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Optimal Decision-Making in Photovoltaic System Selection in Saudi Arabia

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Abstract: In this study, optimal decision-making process in photovoltaic (PV) system location selection in Saudi Arabia is described. First, to identify the criteria that influence the decision of selecting a suitable location for the PV system, the geographical information system (GIS)-based multi-criteria decision making (MCDM) approach is used. Next, to assess the weights of the criteria that present different aspects of the investigated locations, four major criteria and 11 sub-criteria are proposed, and analytic hierarchy process (AHP) is applied to develop comparison decision matrix. Finally, the order preference by similarity to ideal solution (TOPSIS) technique evaluates and classifies 17 cities (such as Riyadh, Jeddah) in Saudi Arabia. The result shows that Tabuk city in the northern of Saudi Arabia is the best location. Among the 17 cities, the performance score of seven cities is above or equal 80%, and Tabuk city has the highest score with 87%. This analytical approach could contribute as an early planning to locate suitable sites for the selection of PV system region in Saudi Arabia.

Keywords: PV system location; geographical information system (GIS); multi-criteria decision making (MCDM); analytic hierarchy process (AHP); the order preference by similarity to ideal solution (TOPSIS)

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1. Introduction

Saudi Arabia is the biggest electricity provider in the Middle East and northern Africa region. The total capacity of the power generation reached 76.9 GW in 2018, while the total load peak reached 61.7 GW [1]. The electrical power demand in Saudi Arabia is growing on an annual basis, which results in burning more barrels of carbon-based fuel, and oil burning to produce electricity, which has a harmful effect to the economy of Saudi Arabia as the oil is recognized as the backbone of the economy. Moreover, the general health will be affected as well due to the emission of the CO_2 gaseous [2]. Therefore, Saudi Arabia has stepped toward a big transformation of changing the current situation of full dependency on oil to new horizons of exploring other sources of renewable energies. Among all the renewable resources of energy, the PV solar energy is the most attractive one to be harnessed in Saudi Arabia. Fortunately, the geographical location of Saudi Arabia is one of the best for solar insolation in the world. The average daily global horizontal irradiance (GHI) received by the lands of Saudi Arabia, is about 6.2 kWh/m^2 with a clear sky during the year [3]. Moreover, the costs of manufacturing the PV modules has decreased globally during the current decade to an attainable limit, whereas the life span of the modules has increased to reach almost to 30 years [4]. The total installed capacity of a PV solar energy indicator is a growing arrow over time, as it was 40.3 GW in 2010 and went up to 480.6 GW in 2018. Nevertheless, more capacities are expected to be installed in the coming decade to generate approximately 3278 TWh by 2030, which is almost six times the 585 TWh generated in 2018 [5].

The warm climate of Saudi Arabia and the high temperature at the PV module surface may cause a decrease in the module performance [6]. Power flow from the PV system in a direction opposite that of conventional power flow may lead to changes to network voltage profiles and are perhaps in violation of node voltage limits, a reduction or an increase in line losses, and increased fault current levels [7]. Thus, the integration of large-scale PV systems to the existing electrical power networks of Saudi Arabia could have positive or negative impacts on the network, depending on the network configuration and the solar resource of the location. The importance of creating new regulations and policies to integrate a large scale of solar systems with the existing network in Saudi Arabia is highly required. Likewise, conducting research studies by the aid of developed software programs and tools to analyze the potential risks, to evaluate the technical impacts from/on the existing network and to study the economic feasibility of constructing such projects will surely pave the road for the decision makers to choose the suitable decision. To formulate appropriate policies and regulations, the decision makers require data on the impacts of network integration of the PV systems under the meteorological conditions of the country. It means that the PV system location problem needs to solve those related elements to overall goals and for evaluating alternative solutions. The analytic hierarchy process (AHP) is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. The AHP method is used widely in integration with GIS for assigning weights to the criteria and analyzing data in many studies due to its solidity of the analysis procedure [6,8–20]. The technique for order of preference by similarity to ideal solution (TOPSIS) is a different approach and an important MCDM technique as well. The authors in [9,11,12,15] have proven the value of utilizing the TOPSIS technique, integrated with GIS, in the data analysis process of evaluating the location of the PV system. However, there are very few detailed studies conducted to assess the impact of network integration of the large-scale PV systems in Saudi Arabia or to justify the benefits of building such projects [21–24]. Through references, there are many studies to use AHP and TOPSIS approaches for PV system location, but this article suggests 11 characterized criteria for Saudi Arabia such as solar irradiation and dust storms and applies 17 locations such as Riyadh, Jeddah, etc., in Saudi Arabia. In this paper, the selection of the optimal site for installing the PV system in Saudi Arabia is studied by the following means:

- Environmental, location, climate and orographic criteria are proposed to identify the suitable locations by a GIS based multi criteria decision making techniques (MCDM).
- To obtain the weights of the criteria which influence the proposed locations, the analytic hierarchy process (AHP) is used. Then, the suitable locations will be evaluated and classified using one of the multi-criteria decision methods, The technique for order preference by similarity to ideal solution (TOPSIS).

