summarized in the following steps according to Saaty (1980) as illustrated in Fig. 7.

2.4.1. Structure of the AHP hierarchy

Structuring the decision problem as a hierarchy in the AHP process is the first stage, by determining the main goal (selecting the optimum sites for the PV power plant), criteria (technical, economical and

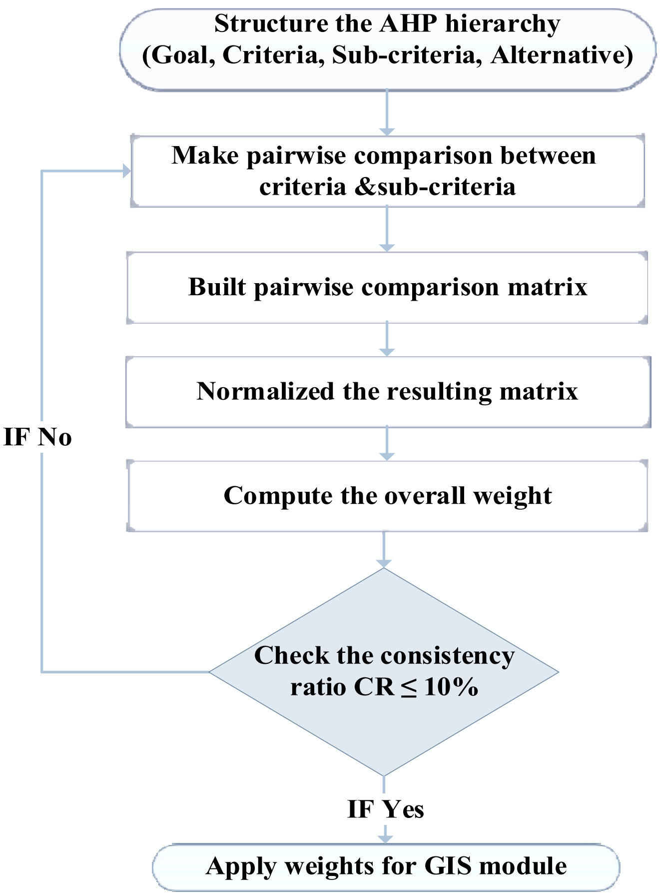

Fig. 7. Steps of the AHP method.

Table 2
Relative scale for pairwise comparison.

Importance scale of criteria *j* to criteria *k* (a_{jk})	Interpretation
1	Criteria *j* and *k* are of equal importance
3	Criteria *j* is slightly more important than *k*
5	Criteria *j* is moderately more important than *k*
7	Criteria *j* is strongly more important than *k*
9	Criteria *j* is extremely more important than *k*
2, 4, 6, 8	Intermediate values

Table 3
The pairwise comparison matrix of the technical criteria.

Criteria	Shadow	Temperature	RH	Wind speed	Aspect
Shadow	1	3	2	3	1
Temperature	0.3	1	0.5	2	0.5
RH	0.5	2	1	2	0.3
Wind speed	0.3	0.5	0.5	1	0.3
Aspect	1	2	3	4	1
Total	3.1	8.5	7	12	3.1

Table 4
The pairwise comparison matrix of the economic criteria.

Criteria	Slope	Dis.to road	Dis.to PTL	Dis.to railway	Dis.to urban	Solar radiation
Slope	1	3	3	5	3	0.33
Dis.to road	0.33	1	2	3	1	0.33
Dis.to PTL	0.33	0.5	1	3	0.5	0.14
Dis.to railway	0.2	0.33	0.33	1	0.25	0.14
Dis.to urban	0.33	1	2	4	1	0.2
Solar radiation	3	3	7	7	5	1
Total	5.19	8.83	15.33	23	10.75	2.14

environmental) and sub-criteria. The main goal is the top and the set of criteria and sub-criteria are branching from that top.

2.4.2. Make pairwise comparisons

The pairwise comparison of the criteria or sub-criteria is computed on a quantitative scale from 1 to 9 based on relative importance for each criteria or sub-criteria, developed by Saaty (1980) as shown in Table 2.

