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Solar PV power plant site selection using a GIS-AHP based approach with application in Saudi Arabia

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HIGHLIGHTS

- The paper addresses the problem of site selection for solar PV projects.
- A GIS-AHP based approach is proposed.
- Land suitability index is computed to determine the best sites.
- Economic and technical factors are considered to assess site feasibility.
- A case study for Saudi Arabia is conducted.

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ABSTRACT

Site selection for solar power plants is a critical issue for utility-size projects due to the significance of weather factors, proximity to facilities, and the presence of environmental protected areas. The primary goal of this research is to evaluate and select the best location for utility-scale solar PV projects using geographical information systems (GIS) and a multi-criteria decision-making (MCDM) technique. The model considers different aspects, such as economic and technical factors, with the goal of assuring maximum power achievement while minimizing project cost. An analytical hierarchy process (AHP) is applied to weigh the criteria and compute a land suitability index (LSI) to evaluate potential sites. The LSI model groups sites into five categories: "least suitable," "marginally suitable," "moderately suitable," "highly suitable" and "most suitable." A case study for Saudi Arabia is provided. Real climatology and legislation data, such as roads, mountains, and protected areas, are utilized in the model. The solar analyst tool in ArcGIS software is employed to calculate the solar insolation across the entire study area using actual atmospheric parameters. The air temperature map was created from real dispersed monitoring sensors across Saudi Arabia using interpolation. The overlaid result map showed that 16% (300,000 km^2) of the study area is promising and suitable for deploying utility-size PV power plants while the most suitable areas to be in the north and northwest of the Saudi Arabia. It has been found that suitable lands are following the pattern of the approximate range of the proximity to main roads, transmission lines, and urban cities. More than 80% of the suitable areas had a moderate to high LSI. The integration of the GIS with MCDM methods has emerged as a highly useful technique to systematically deal with rich geographical information data and vast area as well as manipulate criteria importance towards introducing the best sites for solar power plants.

1. Introduction

There is great potential in the deployment of renewable energy sources (RES) technologies, as these resources are natural, free, rapidly replenished, and spread across the globe. Examples include solar, wind, biomass, and geothermal energy. Many countries have set RES portfolios to prompt a diversified energy sector for a more sustainable, secure, and low-carbon emission future. Solar photovoltaic (PV) technology is one of the fastest growing RES technologies worldwide. Recently, the prices of PV modules have dropped by 80%, and they are anticipated to continue falling in the coming years, taking into account the likelihood of historic drivers continuing into the future, including the steadily reducing production costs and the market expansion impact on lowering prices [1,2].

Utility-size solar PV technology has promising potential for deployment in vast land areas where the amount of solar irradiation per year is very high. Though, one of the barriers in solar power development is the inconsistency and variability of solar irradiation which can

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be geographically dissimilar from one site to another. To select a site for such an installation, certain aspects must be investigated, such as how good the PV power plant location is, and how to minimize the total cost of the project concerning proximity to existing infrastructures while maximizing power output from the solar panels. Performing a comprehensive solar site analysis is a strategic step towards ensuring a cost-effective and well-performing solar project.

Given the fact that several criteria can influence site selection, applying multiple criteria decision-making (MCDM) methods can help facilitate site selection for utility-scale grid-connected PV solar energy systems by considering key factors in the decision process. The utility-scale PV can be defined as large-scale PV projects which can generate at least 5 MW [3,4]. MCDM methods have been successfully applied in many energy-planning projects. Pohekar and Ramachandran [5], Mateo [6], and Wang et al. [7] provide an excellent literature review on application of MCDM approaches in the RES planning.

In recent years, the Geographical Information System (GIS) has become increasingly popular for various site selection studies, particularly for energy planning [8–22]. Screening possible sites for PV projects is a prime strategic process as suggested by several studies and strategic organizations such as the National Renewable Energy Laboratory (NREL) [4,23–25].

The decision-making process for site selection can be structured into the following general phases [15]:

- Development of decision criteria and restriction factors for the site selection study;
- Model-based prioritization of selected potential sites;
- Sensitivity analysis to draw insights into the relevance of decision criteria.

Evaluation of renewable sources in Saudi Arabia [26] shows that considering 14 criteria, solar PV technology is the most favorable option. This article facilitates site selection for utility-scale grid-connected solar PV projects by proposing a decision model that integrates AHP as a MCDM technique with data on sites from the GIS. Such combination technique will provide further insights into various subjective and conflicting factors which can aid decision makers (DMs) in the process of site selection.

The following points are the main contributions of this research:

- Presents an original approach of developing a criteria layers using real atmospheric sensors data in siting utility size PV power plant using GIS tools. Solar irradiation and air temperature criteria were generated in ArcGIS software and facilitated for AHP process.
- To the best of author's knowledge, GIS-based AHP has not been conducted for utility-size PV site suitability study on such scale yet involving economic and technical criteria.
- Currently, no solar farm studies are applying GIS-MCDM within Saudi Arabia. This research is the first contribution in this direction.

The remainder of the paper is organized as follows. Section 2 presents a literature review – the basics of AHP and GIS are highlighted. Section 3 presents the proposed methodology for site selection of PV power plants. In Section 4, a case study for Saudi Arabia is provided. Finally, Section 5 introduces the conclusions and future works of this research.

2. Literature review

2.1. Decision criteria and restriction factors

In this research, the decision criteria are derived based on the existing literature, the study objective, and accessibility to the geo-referenced database. Solar irradiation is an essential criterion for large-scale PV solar power projects. High amounts of solar energy play a major role in producing more electrical power from available resources. The majority of solar site suitability studies consider solar irradiation as one of the most important decision criteria, as shown in Table 1.

Table 1
Solar PV site suitability criteria.

Criteria	Sub-criteria	References
Environmental	Land use	[27–31]
	Agrological capacity	[11,32,33]
Location	Distance to urban areas	[9,11,12,24,27,28,32–36]
	Distance to substations	[11,12,32,33]
	Land Cover	[9,28]
	Population density	[9,30,31,37]
	Distance to main roads	[9,11,12,27,28,31–33,35,36,38–40]
	Distance to power lines	[9,11,12,24,27,28,31–38,40–42]
	Distance to historical areas	[36,28]
	Distance to wildlife designations	[36]
Economic	Land cost	[37]
	Construction cost	[37]
Climatic	Solar irradiation	[9,11,12,24,28–45]
	Average temperature	[11,12,32,33,38,39,42,45]
Orography	Slope	[11,12,27–29,32–35,39]
	Orientation (aspect angles)	[11,12,29,32,33,35,44]
	Plot area	[11,12,32,33]

In the context of solar irradiation, the global horizontal irradiance (GHI) is the sum of direct normal irradiance (DNI), diffuse horizontal irradiation (DHI) and ground-reflected irradiation as depicted in Fig.1. The DNI is the amount of directed sunlight while DHI is the irradiation components scattered by clouds or another object in the atmosphere; however, the irradiation reflected from ground considered lesser compared to the other components and could be neglected. However, PV technology works in the presence of both DNI and DHI solar irradiation, unlike concentrated solar thermal (CSP) technology which works using only DNI [46].

Close proximity to utilities prompts sufficient accessibility and aids to avoid high cost of infrastructure construction as well as harmful consequences to the environment. Moreover, minimizing the distance to electric transmission lines is an economical way to avoid the high cost of establishing new lines as well as minimizing power loss in the transmission. Certain studies [9,11,27] consider locations that are further away from cities more suitable for RES development to avoid negative environmental impact on urban development and to avoid not in my back yard (NIMBY) opposition. On the other hand, other studies [34,35] indicate that sites nearby cities have more economic advantages. To obtain more accurate decision results, the study area could be screened to eliminate infeasible locations that pose hindrance to the

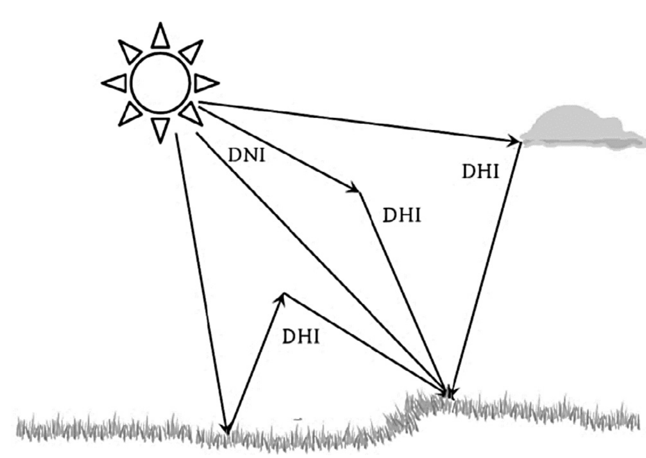


Fig. 1. Components of Solar irradiation intercepted by earth surface [47].

Table 2
Restrictions used in solar energy studies.

Layers of restrictions	References
Urban lands	[11,12,27,33,35,36,38,39,45]
Protected land	[9,11,27,33–35,37,45]
Cultivated land	[35,36,30,40]
Area with high landscape	[9,11,12,27,33–37]
Water infrastructure	[12,30,33,43]
Military zones	[11,27,32,33]
Cattle trails (wildlife areas)	[11,27,32,33]
Cultural heritage	[9,11,32,33,36,38]
Archaeological sites	[9,11,12,27,32,33,37,38]
Paleontological sites	[11,32,33]
Roads and railroad network	[11,12,27,33,35,38]
Sand dunes	[38,39]
Natural disaster (Flood Area etc.)	[37,38]
Area with higher slope (> 5°)	[36–38,45]
Mountains	[32,33]
Soft soil	[37]
Community interest sites	[11,32,33,37]
Dams	[38,40]
Flight security	[34]
Biological significant areas	[27]
Watercourses and streams	[33,40]
Special protection area for birds (SPA)	[33,36]
Coast	[33]
Land aspects	[36]

installation of a utility-scale PV plant. Unsuitable locations which prohibit the deployment of such facilities will be discarded using the GIS. Table 2 presents the most common restrictions applied for solar site suitability.