This paper is composed as follows. Section 2 presents the literature review and selection methodology. In the literature review, references are classified as four major criteria and 11 sub-criteria and assessment of the weighting and analysis method. In selection methodology, GIS-MCDM for criteria and restriction date collection, AHP for criteria weighting, and TOPSIS for performance matrix generation and evaluation are explained. Section 3 provides results that shows optimum region of Saudi Arabia to host PV system facilities. Finally, the conclusion is given in Section 4.

2. PV System Site Selection

The selection of a suitable site is the basic important step towards developing a feasible and efficient PV System project. The process of conducting a solar site analysis considers decision criteria and restriction factors that may have technical, financial, social, and environmental impacts [25]. However, it was recognized by many researchers that site selection along with careful design, allow the impacts to be mitigated [26]. It is a crucial, strategic step for Saudi Arabia to document as much as possible of potential sites for which certain criteria are applied to achieve the highest possible production with less negative impacts as possible. Therefore, when it comes to solar farm site selection, there are two key tools available to the decision maker: MCDM techniques and GIS software [8]. Their complimentary nature makes them very useful tools in the analysis process of selecting the best potential site [9].

MCDM is a form of a numerical integrated technique that can provide solutions to evaluate the sustainability. In addition, it helps to deal with the operations of decision making, in the presence of multiple alternatives featuring high uncertainty. However, a decision-maker is required to choose among those alternatives, which usually contain complex problems, conflicting objectives, and different forms of data. Therefore, the solution is highly dependent on the preferences of the decision-maker and it is normally aimed at identifying the most efficient options at a low cost. In most of the cases, several decision-makers cooperated to identify the criteria. Each group brings along different criteria and points of view that must be resolved within a framework of understanding and mutual compromise [27].

A GIS can be defined as an information system that is designed to work with spatially referenced data. Furthermore, it can deal with those data, by analyzing, storing, modeling, managing, and mapping them [9].

However, employing MCDM techniques, integrated with GIS, leads to choose the suitable decision regardless the effect of many factors in the decision process. Hence, the site selection of large-scale PV system, depending on the analyzed data by GIS and MCDM techniques, offers significant advantages as follows [28]:

- Enhancing the performance of the system; if the site has suitable climate conditions such as high solar irradiance, moderate temperatures, and long days hours per year.
- Optimizing the installations by building the PV system on a flat ground, facing the south and avoiding the shadow.
- Minimizing the cost impact; if the system is built near urban areas, power transmission and constructed roads are the main consumption points.
- Reducing the impact on the environment, society, and infrastructures.

2.1. Literature Review

The main objective of the literature review in this section is to emphasize the common decision criteria in this research and to avoid the restriction factors, to highlight the MCDM methodology for criteria weighting and analysis technique to find the best alternative location. In fact, in most of the solar PV site analysis studies, decision criteria for site selection fall into general major criteria, and each general criterion contains sub-criteria as shown in Table 1.

Table 1. Reference classification by four major criteria and 11 sub-criteria.

Major Criteria	Sub-Criteria	References
Climatic	Solar irradiation	[6,9,10,12–16,29–35]
	Average temperature	[6,9,10,12,15,29,33–35]
	Relative humidity	[17,18,36]
	Wind speed	[18,33,34,36]
	Dust storm	[37]
	Sun hour duration	[17,18,33,34,38]
Orography	Slope	[6,9,12,13,15,29,32]
	Aspect angles	[15,26,27,35,39]
	Plot area	[9,12,15,29]

Table 1. *Cont.*

Major Criteria	Sub-Criteria	References
Location	Distance from residential areas (m)	[6,8,9,11–13,15,17,29–31]
	Visual impact	[9,30]
	Population density	[40–43]
	Distance to power lines	[8–10,12–15,29–31,33,34,40,41,43]
	Distance to historical areas	[8,37]
	Distance to wildlife designations	[8,16,37]
	Distance to main roads	[8–15,29,40,43]
	Land cover	[40]
	Distance to substations	[9,12,15,29]
Economic	Land cost	[41]
	Construction cost	[41]
Environmental	Carbon emission savings	[44]
	Agrological capacity	[9,12,29]