2.4.3. Build a pairwise comparison matrix

The pairwise comparison matrix M is a square matrix (n x n), where n is the number of sub-criteria. Each cell a_{jk} of the matrix M represents the comparison values between the jth (row) criteria relative to the kth (column) criterion. If the cell $a_{jk} > 1$, the jth criteria is more important than the kth criteria vice versa. But if a_{jk} equals 1, that indicates two criteria have the same importance. The pairwise comparisons matrix was applied only for the technical and the economic criteria as presented in Tables 3 and 4. However, environmental criteria didn't require applying the AHP method, because it included two sub-criteria both have the same priority.

2.4.4. Normalizing comparison matrix ($\overline{a}_{jk}$)

After building the previous pairwise comparison matrixes, it is easy to drive the normalized pairwise comparison matrixes, to obtain the priority (weights) of each sub-criteria. For building a normalized pairwise comparison matrix M, the sum of each column must equal to 1. This can be obtained by using equation (3), to calculate $\overline{a}_{jk}$ for each cell of the matrix M as shown in Tables 5 and 6.

$$\overline{a}_{jk} = \frac{a_{jk}}{\sum_{l=1}^{n} a_{lk}} \tag{3}$$

2.4.5. Compute the overall weight vector (W_j)

The criteria weight vector W_j is calculated by averaging across rows to obtain the relative weights using equation (4). Where: m is the number of values in the row. The weights of each sub-criteria under technical and economical criteria is shown in Tables 5 and 6. A higher weight indicates a greater influence of the element to the solar PV power plant site.

$$W_j = \frac{\sum_{l=1}^{n} \overline{a}_{jl}}{m} \tag{4}$$

2.4.6. Check the comparison matrix consistency

The last stage in AHP is checking the Consistency Ratio (CR) of the pairwise comparison matrix. If CR $\leq$ 10%, the degree of consistency is acceptable to be used in the analysis. If it is greater than 10%, it will be necessary to revise the judgments to locate the cause of the inconsistency and correct it. CR is given in equations (5) and (6).

$$CR = \frac{CI}{RI} \tag{5}$$

Where: CI = Consistency Index.

Table 5
Normalized technical pairwise comparison matrix.

Criteria	Shadow	Temperature	RH	WS	Aspect	Normalized priority	Weight%
Shadow	0.32	0.35	0.29	0.25	0.32	0.31	30.60
Temperature	0.10	0.12	0.07	0.17	0.16	0.12	12.45
RH	0.16	0.24	0.14	0.17	0.11	0.16	16.20
WS	0.10	0.06	0.07	0.08	0.08	0.08	7.98
Aspect	0.32	0.24	0.43	0.33	0.32	0.33	32.77

Table 6
Normalized economic pairwise comparison matrix.

Criteria	Slope	Dis.to road	Dis.to PTL	Dis.to railway	Dis.to urban	Solar radiation	Normalized priority	Weight%
Slope	0.19	0.34	0.20	0.22	0.28	0.15	0.23	22.98
Dis.to road	0.06	0.11	0.13	0.13	0.09	0.15	0.11	11.42
Dis.to PTL	0.06	0.06	0.07	0.13	0.05	0.07	0.07	7.13
Dis.to railway	0.04	0.04	0.02	0.04	0.02	0.07	0.04	3.83
Dis.to urban	0.06	0.11	0.13	0.17	0.09	0.09	0.11	11.13
Solar radiation	0.58	0.34	0.46	0.30	0.47	0.47	0.44	43.52

Table 7
Values of the Random Consistency Index (RI).

n	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.9	1.1	1.2	1.32	1.4

RI = Random Index.

$$CI = \frac{\lambda \max - n}{n - 1} \tag{6}$$

λmax = The maximum Eigenvalue of the comparison matrix.

The appropriate consistency index is called Random Consistency Index (*RI*), which varies subject to the sub-criteria number (*n*) in a comparison (M) as shown in Table 7 according to Saaty (1980).

2.5. Applying GIS simulation model

For modeling LSI of PV power plant, all criteria were evaluated and categorized into 2 classes: zero and one as presented in Table 8. The value of zero refers to restricted constraints, while the value of the one indicates the most suitable locations without any limitation to install the PV power plant. After the previous step, AHP weights were applied then overlaid the weights of the layers (criteria) by weighted overlay functions in the environment of the GIS model as presented in Fig. 8.