2.2. Methods in solar site selection

MCDM techniques aid DMs to select the best option among several alternatives in the coexistence of various criteria. These techniques have been frequently deployed in the planning of RES, especially for site selection under environmental, technical, and economic factors. Furthermore, multiple DMs could have different opinions regarding the specific criteria or alternatives that should be involved in the decision framework. The selection of sites for RES based merely on one criterion is inadequate [48]. Huang et al. [49] and Loken [48] propose site selection to be suitably handled through the use of MCDM, particularly for energy planning complexity. Recently, the integration of the GIS with MCDM has become increasingly popular for various siting applications, such as landfill site selection [50,51], urban planning [52,53], and the planning of RES sites [5,17,43,54,55].

The GIS has demonstrated its principal role in exploiting geographical information for developing a spatial decision support system for locating solar facilities. Extensive information from the GIS offers significant advantages for determining site suitability for utility-scale solar PV power plants [56]. These include the following:

- Improved performance of the solar project by ensuring a high level of solar irradiation and moderate air temperature;
- Optimization of the orientation of the site when the project is installed on a flat ground placed towards the south in regions with no large shadows;
- Minimizing loss from transportation, power transmission, and production by considering sites near these utilities as well as nearby urban areas, which are the main consumption points;
- Reducing environmental, societal and infrastructural impacts;
- Excluding protected areas and unsuitable sites from the study areas;
- Using GIS extensive information to develop decision support system for locating solar facilities could support new infrastructure development near those locations to promote utilization of free energy.

Therefore, incorporating both fields of GIS and MCDM yields mutual benefits and can offer a more reliable decision for solar site selection. A study conducted by the NREL on feasibility assessment of concentrated solar thermal potential in the southwestern United States (U.S.) utilized GIS screening techniques [57]. After interpreting several constraints, such as protected areas, slope, and distance from the transmission, solar resource maps were generated and potential areas for project development were highlighted.

Various MCDM methods are available in the literature; however, research on GIS-MCDM has utilized relatively few approaches, such as the weighted linear combination (WLC) [34], the technique for order of preference by similarity to ideal solution (TOPSIS) [58], AHP [27,32,33,35,36,38], grey cumulative prospect theory [16], and Elimination and Choice Translating Reality (ELECTRE) [11]. Jankowski [59] clarified the role of the GIS and MCDM methods in supporting spatial decision making and presented a framework for their integration. Greene et al. [60] provided an overview of MCDA and its spatial extension using the GIS. The authors suggested improving the integration of MCDA with GIS software for increasing accessibility.

Chandio et al. [52] investigated a GIS-based AHP for the assessment of land suitability for solar energy sites. A variety of criteria have been considered, including solar irradiation, slope, land orientation, urban areas, protected areas, transmission lines, and road accessibility. Rumbayan and Nagaska employed MCDM methods with the GIS to prioritize RES (solar, wind, and geothermal) in 30 provinces in Indonesia considering the availability criteria [43]. Sánchez et al. [11] optimized solar farm locations using ELECTRE and the GIS. Effat [35] used the GIS and remote sensing tools with an AHP to calculate the criteria weight of a spatial model. Uyan [27] applied a GIS-based solar farm site selection in Konya, Turkey.

In their work on optimal placement of PV solar power plants in the area of Cartagena, Spain, Sánchez et al. [32] considered an AHP for weighting decision criteria, whereas TOPSIS was applied for assessment of alternatives. Sánchez et al. [33] applied an AHP to weigh the criteria, whereas fuzzy TOPSIS was applied for the installation of solar thermoelectric power plants on the coast of Murcia, Spain. The results were validated using ELECTRE-TRI methodology.

Charabi and Gastli [38] conducted an evaluation of land suitability for the implementation of large PV farms in Oman. They combined an AHP with ordered weighted averaging (OWA), using fuzzy quantifiers in GIS. Aydin et al. [34] considered a fuzzy decision-making procedure that deploys the OWA algorithm for aggregating multiple objectives and prioritizing the most feasible locations for hybrid solar PV-wind systems. Janke [9] applied a multi-criteria GIS to identify areas for the installation of wind and solar farms in Colorado. A large area of Southern England was assessed for the suitability of wind and solar farms by Watson and Hudson [36] using AHP and GIS. A recent study by Liu et al. in [16] investigated the site selection of PV power plants to support decisions in optimal installation site by using grey cumulative prospect theory. Table 3 summarizes the applications of MCDM techniques in different studies for RES site selection.

The AHP has been frequently utilized for the planning of renewable and conventional energy, the allocation of energy resources, the management of building energy, and the planning of electricity utilities [5,41].

3. Proposed methodology

The proposed methodology is depicted in Fig.2. This study aims to provide an evaluation of site alternatives for the sake of discovering the most suitable sites for utility-scale PV projects in Saudi Arabia. The raw data of this research is collected from different resources including governmental agencies, open sources, and related literature. A four-stage analysis is performed to facilitate decision support for PV solar farm site selection.

Table 3
Applications of multicriteria decision-making techniques in different studies.

No.	MCDM Technique	RES	Location	References
1	AHP	Solar PV-wind-geothermal	Indonesia	[43]
2	ELECTRE	Solar PV	Southeast of Spain	[11]
3	AHP	Solar PV and CSP	Ismailia, Egypt	[35]
4	AHP	Solar PV and CSP	Konya, Turkey	[27]
5	AHP – TOPSIS	Solar PV	Southeast Spain	[32]
6	AHP–Fuzzy TOPSIS and ELECTRE	CSP	Murcia, Spain	[33]
7	AHP-Fuzzy OWA	Solar PV and CSP	Oman	[38]
8	Fuzzy OWA	Wind-solar PV	Western Turkey	[34]
9	WLC	Wind-solar PV and CSP	Colorado, USA	[9]
10	AHP	Wind-solar PV and CSP	Central England	[36]
11	Grey Cumulative Prospect Theory	Solar PV	Northwest China	[16]
12	TOPSIS-ELECTRE	Solar PV	Southeast of Spain	[12]
13	AHP	PV	Serbia	[61]
14	AHP-Fuzzy TOPSIS	PV	India	[62]
15	Fuzzy ANP and VIKOR	PV	Taiwan	[63]
16	WLC	PV-CSP-Wind	Afghanistan	[64]
17	AHP	PV-CSP	Tanzania	[65]
18	FAHP	PV	Ulleung, Korea	[66]
19	ELECTRE-II	PV-Wind	China	[67]
20	AHP	PV	Morocco	[68]

- In the first stage, a GIS map overlay technique is applied taking different constraints and restrictions into consideration to rule out unsuitable sites.
- In the second stage, an AHP technique is applied to determine the relative importance and priority weight of each criterion.
- In the third stage, the overall evaluation of the candidate site is determined by applying a weighted sum overlay approach in the ArcGIS tool. The main concept of this technique involves overlaying several criteria maps with consideration of the input criteria and their relative weights obtained from AHP to create an integrated analysis. The weighted sum overlay receives the scaled data inputs, weights the input layers, and adds them together.
- Finally, the unfeasible sites generated in the first stage are excluded from potential areas for the selection of solar PV sites. A land suitability index (LSI) is developed to demonstrate the suitability distribution of the potential sites and to visualize their spatial allocation on the suitability map [69]. A reclassification is performed to achieve the LSI map and the results are grouped into five scales from 1 (least suitable) to 5 (most suitable). Depending on the chosen PV technologies, the required area per 1 MW can vary. Assuming a PV system on 18,000 m^2 generates approximately 1 MW of power, the potential areas were limited to utility size areas to ensure that the total system size is large enough to be considered for a utility-scale project [3,4].

3.1. Criteria for site selection

The location of utility-scale PV projects involves technical feasibility criteria, which directly affect the performance of the solar power plant. These include the amount of solar irradiation and the average of the air temperature criteria. Economic factors express the impact of the placement of solar farms on the project cost. These include proximity to urban areas, proximity to highways, proximity to power lines, slope, and the aspect of the land criteria (Fig.3). The two technical feasibility criteria are explained in detail as follows:

Solar irradiation (C1) (kWh/m^2): The solar analyst tool in the ArcGIS software supports solar irradiation mapping and analysis for specific areas or points and specific time. It has been chosen because it is viable for modeling solar irradiation for a field with diverse terrain as it considers local factors such as orientation, slope, and weather conditions [70].

In addition, the solar analyst tool uses the digital elevation model (DEM) as input, which was used to generate slope and land aspects layers. This will result in a perfect match between the incorporated layers. Three map layers were used internally in the model for calculating the solar irradiation. These include viewshed map, sky map, and sun map. The value of diffuse proportion variable ranges from 0 to 1, where higher values indicate a less clear sky [71]. The diffuse proportion considered in this study was elicited from a King Abdullah City for Atomic and Renewable Energy (K.A.CARE) study that used twelve months of data from 30 stations distributed across the country based on one-minute measurements of GHI and DHI [72]. The transmittivity is the property of the ratio of energy that is received by the earth's service to the amount received by the upper limit of the atmosphere, and its values range from 0 (no transmission) to 1 (complete transmission). This study considers a value of 0.65, which has been applied in several studies that have similar arid regions [38,73]. The parameters applied in ArcGIS solar analyst are presented in Table 4.

- **Average temperature (C2)** (°C): New network monitoring systems have been installed in Saudi Arabia as part of the Renewable Resource Monitoring and Mapping (RRMM) program initiated by K.A.CARE to provide more reliable and real-time measurements for large-scale deployment of RES technologies. A study by Zell et al. [72] summarizes the analysis of the measurement data used in 30 stations spread across the country. At each site during the study period, the annual average based on 24 h of data for each day's temperature is recorded. In this study, real measurements are utilized for interpolating the yearly average temperature for the entire study area. The spatial analyst tool in ArcGIS 10.3.1 employs several interpolation tools that can generate a surface grid from points data. Natural Neighbors, Trend methods, Topo to Raster, Inverse Distance Weight, Spline, and Kriging are available interpolation methods. The Spline interpolation tool can estimate the values very smoothly using a mathematical model which minimizes the overall surface curvature. It can predict valleys in the data, and it is the best interpolation tool for smoothing varying phenomena such as temperature [74,75]. The tension spline type was used to obtain higher values for the weight parameter resulting in a coarser surface (weight = 10, No. of points = 4).
- **Slope (C3) and land aspects (C4):** Flat areas or mild steep slopes will help to avoid the high construction cost required in high slope areas. Flat terrain is essential for large-scale PV farms; as such, high slope areas are not preferable for such projects due to low economic feasibility. A south-facing slope is an ideal orientation for solar farm sites and must be less than 5° in this study. Higher slope areas such as valleys and steep lands should be avoided. Using the DEM, the aspects of the survey area have been generated.
- **Proximity to urban areas (C5), proximity to highways (C6), and proximity to power lines (C7)** (m): In this study, the proximity to residential areas is considered as a favorable factor. A buffer of 1.5 km from urban cities and a maximum radius of 50 km are considered, where close proximity to the city is preferable. The Euclidean distance is used to calculate the closest source based on straight-line distance with a maximum of 50 km. Proximity factors to such utilities are crucial in creating a distributed generation network and for grid-connected PV solar power.