However, not all the criteria have the same weight of importance. Therefore, the criteria should be selected based on the subjective circumstances and accessibility to the database [10]. Moreover, the selected criteria should not exceed more than 15 criteria to avoid the complexity of the analysis [39]. Most of the criteria are associated with essential factors and boarders that guarantee the quality and the efficiency of the PV system plant location. It is important that to receive high solar irradiation in the location, acceptable distance, and connections to a grid point source, as well as taking into account the environmental conditions for the installation in the area [11]. In the literature, there are several studies that specified a wide range of the determinant factors that must be avoided during the plan of choosing the optimum location of the PV system plant. The authors of [37] have advised that high risk or frequency areas, which resulted from natural or weather conditions like wildfires, earthquake, dust storm and flash floods, are hazard zones for PV development. Flat areas without shadows are a most preferable location for installing PV system projects, so as per [45], hills or big mountains, lakes, sand dunes, permanent snow areas and natural forest are restricted due to their location or topographic status. In [29], the restriction factors should include military zones, cattle trails, watercourses and streams, archaeological sites, paleontological sites, cultural heritage, railroad network, and community interest sites. In fact, the restriction factors can go beyond the geographical conditions as it is mentioned in [30] that, the unavailability of skilled manpower, noise and visual negative impact, and toxin emissions can be considered as restricted factors as well. However, as the restriction factors are specified, the major role of GIS-analysis is to exclude those areas that are unsuitable for installing large-scale solar power plants.

After defining the problem, identification of alternatives, criteria selection, and restriction factors determination, MCDM are also important methods for assigning weights to the criteria and analyzing data with the aid of GIS. Table 2 shows various MCDM methods classification in the references.

The authors of [12,29] analyzed technique in integration with GIS. They have concluded how it is worth to utilize the field of renewable energy system location identification. The author in [46] shows that two-sided matching decision making (TSMDM) problems exist widely in the daily lives of humans. An approach to TSMDM with multi-granular hesitancy and thus provide hesitant fuzzy linguistic term sets is developed and an example for the matching of green building technology supply and demand is provided to demonstrate the characteristics of the proposed approach. In fact, only one study in the literature that utilized the GIS-MCDM integration technique identified the best location of PV system in Saudi Arabia by considering five criteria only [6]. Therefore, it is of vital contribution for this research to be one of the first studies to utilize the GIS-MCDM integration technique in Saudi Arabia to find the best location of the large-scale PV system by using different approaches than the other conducted researches.

Table 2. MCDM methods classification in the references.

RES Technology	Site Location	Weighting Method	Analysis Method	References
PV	Saudi Arabia	AHP	WSM (Weighted Sum Model)	[6]
PV-CSP-Wind	Southern England	AHP	AHP	[8]
PV	Murcia, Spain	AHP	TOPSIS	[9]
PV	Oman	AHP	FLOWA(Flow Analysis)	[10]
PV	Brazil	AHP	TOPSIS	[11]
Solar Thermoelectric	Murcia, Spain	AHP	Fuzzy TOPSIS-ELECTRE	[12]
PV	Konya, Turkey	AHP	AHP	[13]
PV	Eastern Morocco	AHP	AHP	[14]
PV	Murcia, Spain	AHP	TOPSIS-ELECTRE TRI	[15]
PV	South Korea	Fuzzy Set	AHP	[16]
PV	Serbia	AHP	AHP	[17]
PV	Northwest cost of Egypt	AHP	WSM (Weighted Sum Model)	[18]
PV-CSP	Tanzania	AHP	AHP	[19]
PV-CSP-Wind	China	AHP	AHP	[20]
PV	Murcia, Spain	ELECTRE TRI	ELECTRE TRI	[29]
PV	India	AHP	Fuzzy TOPSIS	[30]
Hybrid	Western Turkey	Fuzzy	OWA (Ordered Weighted Averaging)	[31]
PV-CSP-Wind	Colorado, USA	WLC	WLC	[40]
PV	Northwest China		Grey cumulative	[44]
PV-CSP-Wind	Afghanistan		WLC(Weighted Linear Combination)	[45]

2.2. *Selection Methodolgy*

This section explores, investigates, and evaluates the optimum location of a large-scale grid connected PV system among 17 cities distributed all over the Saudi Arabia country. The access to the available geodatabase is the limitation of the research expansion. The proposed framework is presented in Figure 1, and summarizes as the following steps:

- Identifying the criteria that influence the decision of selecting the PV plant location.
- Loading the geodata of the identified criteria into the GIS. The important restriction inputs are applied to discard the unsuitable locations.
- Applying the AHP technique for determining the criteria weights, based on the relative importance of each one.
- Evaluating the remaining alternatives using TOPSIS analysis method.