2.6. Estimating the technical potential of the PV power plant

One of the main applications of solar energy is a large-scale photovoltaic system, which directly converts sunlight into electricity. The technical potential for the electricity generation in a grid cell *i* from the most common photovoltaic systems, according to Mahtta et al. (2014) and Hoogwijk (2004), can be expressed in equation (7). The technical potential (E_i) is the geographical potential (G_i), which may be reduced by losses associated with conversion from solar energy to electrical power (kWh.day^{-1}).

$$E_i = G_i{}^*\eta_m{}^*p_r \tag{7}$$

Where the geographic potential G_i can be given by:

$$G_i = A_i{}^*h^{-1}{}^*I \tag{8}$$

I: The insolation (solar radiation) (kWh/m^2/day).
A_i: The most suitable area for PV installation (m^2).
H: The number of sunshine hours in a day.

Table 8
Evaluation of multi-criteria for LSI.

Sub-criteria	Constrains	Categories	Suitability index
C1: Solar radiation (kWh/m^2/day)	≥4.5 kWh/m^2/day	4.67	0
		4.67-5.86	1
C2: Slope (%)	≤5%	0–5	1
		5–21.4	0
C3: Distance from power transmission lines (m)	500 m ≤ X ≤ 50 km	0–500	0
		500–24898.6	1
C4: Distance for major road (m)	150 m ≤ X ≤ 50 k m	0–150	0
		150–19528.6	1
C5: Distance for railway (m)	150 m ≤ X ≤ 50 km	0–150	0
		150–25980.5	1
C6: Distance for residential area (m)	1.5 km ≤ X ≤ 50 km	0–1500	0
		1500–18989.3	1
C7: Shadow	Excluding dark pixels value	111–120	0
		120–195	1
C8: Aspect	Only flat, south, southeast and southwest direction	−1	1
		0–112.5	0
		112.5–247 .5	1
		247.5–359.03	0
C9: Average annual relative humidity (%)	Excluding the high RH% pixels value	61.9–62.6	1
		62.6–63	0
C10: Average annual wind speed (m/sec)	Excluding the low wind speed pixels value	15.7–16	0
		16–17	1
C11: Average annual temperatures (°C)	Excluding the high-temperature pixels value	23.7–24.5	1
		24.5–24.6	0
C12: Land use/Land cover	Only barren land and sabkha	Urban	0
		Sabkha	1
		Water bodies	0
		Barren land	1
		Agri. land	0
C13: Land capability	Only poor& Non-agriculture land	Fair	0
		Low and high Tableland	0
		Non-agri. land	1
		Poor	1
		Ridges	0
		Good	0
		Lagoon	0

η_m: The conversion efficiency for PV modules depends on the type of PV cells.
P_r: The performance ratio of the PV system.