3.2. Restrictions for site selection

For suitability analysis, aspects such as urban areas, protected land, major road networks and higher slope lands (> 5°) have been selected as restriction factors. These four constraints are commonly applied in

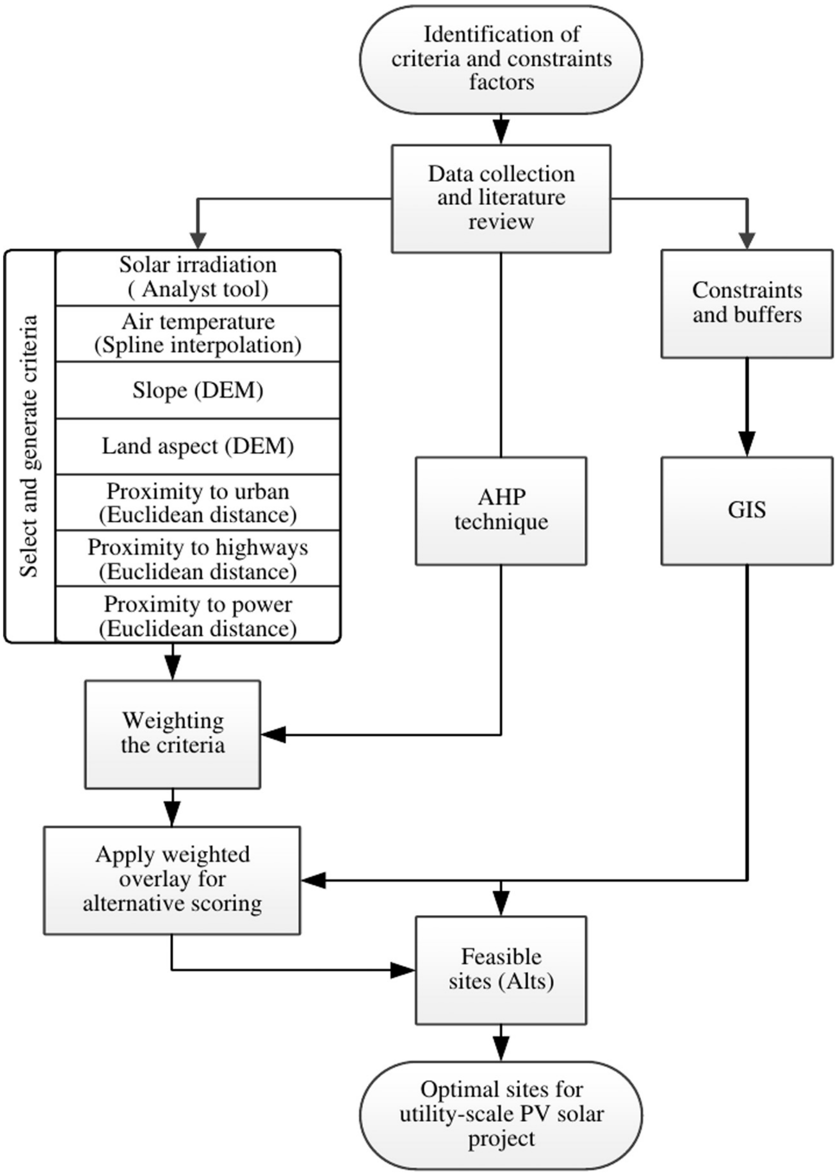


Fig. 2. Flow chart of the proposed methodology.

similar solar site suitability studies. In addition, these factors were available as a dataset for the study area and serve the objective of this research. The protected areas include wildlife sanctuaries, national parks, industrial cities, and sacred places. According to the Saudi wildlife authority (SWA), there are 75 wildlife-protected areas in Saudi Arabia to encourage sustainable rural development and preserve wildlife, 62 of which are wilderness areas and 13 of which are coastal and marine areas as shown in Fig. 4. The thematic layers of protected areas in this study are obtained from governmental agencies while the buffer distances have been adopted from the literature as shown in Table 5. The total area of the existing and proposed protected lands is approximately 10.42% of the country's total area.

High slope areas are not viable for solar PV projects due to low economic feasibility. Based on the data from various literary works [27,35,36,38], the slope factor for this study should be less than or equal to 5°. Higher slope areas including valleys and steep slopes were eliminated. Moreover, to limit the feasibility analysis, urban areas, highway networks, developed areas, and major roads were discarded due to the high density of population and buildings in addition to traffic safety issues.

The restriction layers shown in Fig. 5 were integrated into one layer including the necessary buffers. They were then assigned a binary scale (1 and 0), where "one" indicates the absence of the allocated constraint indicating that the development of the project is possible, whereas "zero" indicates the presence of limitations, indicating that the development of the project is impossible. The initial resulting layer was reclassified as exploitable areas attributed by one. Once the constraints layer was converted to binary, the multiplication of this layer with the criteria layer in Section 3.1 was performed to generate the preliminarily suitable sites map.

3.3. *Determining locations for PV power plants using GIS-AHP based approach*

3.3.1. *Basics of analytical hierarchy process*

The AHP, developed by Saaty [77], is one of the most comprehensive MCDM tools for ranking alternatives by introducing a decision structure to deal with multiple objectives. AHP allows for the combination of qualitative and quantitative inputs, which offers an appropriate approach to deal with complex MCDM problems in energy planning. The AHP accounts for inconsistency if there is inconsistency in the decision maker's (DM) evaluations.

GIS-AHP applications are among the most often used approaches for integrating AHP with other decision support techniques. The AHP has

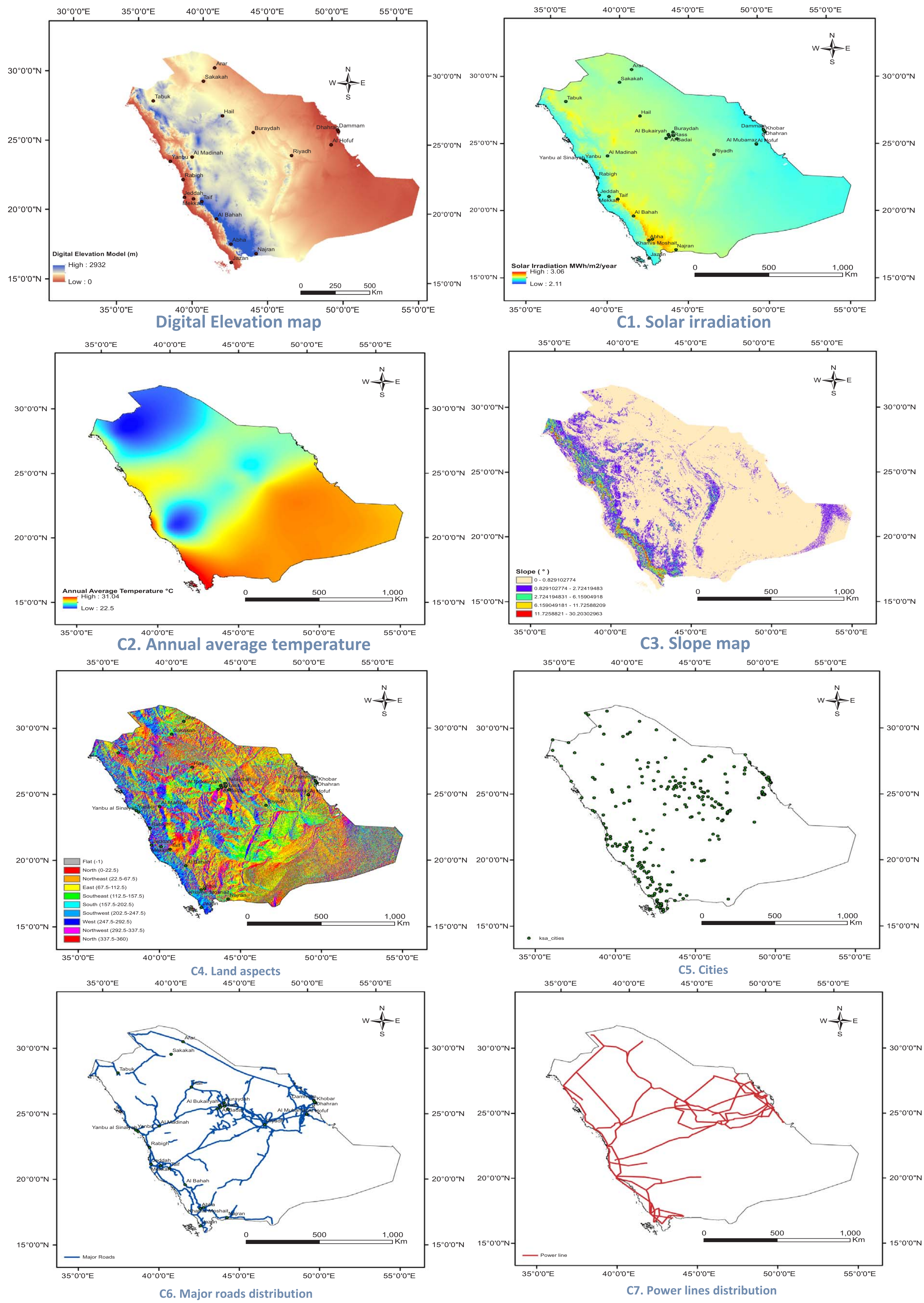


Fig. 3. Criteria maps applied in the proposed GIS-MCDM.