2.2.1. Criteria and Restrictions

Since each region has different environmental, cultural, climate, orography, political, and economic aspects, the following 11 sub-criteria and four major criteria suggested in this study research are: solar irradiation; average temperature; relative humidity; dust storm; distance to power lines; distance to main roads; distance to residentials areas; slope; orientations (aspect angles); population density; and carbon emissions reduction. These sub-criteria were subset of four major criteria: environmental; location; climate; and, orographic, as shown in Figure 2. The explanation of each factor is presented in the following:

- Solar irradiation (m1): The continuous operation of a PV plant depends on the received solar irradiance, the annual solar radiation is considered as a climatic factor which is used to measure the intensity of sunshine for a candidate site and is normally expressed as an average of several years. The PV power output is related proportionally to the solar radiation. In this study, the annual average daily solar irradiation was calculated for all the locations chosen using PVGIS, which is a web-based calculator developed by the JRC (Joint Research Centre) of the European Commission.

- Average temperature (m2) and relative humidity (m3): As the temperature increases, the output power and the efficiency of the modules decreases [18]. In the contrary, high relative humidity is unlikable for PV module efficiency. Both descend factors are classified as climatic factors too. In this study, the data of the annual temperature and relative humidity were driven from the new network monitoring systems which have been developed by K.A. CARE as part of the Renewable Resource Monitoring and Mapping (RRMM) program.
- Dust storm (m4): The third climatic factor in this study is the dust storms. The Arabian Peninsula has been recognized as one of the five world regions where sand and dust storm generation are especially extreme [47]. Thus, this factor cannot be neglected in regions that have a climate such as Saudi Arabia. In this study, the data of the dust storm frequencies were driven from the presidency of the meteorology and environment of Saudi Arabia over the period of 2013–2016.
- Slope (m5) and orientations (aspect angles) (m6): The slope and aspects of the land are crucial topographical factors which play a considerable role for land suitability for PV system location [37]. Therefore, a land with a slope of more than 5 degree and non-south facing will be eliminated in order to avoid the shadow effect on the generation of the PV system [10]. In this study the data of slope and topographic orientation of Saudi Arabia have been downloaded as a digital elevation data form Alaska Satellite facilities database.
- Distance to power lines (m9), main roads (m10), and residentials areas (m7): The three mentioned sub-criteria here are sometimes classified as a location criterion and economic criterion. Generally, the importance of a solar power plant being close to the road network is for facilitating the transportation of modules and equipment, and the maintenance during and after the construction phase [14]. Moreover, it has to be close enough to residential areas and to the electrical grid to supply the electricity and to avoid constructing new power transmission lines [25]. In this study, the data of the power lines locations were collected from the internal website of Saudi Electricity company, and from KAPSARK data portal for the main roads, and Google Maps for residentials areas. A buffer distance restriction of 2 km for power lines, 0.5 km for main roads, and 50 km for residential areas has been applied to get an optimum location of the PV system.
- Population density (m8): is the fourth sub-criteria that classified as a location criterion. The establishment of a solar system must be close enough to a location that has adequate consumers and well skilled manpower to lower the cost of employing nonlocality manpower to construct, operate and maintain the PV system [30,41]. In this study, the data of the population for each alternative has been derived from KAPSARK data portal.
- Carbon emissions reduction (m11): is one of the critical sub-criteria that classified as an environmental criterion. Many studies discussed the carbon emission savings in terms of the manufacturing supply chain [44]. In this study, a different approach in minimizing the carbon emissions is considered by installing the PV system in the locations that have higher emissions of CO_2. Thus, the data of total CO_2 of power plants which are speared all over Saudi Arabia has been derived from the KAPSARK data portal and Google Maps.