P_r is defined as the coefficient of losses of the system suffers from

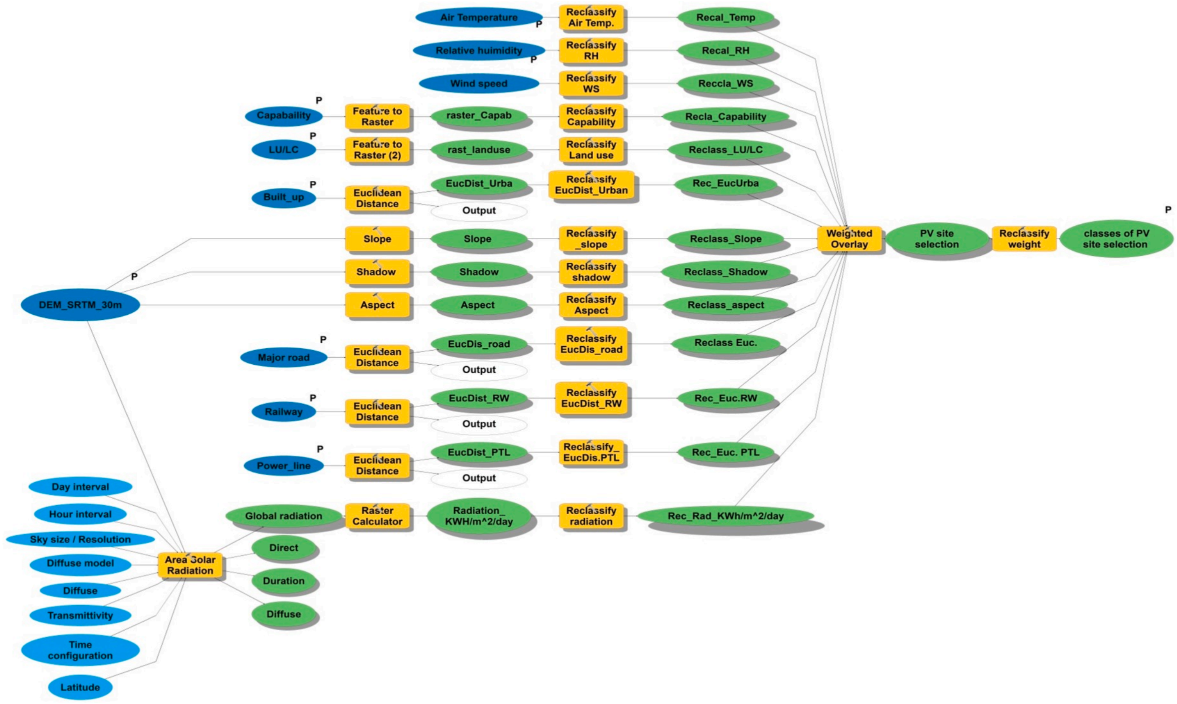

Fig. 8. Displays the AHP-GIS model.

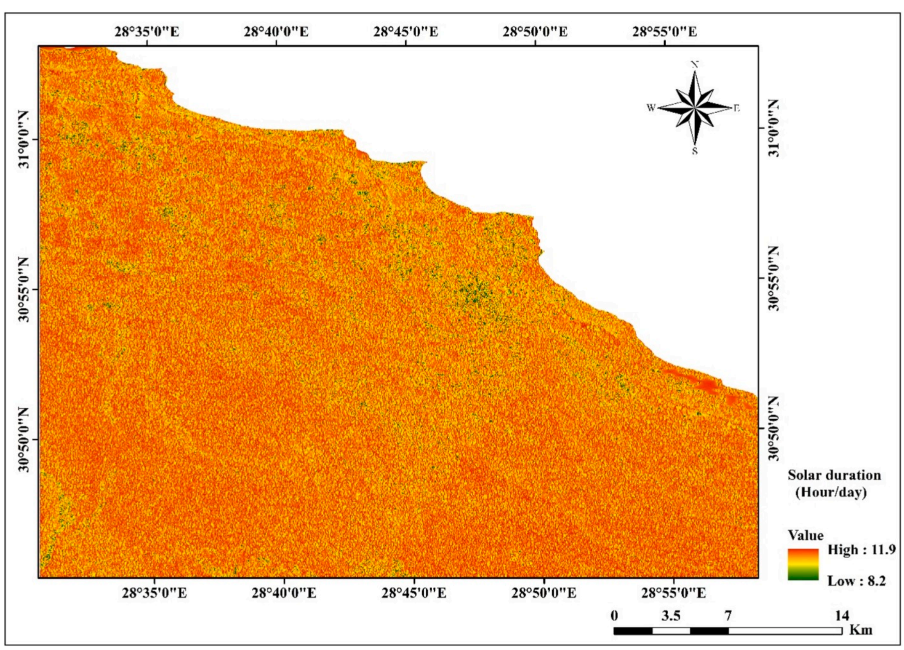

Fig. 9. Number of sunshine hours of the study area for the year 2018.

losses occurring within the rest of the PV system, e.g. inverter losses, mismatch losses, shading and cable losses, etc. P_r is expressed as the ratio between the actual performance of the system and the performance of the module under standard test conditions of 1000 W/m^2 global insolation, 25 °C air temperature and 1.5 air mass (Ramachandra et al., 2011). The optimum system has P_r between 0.66 and 0.85 (Hoogwijk, 2004). This estimation was performed by the raster calculator function in ArcGIS and the number of sunshine hours is one of the solar analyst tool outputs as shown in Fig. 9.