Table 4
Parameters used in ArcGIS solar analyst tool.

Parameter	Value	Parameter	Value
DEM	Resolution of 90 m	Slope Aspect Input Type	DEM
Latitude	24.1 (Auto)	Calculations Directions	32
Sky size	200 (Default)	Zenith Divisions	8
Time configuration	Whole Year (2014)	Azimuth Number	8
Day interval hour	14 (Default)	Diffuse Model Type	Uniform_Sky
Hour interval	0.5 (Default)	Diffuse Proportion	0.36
Z units	1	Transmittivity	0.65

been accepted by the international scientific community as a robust and flexible MCDM technique to facilitate solving complex decision problems [78]. The top level of the AHP hierarchy encompasses the primary goal, whereas the middle and bottom levels represent the decision criteria and the alternatives, respectively. The DMs assess each level parameters in pairwise comparisons against their parent node. The AHP decomposes a large problem into smaller sub-problems in hierarchical levels and assigns weights to the decision-making criteria.

Within the scope of the AHP method, a decision matrix is formed as a result of pairwise comparisons. Criteria weights are then reached as a result of these calculations. Furthermore, a consistency ratio (CR) is employed to screen out inconsistent judgments of decisions in the pairwise comparison process. The following steps are required to perform an AHP for n number of criteria [77]:

(1) To form a pairwise comparison matrix $m = (n*n)$ for several criteria, let P_{ij} reveal the preference score of criteria i to criteria j using the nine-integer value scale suggested by Saaty [77], as presented in Table 6. P_{ij} denotes the entry in the i th row and the j th column of matrix m. The entries of preference score P_{ij} and P_{ji} must satisfy the following constraint in Eq. (1):

$$P_{ij}.\ P_{ji} = 1 \tag{1}$$

(2) Second, to establish a normalized pairwise comparison matrix $\overline{m}$, the sum of each column must equal to 1. This can be obtained using Eq. (2) to calculate $\overline{P_{ij}}$ for each entry of the matrix $\overline{m}$.

$$\overline{P_{ij}} = \frac{P_{ij}}{\sum_{l=1}^{n} P_{lj}} \tag{2}$$

(3) Then, the average across rows is computed to obtain the relative weights using Eq. (3). For each element, the relative weight is within the range of 0–1; a higher weight shows a greater influence of the element to the solar PV power plant site.

$$w_i = \frac{\sum_{l=1}^{n} \overline{P_{ij}}}{n} \tag{3}$$

(4) Finally, to obtain the solar PV suitability map (SSM), Eq. (4) has been applied for each pixel of study area layer. If restriction (r)

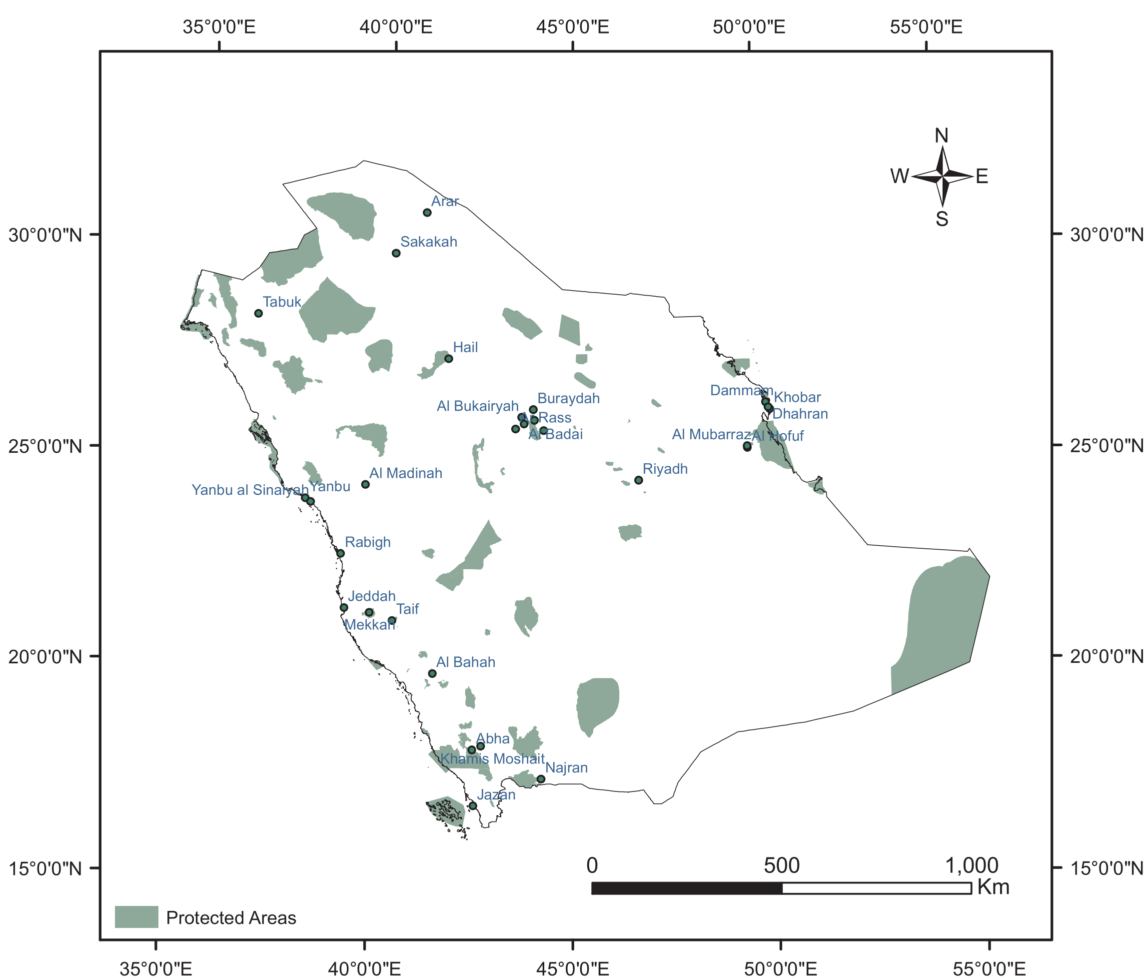


Fig. 4. Protected areas.

Table 5
Restrictions layers considered for utility-scale PV in Saudi Arabia.

Restriction	Data source	Accessed on	Buffer	References
Protected lands	Renewable Resource Atlas of Saudi Arabia	Feb 9, 2014	< 1000 m	[36]
Major roads	http://faculty.ksu.edu.sa/falmutlaq/pages/gis_data.aspx	Oct. 15, 2015	< 500 m	[76]
Slope	Renewable Resource Atlas of Saudi Arabia	Feb 9, 2014	≤ 5°	[38]
Urban areas	Renewable Resource Atlas of Saudi Arabia	Feb 9, 2014	< 1000 m	Modified from [27,36]

exits, then $r = 0$ which leads to the *SSM* value of an unsuitable site. Otherwise *SSM* could be obtained by finding the summation of each criteria value (x_i) multiplied by corresponding criteria weight (w_i).

$$SSM = \sum_{i=1}^{n} x_i.\, w_i.\, r \quad where \quad r \in \{0,1\} \tag{4}$$

(5) The CR is given by $\frac{CI}{RI}$, where RI is the random consistency index that varies according to the number of criteria in a comparison (n) as shown in Table 7. The consistency index (CI) is calculated using Eq. (5).

$$\boldsymbol{CI} = \frac{(\boldsymbol{\lambda_{max}} - \boldsymbol{n})}{(\boldsymbol{n} - 1)} \tag{5}$$

where λ_{max} is the maximum eigenvalue of the comparison matrix. Table 8 presents the eigenvalue obtained by pairwise comparisons of criteria with respect to the goal of selecting the best site for solar PV.

(6) If $CR \leqslant 0.10$, the degree of consistency is considered satisfactory; otherwise, there are serious inconsistencies in the pairwise comparison. Therefore, the AHP may not return meaningful results [5].

The present study has seven elements associated with decision criteria or $n = 7$. Accordingly, RI = 1.32 and CR = 0.02 which is in acceptable range.

The original high-level maturity and advanced embedded features enable the GIS to be a powerful tool for strategic planning of energy development projects, including solar technologies [4,8]. In the present research, ArcMap 10.3 was utilized to perform spatial processes and manipulation for both vector (points, lines, or polygons) and raster (pixels or cells) files of the study area's dataset. It has been used to overlay the different layers to create composite map results and smart visualizations for insightful decision-making.

3.3.2. Steps in determining best sites

The key steps in determining the best sites for deploying solar PV plants are as follows:

- First, the decision problem was structured into a hierarchical model as shown in Fig.6. The goal represents the top-level of the hierarchy, which is to select the most suitable site to install utility-size PV power plants. The decision criteria are represented in the second level of the model.
- The second key step is to obtain the comparison matrix of criteria including solar irradiation, yearly average temperature, slope, land aspects, proximity to an urban area, proximity to the main road, and proximity to power lines, all of which are elements towards the goal of the study in the proposed decision framework. Aran et al. [56] introduced an approach to obtain a pair-wise comparison matrix and determined the priority weights of the criteria. Several points highlight the rationale behind the criterion weighting. First, the climate criteria, including solar irradiation and the yearly average temperature, are considered the most important criteria as they define the output power of the PV power plant. In subsequent order of importance are the slope and the land aspects criteria, as they determine the amount of irradiance received by the solar panels. Their importance essentially depends on the steepness or mildness

Table 6
Preference score values interpretation.

Score of criteria $\boldsymbol{i}$ to criteria $\boldsymbol{j}(\boldsymbol{P_{ij}})$	Definition
1	Criteria $\boldsymbol{i}$ and $\boldsymbol{j}$ are of **equal** importance
3	Criteria $\boldsymbol{i}$ is **slightly** more important than $\boldsymbol{j}$
5	Criteria $\boldsymbol{i}$ is **moderately** more important than $\boldsymbol{j}$
7	Criteria $\boldsymbol{i}$ is **strongly** more important than$\boldsymbol{i}$
9	Criteria $\boldsymbol{i}$ is **extremely** more important than $\boldsymbol{j}$
2, 4, 6, 8	Intermediate values

Table 7
Random index for different values of number of elements [77].

n	2	3	4	5	6	7	8	9	10	11	12
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48

Table 8
Eigenvalue of criteria.