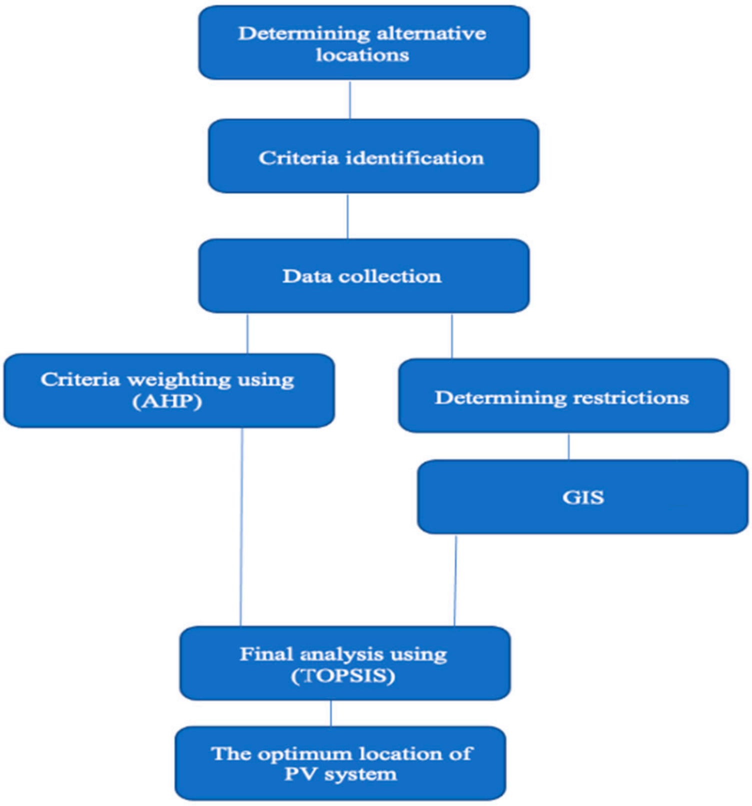

Figure 1. The flowchart of the proposed process.

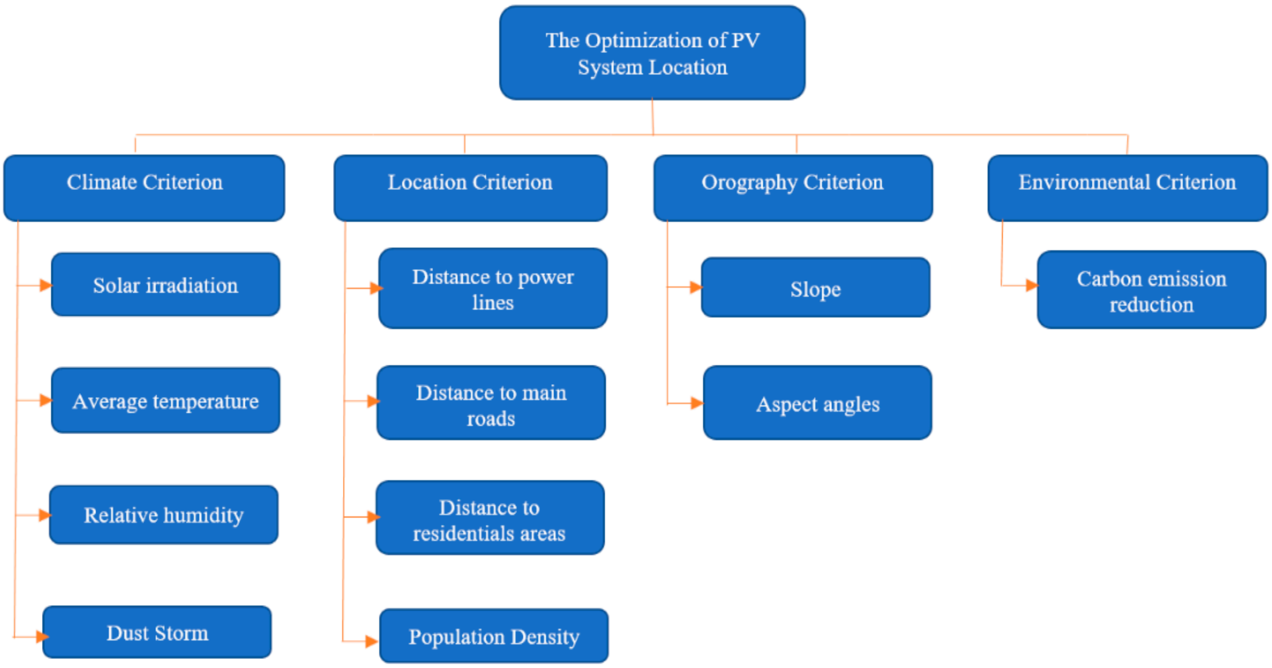

Figure 2. The major and sub-criteria classifications.