3. Results and discussion

The obtained results will be discussed in the following sub-sections. The first part is the evaluation of the solar radiation map. The second part is the estimation of the AHP final weights. The third part is the selection of the most suitable sites for solar energy production based on the AHP method integrated with GIS and RS. Finally, the last part is the determination of the technical potential for the most and highly suitable sites for the solar PV power plant.

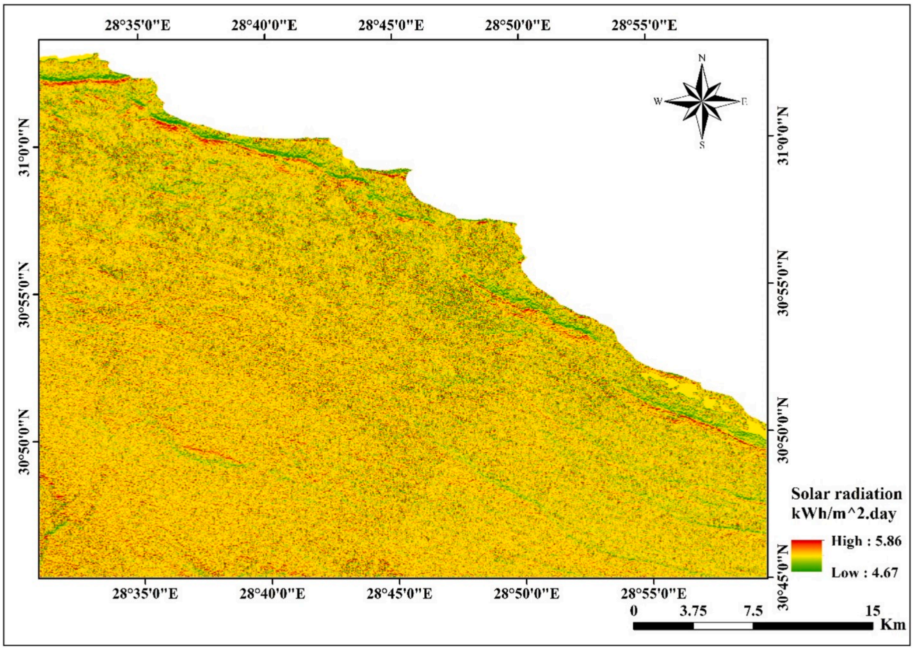

Fig. 10. Solar radiation map of the study area for the year 2018.

Table 9
The final weights of the sub-criteria by AHP method.

Goal	Criteria	Weight%	Sub-criteria	CR%	Weight%	Final weight%
Selecting the optimum sites for the PV power plant	Economical	50	C1: Solar radiation (kWh/m^2/day)	3.7	44.3	22.1
			C2: Slope (%)		23	11.5
			C3: Distance from power transmission line (m)		6.9	3.5
			C4: Distance for the major road (m)		11.2	5.6
			C5: Distance for railway (m)		3.8	1.9
			C6: Distance for the residential area (m)		10.8	5.4
	Technical	25	C7: Shadow	2.6	30.6	7.7
			C8: Aspect		32.9	8.2
			C9: Average annual relative humidity (%)		16.2	4.1
			C10: Average annual wind speed (m/sec)		7.9	2.0
			C11: Average annual temperatures (°C)		12.4	3
	Environmental	25	C12: Land use/Land cover		50	12.5
			C13: Land capability		50	12.5

3.1. Evaluation of solar radiation map

The annual solar radiation map was created with a spatial resolution 30 m/pixel as shown in Fig. 10 for the quantitative evaluation of the solar energy in the investigation area, in which each pixel includes a certain value of solar radiation. The variation of pixels' values was related to the topographic characteristics, while the climatic conditions were constant along the study area. The insolation map will be easy to locate the regions with the highest values. It was shown that the maximum and the minimum values of solar radiation for the study area were 4.7 and 5.9 kWh/m^2/day, respectively.

The result shows that the entire region's surface of the study area receives a large amount of radiation which would be sufficient for establishing the PV systems. Thus, it will encourage investors and the Egyptian government to develop the solar industry, in the investigated area of the northwest coast of Egypt, for creating new jobs, producing green electricity and supporting sustainable development.