Criteria	Eigenvalue
C1	0.350
C2	0.237
C3	0.159
C4	0.106
C5	0.032
C6	0.046
C7	0.070
Total	1.000

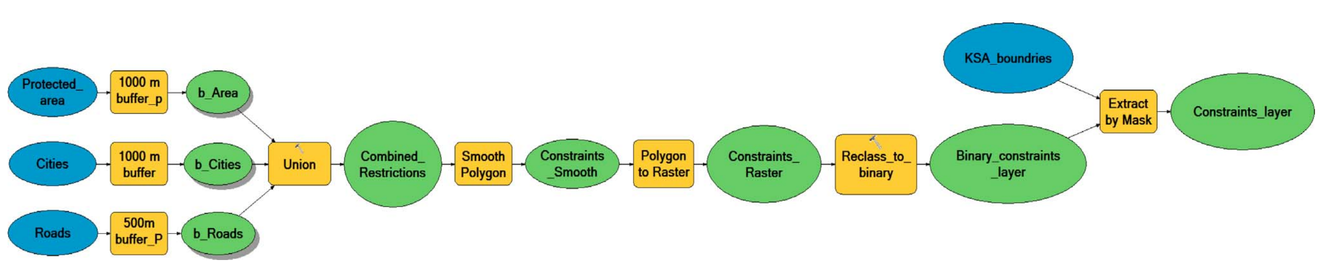


Fig. 5. Restrictions part of the model.

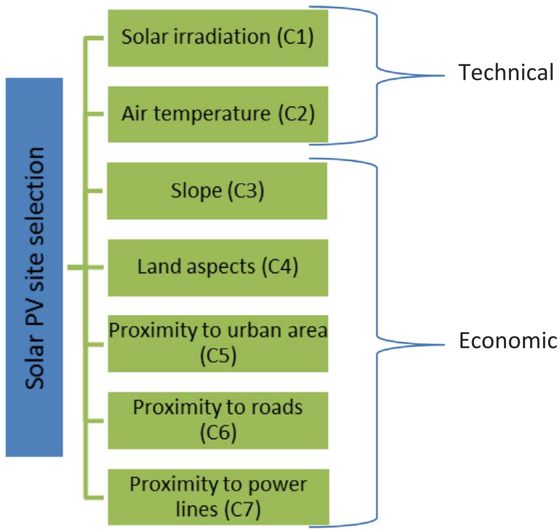


Fig. 6. Decision criteria considered in solar site selection.

of the slopes and the orientation of the area. Milder slopes and south aspect areas are considered high importance factors. From an economic perspective, the distance to the electricity grid, major roads, and cities follow in importance, as they determine the infrastructure and transmission cost of installation.

Based on the above reasoning, and considering the criteria weights presented in similar solar site suitability studies [33,38,69] the pairwise comparison matrix was established, as shown in Table 9. The importance of such criteria is also emphasized by strategic organizations such as the NREL and the environmental protection agency (EPA) in U.S. [23,56,9,38].

- The third key step is to calculate the priority weights and to check for inconsistencies. The eigenvector, which indicates the priority weight of each criterion, was computed and the sum of all weights is equal to one as represented in Fig. 7. To verify the weighted values of each criterion, the CR was calculated (CR = 0.02); as it is less than 0.10, the value judgments are considered to be acceptable [77].

At this point, seven layers of the considered criteria with their corresponding weights (gained from the AHP tool) were obtained. Using the weighted sum overlay tool in the GIS, the PV site selection s tackled as follows [79]:

1. Since the input layers are in different values and ranges, each criterion must be brought to a common scale in order to integrate them in one layer. Subsequently, values in the input maps were reclassified into a common preference scale of suitability ranging from 10 to 100 (with 100 being the most suitable).
2. Each criteria layer is multiplied by the criteria's weight or importance according to the AHP.

Table 9
Comparison matrix of the adopted decision criteria.

Criteria	C1	C2	C3	C4	C5	C6	C7
C1	1	2	3	4	7	6	5
C2	1/2	1	2	3	6	5	4
C3	1/3	1/2	1	2	5	4	3
C4	1/4	1/3	1/2	1	4	3	2
C5	1/7	1/6	1/5	1/4	1	1/2	1/3
C6	1/6	1/5	1/4	1/3	2	1	1/2
C7	1/5	1/4	1/3	1/2	3	2	1

3. The resulting cell values were added together to generate the ultimate combined layer. Therefore, the alternatives are the potential sites generated through the GIS which takes into account the criteria weights obtained from AHP technique.

4. Case study

The field of our study includes Saudi Arabia, which encompasses most of the Arabian Peninsula. The country is located in the southeast of Asia with an area greater than 2 million km^2. The main cities are Riyadh (capital city), Jeddah, Mecca, Medina, and Dammam. The country is majorly arid terrain except the Asir province in the southwest that is influenced by monsoons of the Indian Ocean. Most of the country is dominated by a desert climate with extreme heat during the day and an abrupt drop in temperature at night. The Kingdom's location, massive unused areas, and amount of daily solar irradiation are all factors that offer profound potential for exploiting solar energy in Saudi Arabia. The solar irradiation in the Kingdom is considered one of the highest rates worldwide with an average GHI of 2 MWh/m^2/year as shown in Fig. 8 [80,81].

Rahman et al. [82] studied long-term mean values of sunshine duration and global solar irradiation on horizontal surfaces of over 41 cities in the kingdom. Results showed that the overall mean of yearly sunshine duration in the Kingdom is 3248 h, and the GHI varies between a minimum of 1.63 MWh/m^2/year at Tabuk, a northwestern region of the Kingdom, and a maximum of 2.56 MWh/m^2/year at Bisha, a southwestern region of the Kingdom. The minimum solar irradiation is higher than the average GHI in Germany and many other European countries. Furthermore, the pattern of global solar irradiation intensity and sunshine duration follows that of electricity demand. Solar energy could be the most desirable RES option to encounter the required power, especially during the summer season when demand peak reaches its highest, mainly due to air conditioning systems [83]. Saudi Arabia gained significant experience in the area of solar energy from different studies and research programs conducted in the Kingdom since 1960 [83,84]. Fig. 9 depicts the long-term annual average of GHI and Direct Normal Irradiance (DNI) obtained from the SolarGIS database [85].

Solar PV has great potential for deployment in the kingdom where vast areas of land are available and the amount of global solar irradiation is very high. Currently, Saudi Arabia plans to produce 9.5 gigawatts from renewables, mainly solar and wind power, by 2023 as a part of Kingdom's 2030 vision [86].

4.1. Screening potential sites

The proposed methodology was applied to a study area of Saudi Arabia for site selection of utility-scale solar PV power plants. The final map of unsuitable areas indicates that most of the study area does not fall under any restrictions and does not belong to any protected areas, as illustrated in Fig. 10. The seemingly suitable areas are large zones across the study area, which can be exploited to implement utility-size solar PV power plants.

As a result of MCDM-GIS integration, the overlaid result map showed that 16% (300,000 km^2) of the study area is promising and suitable for deploying utility-size PV power plants as depicted in Fig. 11. The central part of Saudi Arabia has shown more areas that are appropriate for utility-size PV power plants, mainly due to their favorable high solar irradiance, mild slope, and proximity to major roads, grid lines, and urban areas. It has also been found that few sites are suitable north and northwest of the study area. The east and west coasts presented a few strips of suitable sites. The southeast region, which contains the largest contiguous sand desert (known as Rub' al Khali), is mostly unsuitable for installing such a facility due to relatively high air temperature and low density of main roads, power transmission lines, and urban areas.

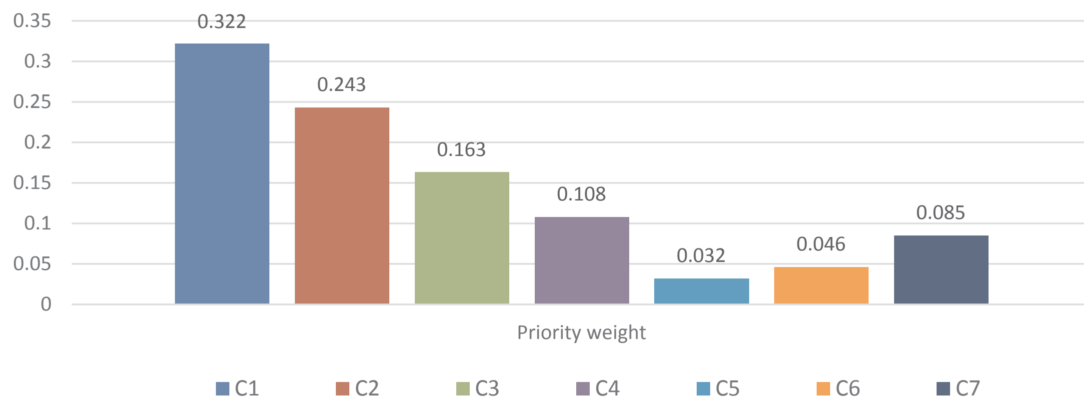
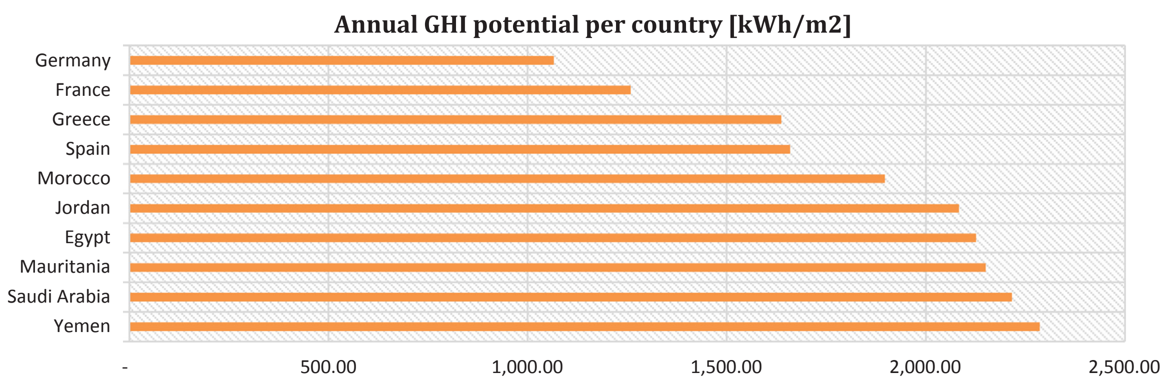


Fig. 7. The priority weights of the criteria.



	Yemen	Saudi Arabia	Mauritania	Egypt	Jordan	Morocco	Spain	Greece	France	Germany
kWh/m2	2,286.00	2,216.00	2,150.00	2,126.00	2,083.00	1,897.00	1,659.00	1,637.00	1,259.00	1,066.00

Fig. 8. The annual global horizontal irradiance among selected countries.

4.2. Site selection results

For better demonstration and insight, the LSI is proposed. The LSI defines the degree to which each site is suitable for the placement of PV plants according to the associated criteria and excluding all restrictions. The resulting data indicates that most of the resulted overlaid values range from 30 to 80 with a mean of 60 considering the common suitability scale (10–100). For this distributed data, the suggested LSI values are shown in Table 10.

According to the LSI analysis, the outcome showed that many of the highly suitable locations are located in the central region as illustrated in Fig. 12. The most suitable areas are located north to northwest, mainly due to higher solar insolation and lower air temperatures in that region. Along the southwest and west coasts, lands have lower LSIs due

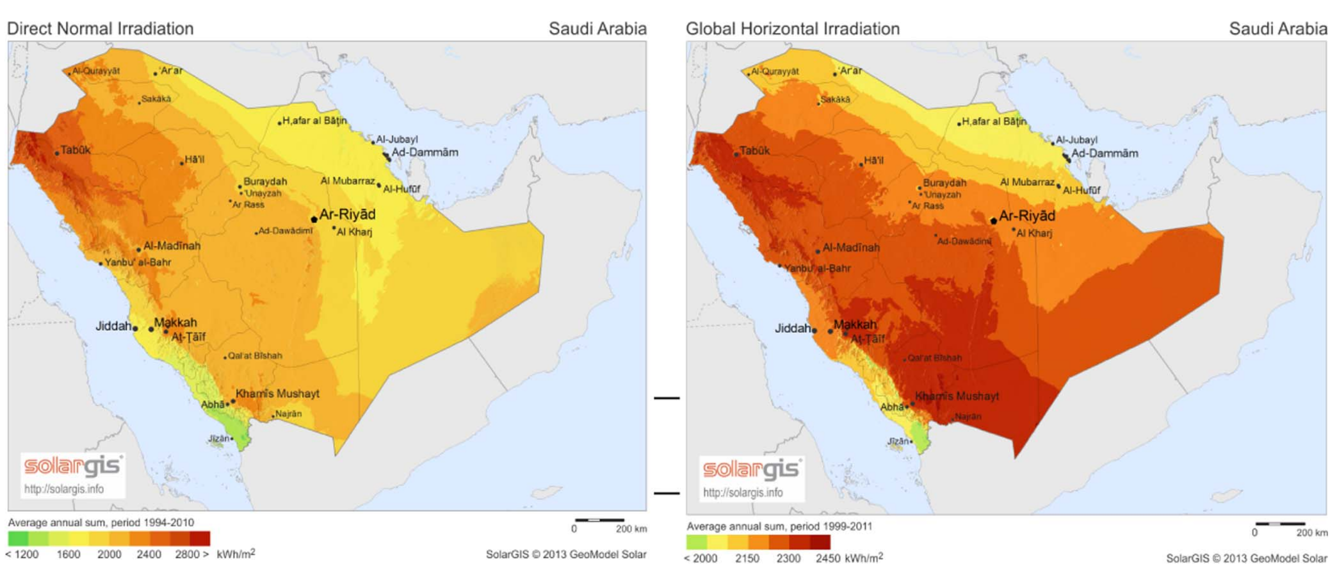


Fig. 9. Long-term average of daily DNI (left) and GHI (right) for Saudi Arabia.

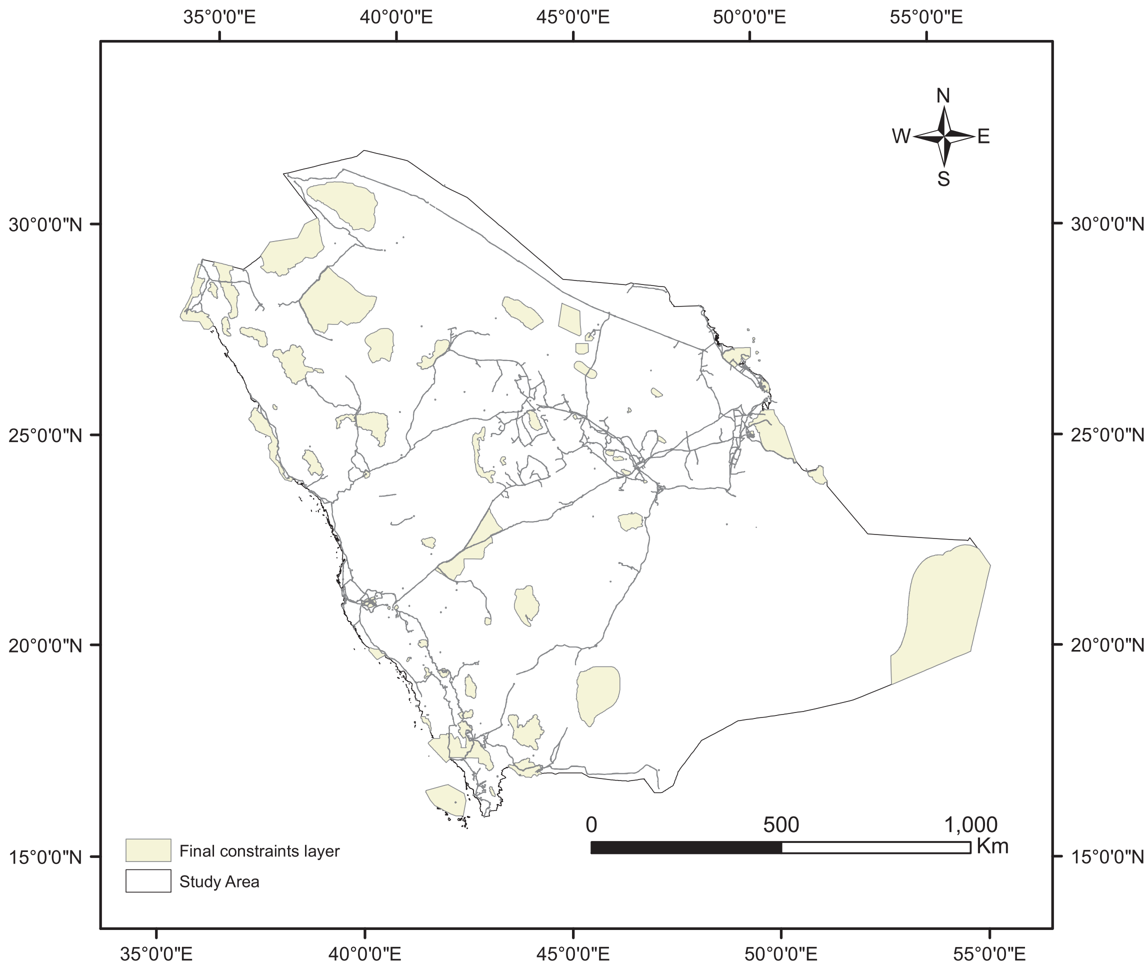


Fig. 10. Restrictions layer map.

to major steep slopes, including the mountain range (Sarawat Mountains) which runs parallel to the west coast. The eastern region of the study area shows moderate to high LSIs since it has adequate infrastructure combined with the high density of high solar irradiation.

Based on the model results, Tabuk and Arar cities located in the North, besides Taif city in the West would be the most suitable sites to implement solar PV on a utility-size scale. While these locations account for only 3% of all the suitable areas, they offer a potential for high performance solar PV projects in terms of power generation and associated infrastructure costs. On the other side, the largest contiguous sand desert located to the East and South East (known as Rub' al Khali) is unsuitable for such projects due to relatively high air temperature and low density of infrastructure.

The suitability distribution for Saudi Arabia developed in this study can support decision makers in selecting the most suitable sites for utility-size solar PV projects. Recently, Saudi Arabia has planned to build 300 MW of solar and wind plants in several locations [87]. Al-Jouf city which is located in the North (East from Tabuk as shown in Fig.12) has been designated for a 50 MW solar PV project. Such a location which is near the most suitable sites is favorable to the PV technology and it offers a high potential for ultimate performance of a solar PV system. Likewise, considering the high suitability sites in central areas, which comprise 50% of the suitable areas, is significant for grid connected utility-scale PV power plants, since these areas are near the most populous city, Riyadh. Lastly, this suitability distribution map can benefit the decision makers by helping them to be proactive in the solar PV development and can aid to achieve the Saudi 2030 diversified energy targets.

Fig.13 outlines the land suitability distribution based on the previous suitability index analysis. We found that more than 80% of the suitable areas had a moderate to high LSI. It has been found that suitable lands are following the pattern of the approximate range of the proximity to main roads, transmission lines, and urban cities. Therefore, there is great potential to have more suitable sites in the north and northwest of Saudi Arabia by improving the efficiency of power lines and major road networks and utilizing these sites to generate power from their abundance of solar energy. However, no sites had a score of 100 in the study results, which indicates that no location is perfect across all of the criteria.

To validate the model the results obtained are compared with a performance study of solar resources in Saudi Arabia conducted in [88]. Based on real-time solar radiation and air temperature from monitoring sensors, the author reviewed the performance of a pilot photovoltaic of in 32 sites across Saudi Arabia. Results are consistent with suitability index map resulting from the proposed GIS-AHP model. For instance, due to the lower air temperature in Tabuk and Taif cities (with yearly average temperature $\approx 30°C$) and high solar irradiation (annual average of GHI $\approx$6.3 kWh/m^2), they show a high energy productivity compared to other sites (generated energy $\approx$210 MWh). Also, Najran site gives the highest generated energy (218.5 MWh) due to the highest solar irradiation compared to all locations (6.8 kWh/m^2). Nevertheless, in our study it has low suitability index due to low distribution of power lines, major roads, and urban areas.