As a result of validation, the isolation map against NASA weather data shows, no significant difference; where NASA recorded an average annual solar radiation 5.74 kWh/m^2/day. Thus, modeling solar radiation using SRTM radar data (DEM) by ArcGIS is a correct technique as the results make sense.

3.2. AHP final weights

The final criteria weights for economical, technical and environmental are displayed in Table 9, which represented 50%, 25%, and 25%, respectively from the overall weight.

The pairwise comparisons of technical and economical criteria are very acceptable and very consistent since CR for economical and technical criteria is 3.7% and 2.6%, respectively after 4 iterations. The solar radiation layer turns out to be the most important criteria since it defines the potential electricity production of a certain photovoltaic plant, then next came the land value (land use and land capability) and slope. Thus, solar radiation, land value, and slope are the keys to increase the suitability index of the PV power plant in the study area.

As a result, the AHP method is an excellent way for determining the weights of the multi-criteria, to select the site suitability of the PV power plant. Moreover, it prevents conflicts between multilayers as defined by Merrouni et al. (2018).

3.3. LSI map for PV power plant

LSI map was reclassified into five categories as "most suitable," "highly suitable," "moderately suitable," "marginally suitable," and

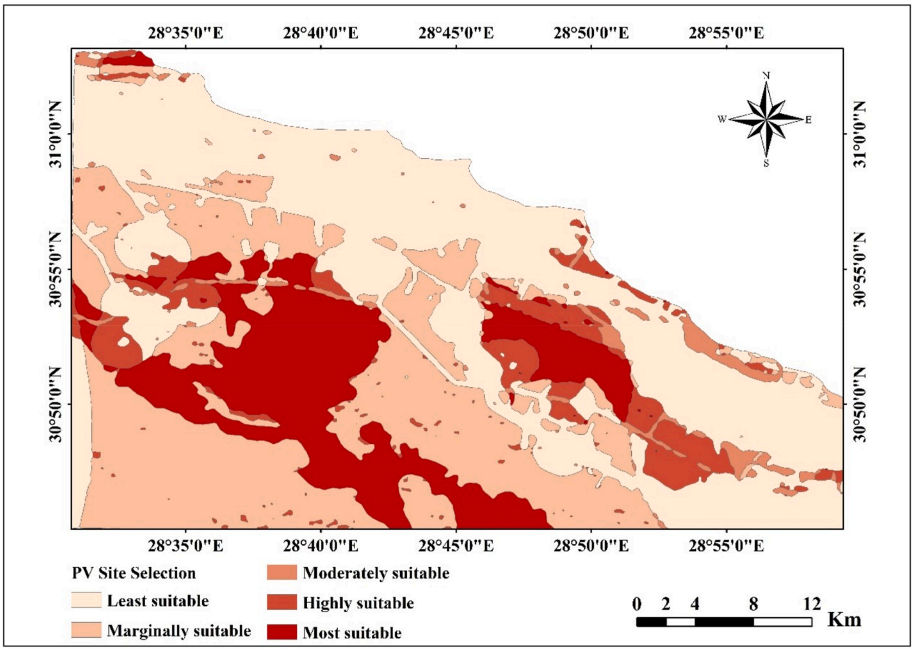

Fig. 11. Land suitability index map (LSI) of the study area.

Table 10
The total area of the suitability indexes.

Suitability index	Shape area_km^2	Percent %
Most suitable	187.1839	17.8
Highly suitable	73.9908	7.1
Moderately suitable	25.998	2.5
Marginally suitable	335.0654	31.9
Least suitable	427.1634	40.7

"least suitable" with an equal interval classification method as presented in Fig. 11.

The most and highly suitable areas were almost located in the south direction, which represents 24.9% (261.1747 km^2) from the total area as shown in Table 10. This area can be sufficient for hosting a utility-scale PV power plant project size, which starts from 5 MW and requires 25 acres (0.10117 km^2) of land as prescribed by Piirisaar (2019).