4.3. Sensitivity analysis

For conducting sensitivity analysis, different criteria weight scenarios were considered and their overall impact on land suitability

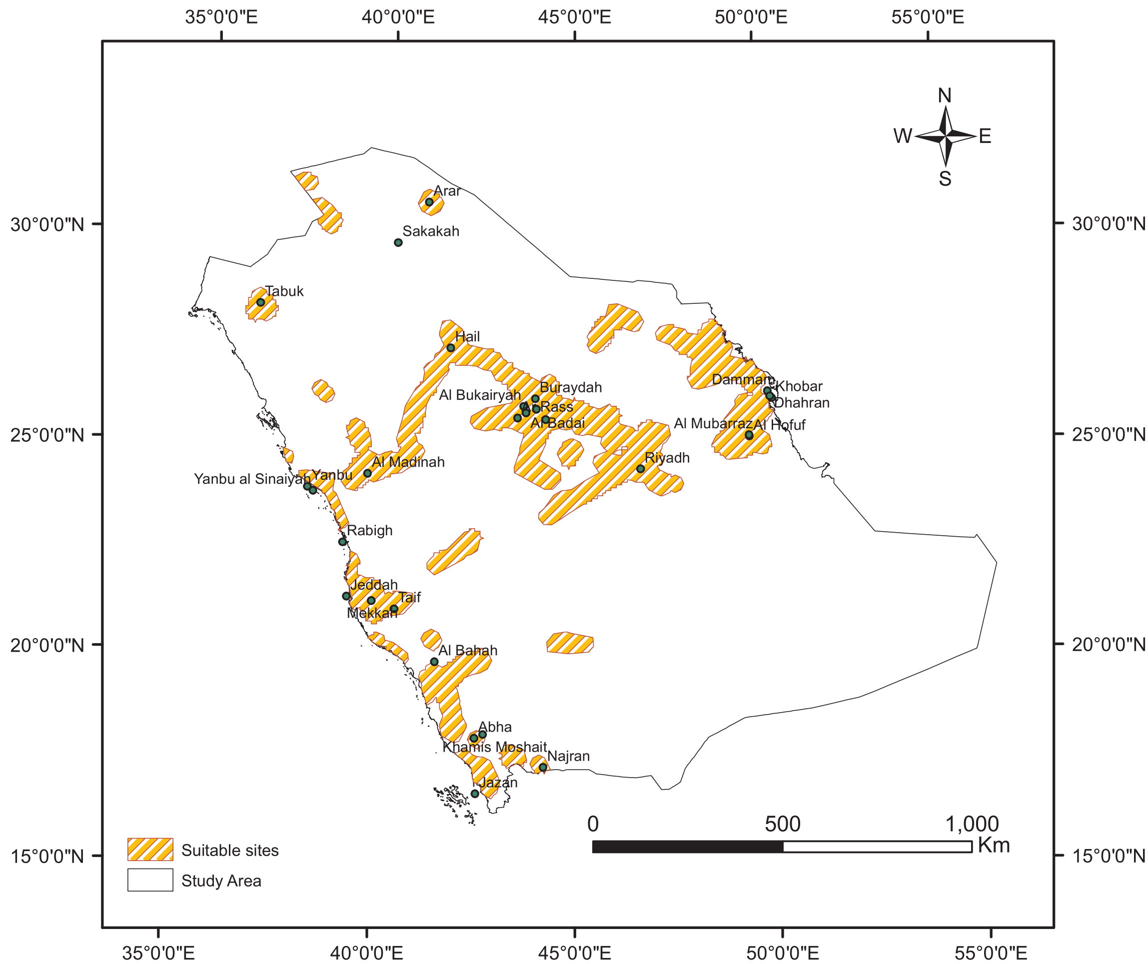


Fig. 11. Preliminary results of potential sites.

Table 10
Land suitability index.

Scale values	Land suitability index
1–40	1 (least suitable)
40–50	2 (marginally suitable)
50–60	3 (moderately suitable)
60–70	4 (highly suitable)
70–100	5 (most suitable)

index was assessed. In addition to the criteria weights assigned using AHP technique, two scenarios including equal weights and higher economic weight have been examined in this study. In the case of equal weights scenario, the weight of 14.28% has been assigned to each criterion to ignore the relative importance of each criterion. This approach is the simplest decision-making method for avoiding risk. On the other side, the economic criteria including slope, land aspect, proximity to urban areas, to power lines and to major roads are given higher weights than others (each 16%) in order to study the influence of economic factors. Fig. 14 depicts the criteria weight used in AHP, equal weights, and higher economic weight scenario.

Alternative sites were assessed and ranked to develop utility-scale solar PV projects using equal weights for associated criteria. This scenario will prompt the even measurement of the influence of the criteria on the resulting suitability layer and will lead to a greater understanding of the importance of each criteria weight. Compared to AHP methodology, the overall suitable area of this scenario has decreased by 0.64% (1,825.55 km^2) of the study area. This is essentially attributable to the decision criteria that offer more weights (14.3%) to economic factors including proximity to major roads, grid lines, and urban areas. Similar to the AHP approach, the result of the similar weight scenario shows that there are vast areas with a high LSI for approximately 48% of the suitable area. On the other hand, marginal LSIs and moderate LSIs have increased from 1.02% to 1.22% and from 5.29% to 5.9% respectively around the whole study area, as shown in Fig. 15.

The most suitable LSI showed a slight decline from 3% to 2.5% of the suitable area (from 0.4% to 0.35% of the study area) when considering equal weightings for all criteria. Most of the moderate to high LSI areas are spread near the central province of Saudi Arabia, as depicted in Fig. 16. More moderate and high LSI sites exist where mountains stretch from the southwest along the west coast, since the slope weights have decreased by 2% (from 16.3% to 14.3%). In the east, the moderate LSI improved to highly suitable and most suitable due to higher weights to the proximity to economic factors and lower weights to the temperature criteria. As solar PV systems present a high initial cost and require relatively large areas of land to produce energy, the land construction costs turn out to be more of an issue, whereby proximity to the national grid, major roads, and urban areas could have significant economic costs which outweighs the electricity generated from the solar farm [89]. Selecting sites on the basis of slope and orientation as well as installation near existing infrastructures will be more pertinent for solar developments.

Assigning higher weights to economic criteria including slope, land aspects, proximity to urban areas, roads, and proximity to power lines could be a viable option. When assigning higher weights to economic factors, the results revealed that the most suitable areas are approximately three times superior compared to equal weight and AHP scenarios as depicted Fig.16.

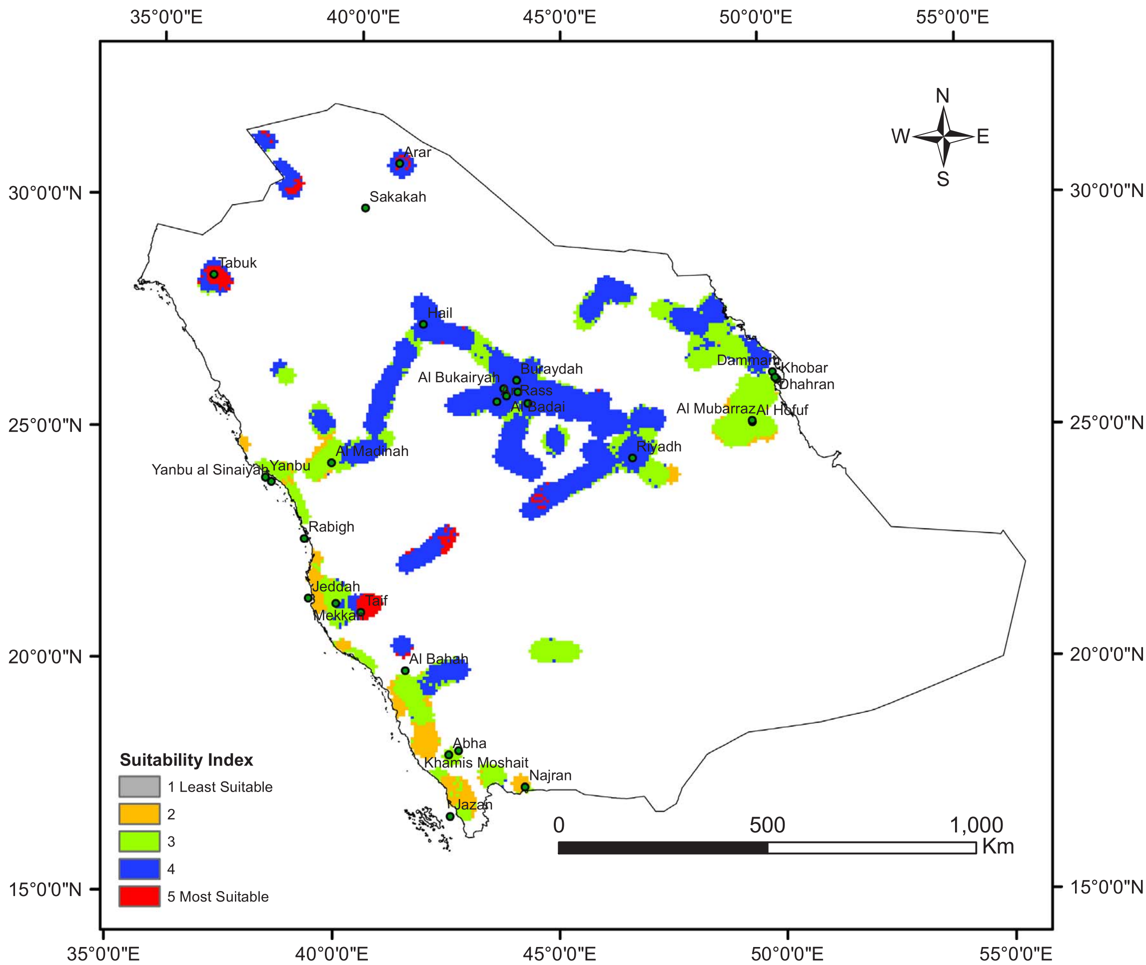


Fig. 12. Suitability Index results using AHP weights.

The central region where the necessary infrastructure exists demonstrates high density of the most suitable LSI areas. The least LSI has increased slightly, whereas the moderate and marginal LSI dropped compared to the same weight scenario.

The results of different scenarios have proven sensitivity to the criteria weights and offer various land suitability distribution. Table 11 illustrates the final results obtained by varying the criteria weights, thus demonstrating that both economic and technical factors are influential in the evaluation of the study area.

5. Conclusions and future works

RES such as solar energy can contribute to electricity generation with a sustainable, secure, and low-carbon emission future. This research presents an original approach of developing criteria layers including solar irradiation and air temperature using real atmospheric sensor data in siting utility size PV power plants. As an initial stage of installing PV power plants, the identification of suitable sites can save DMs a great deal of time and money and can promote future infrastructure developments. The integration of the GIS with MCDM methods has emerged as a highly useful technique to systematically deal with rich geographical information data as well as manipulate criteria importance towards introducing the best sites for solar power plants. Furthermore, by incorporating associated criteria into the decision-making process, we could offer better results and make the solar project more economically and technically feasible.

This research offers a high-level overview of the potential of site suitability of utility-scale PV technology in the study area based on integration of the geographical information system and multi-criteria decision-making tool. The AHP technique is used to evaluate the importance of each decision criterion in selecting the best site for utility-scale solar PV power plants. Technical and economic factors considered

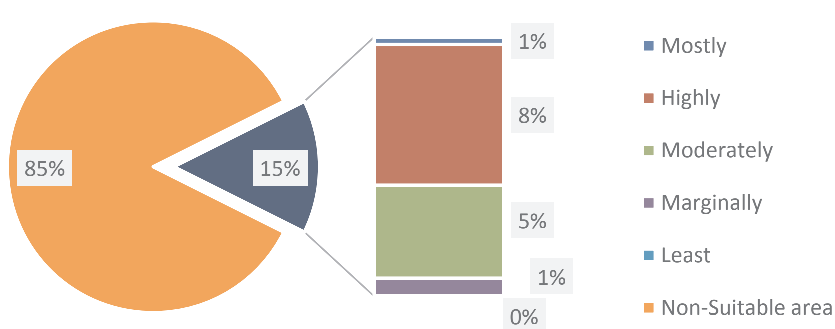


Fig. 13. Land suitability distribution.

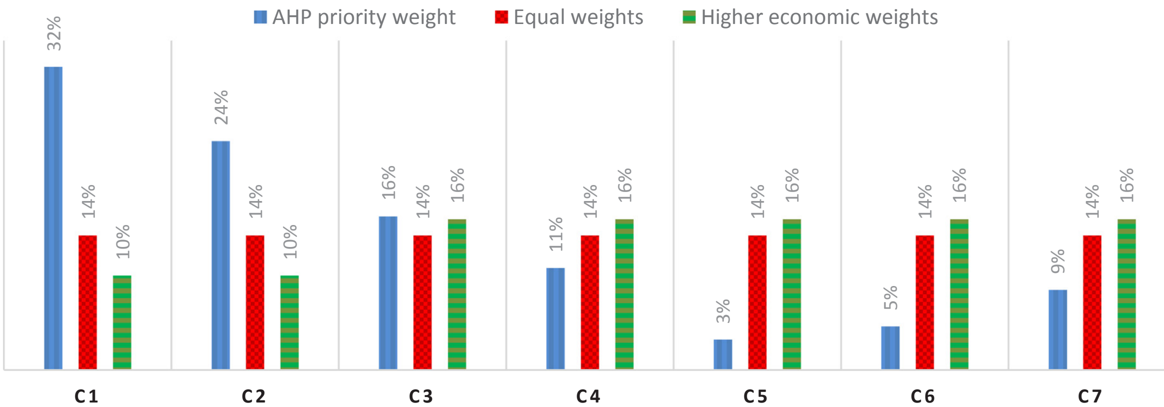


Fig. 14. Weights of decision criteria considering different scenarios.

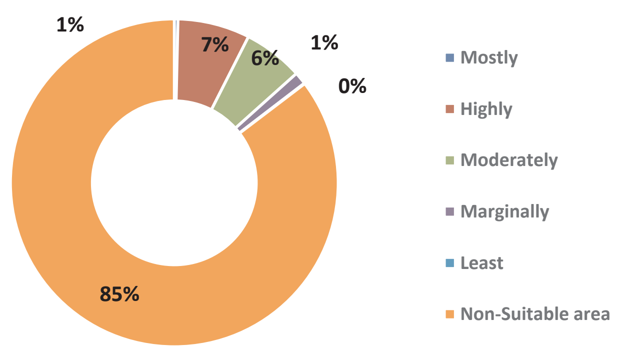


Fig. 15. Suitability Index distribution for equal weights scenario.

Table 11
Land suitability distribution considering different scenarios with respect to study area.

Scenario	Weights	Land suitability distribution (%)				
		5 (Most suitable)	4	3	2	1 (Least suitable)
AHP	Tech. = 0.57 Eco. = 0.43	0.42	8.01	5.29	1.02	0.01
Equal weights	Tech. = 0.5 Eco. = 0.5	0.36	7.12	5.90	1.22	0.06
Higher economic weights	Tech. = 0.2 Eco. = 0.8	1.25	7.67	4.85	0.86	0.08

in the proposed model include the amount of solar irradiation, yearly average temperature, slope, land aspects, and proximity to power lines, major roads, and urban sites. The methodology successfully generates a land suitability index for potential sites where implementing utility-size grid-connected PV power plants are ideal. Our study for Saudi Arabia case indicates that most suitable areas are found north and northwest of the study area as well as west of Taif city near the west coast. High suitability areas comprise 50% of the suitability areas and are mainly spread around the central region. This location will be important to consider for grid connected utility-scale PV power plants since it is one of the most populated areas in Saudi Arabia. The eastern region of the study area shows moderate to high LSIs since it has a decent infrastructure together with the high density of high solar irradiation. More detailed survey for each region will be a direction for future work. These techniques can help Saudi Arabia and other countries to achieve their RES portfolio goals towards a more sustainable energy future.

The main advantage of this research is exploiting the existing resources and infrastructure to provide needed power to the cities in harmony with the environment. The solar analyst modeling in ArcGIS used to generate solar irradiation maps is a very powerful tool due to its flexibility to embed real atmospheric parameters. In addition, actual temperature measurements are considered from sensors spread across the country, and the average yearly temperature is interpolated using the spline tool in ArcGIS. Considering a small number of points for the

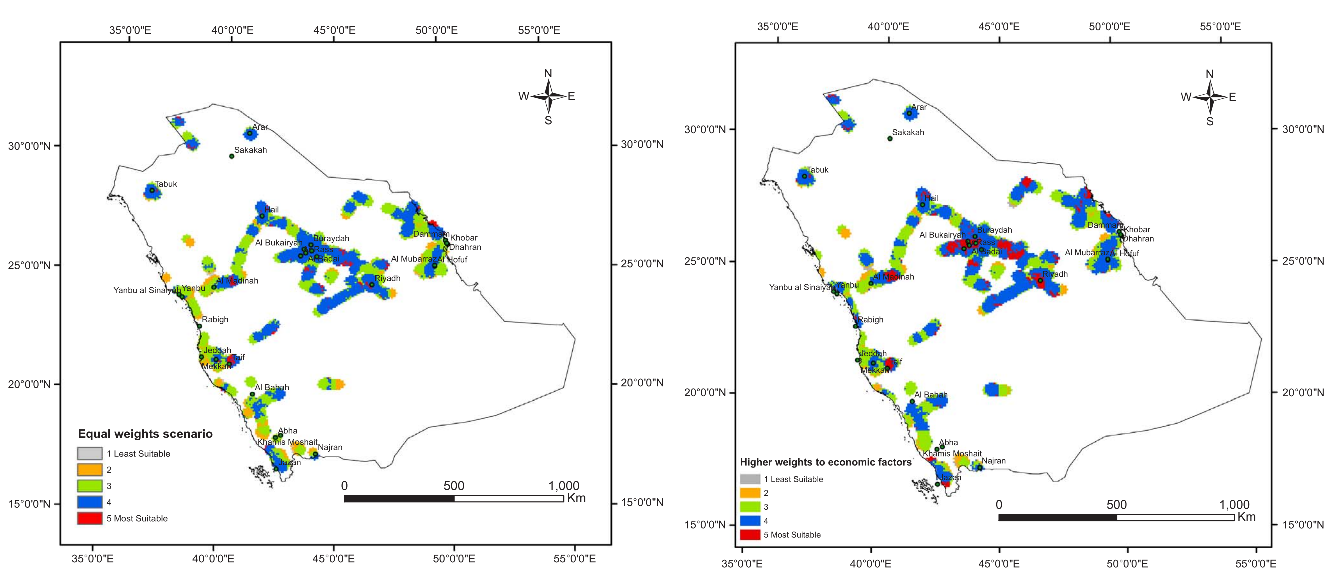


Fig. 16. Land suitability results considering equal weights criteria (left) and higher weights to economic factors (right).

temperature interpolation process could be a limitation of our study which may reduce the accuracy of the temperature layer. Currently, research is actively being conducted on solar resources; however, our results describe for the first time the solar site suitability in Saudi Arabia employing MCDM methods.

In future research, tackling hybrid systems including more than one RES, such as solar PV-wind and solar-biomass could lead to cost effective and technically feasible RES projects. Moreover, applying new techniques as well performing a comparative analysis of such techniques towards an insightful understanding of the best approach, are potential directions for future research. Furthermore, it would be interesting to include other decision criteria to enrich the proposed model, such as population growth, heritage sites, vegetation distribution, and visual impact. Sandstorms, which are a common phenomenon in arid and deserted areas, have a significant impact on PV performance, and therefore avoiding these areas is a crucial factor for more efficient PV systems. Furthermore, considering real long-term data from solar monitoring sensors across the country could enhance the solar irradiation modeling in ArcGIS.

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