The most and the highly suitable indexes are observed to be associated with higher weights' values of solar radiation, land value, and slope. Moreover, it has been found that the most and the highly suitable lands are following the pattern of proximity to main roads, transmission lines, and urban cities.

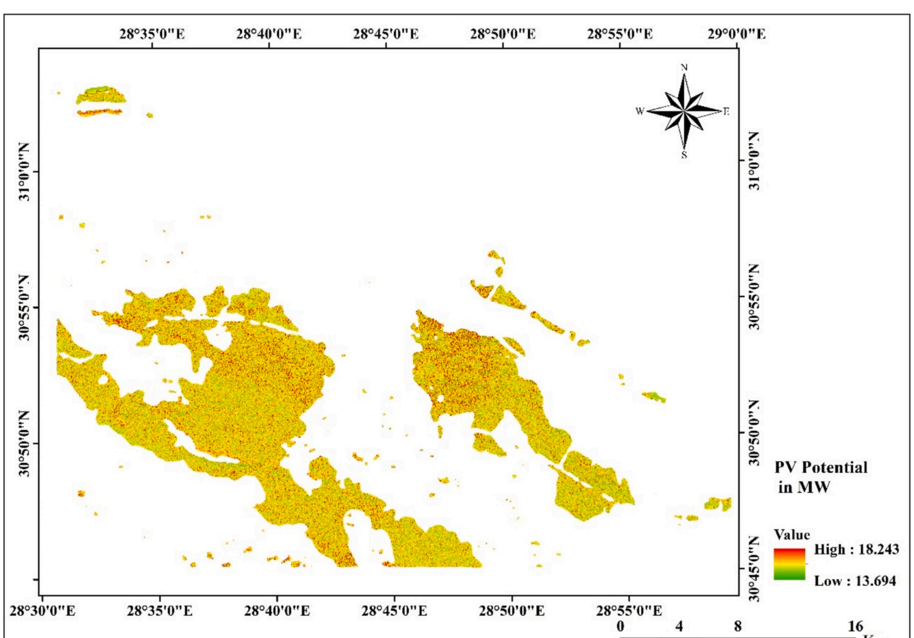

Fig. 12. The PV power technical potential for suitable sites.

3.4. The technical potential of the PV power plant

The PV technical potential of the study area was mapped to facilitate the filtering of the highest pixel values of the PV power. The PV power potential was calculated in MW as shown in Fig. 12 with a spatial resolution 30 m/pixel. The total PV power potential for the entire region comes around to be 13.69 MW and 18.24 MW.

This estimation was considering that the most and the highly suitable indexes are appropriate for PV power generation, the performance ratio was (0.66) to express very harsh conditions in the process of electrical power generation and the system conversion efficiency assumed 15% as a common efficiency of PV, in addition to the minimum and the maximum solar duration of the most and the highly suitable indexes were 9.6 and 11.6 h, respectively.

As a result, the Northwest Coast of Egypt is a promising region for establishing utility-scale PV power plants project size, which can generate greater than 5 MW as identified by Al Garni and Awasthi (2017) and Piirisaar (2019).

4. Conclusion

This study aimed to provide a practical approach to identify the land suitability index of the PV power plant for the Northwest Coast of Egypt by integrating the MCDM technique with RS and GIS techniques.

The result obtained can help in developing the solar energy market, save energy for future demand, and support the sustainable strategies in the region. Solar energy generation can lead to conserve the natural resources by freeing oil and gas for more profitable uses and enhance the export value of traditional energy assets.

GIS integrated with the MCDM approach, have been proven to be an efficient decision support technique for solving solar energy site selection problems. This method offers better results and makes the solar project more economically and technically feasible.

Using RS data in siting utility project size PV power plants is an initial stage for identifying suitable sites, which can save a great deal of time and money, efforts, increase solar power efficiency, save the environment and can promote future infrastructure developments.

The LSI map provides a good understanding of the solar energy potential in the study area, based on the remotely sensed satellite-derived data and weather products. Land suitability modeling considers multi-criteria such as technical, environmental and economical and its limitations, to relate the investigations to real-life situations.

The PV power potential is limited by land availability, the minimum amount of radiation required to install solar power, conversion efficiencies, topography, and climatic condition.

Declaration of competing interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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