The area of Saudi Arabia is big enough to host large solar system projects, as its area is almost 2.15M km^2. Therefore, once the problem has been defined, we must solve the problem of identifying various alternatives. GIS is a suitable tool that can be employed to enable us to obtain such alternatives and considering the criteria and restrictions which are mentioned in Section 2.2 and Figure 2 that affect the study area. These alternatives represent the suitable surface area available in Saudi Arabia to host these facilities after eliminating the restricted areas and are defined in plots of Figures 3 and 4.

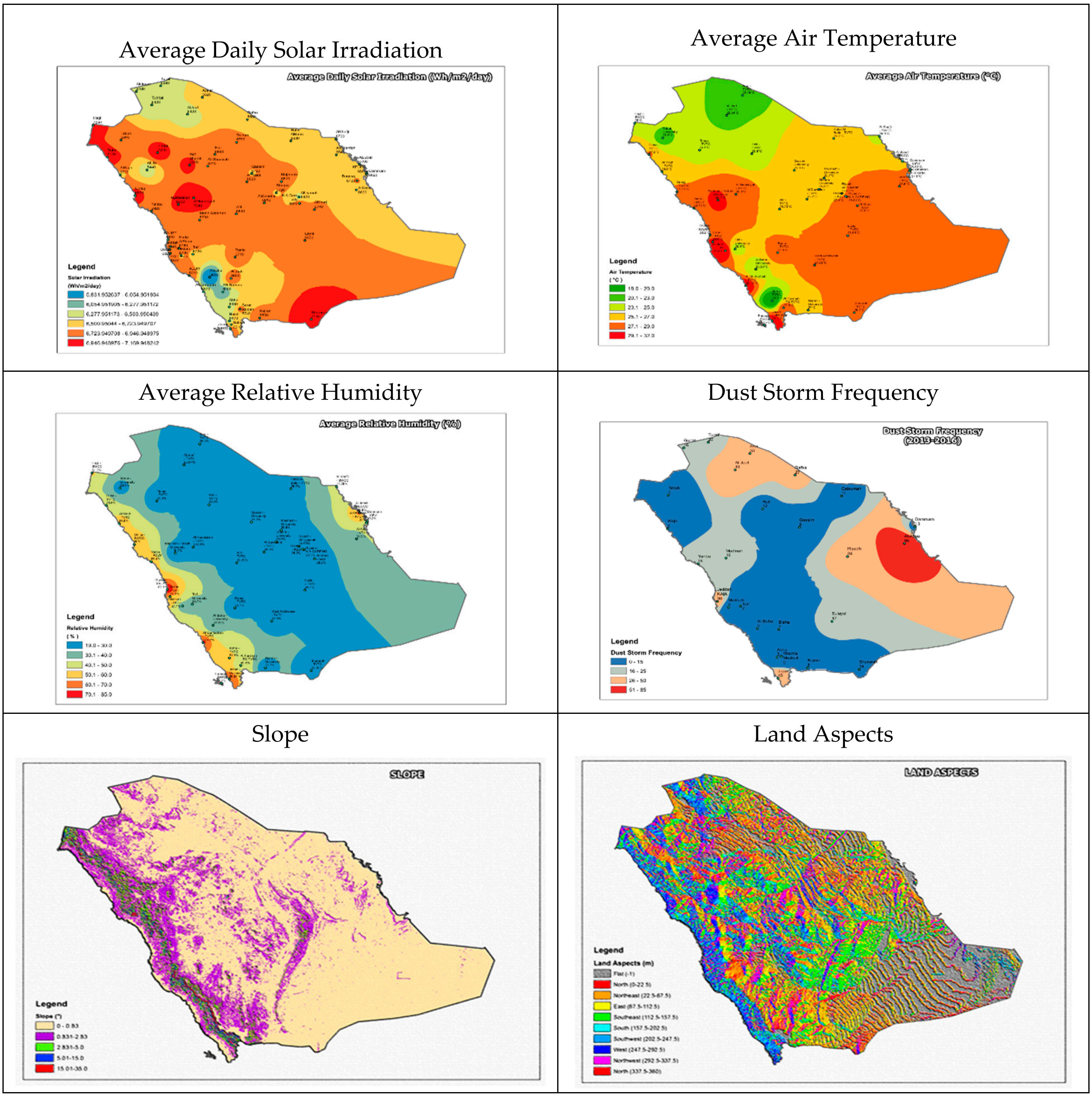

Figure 3. The generated GIS maps after applying the restriction factors.

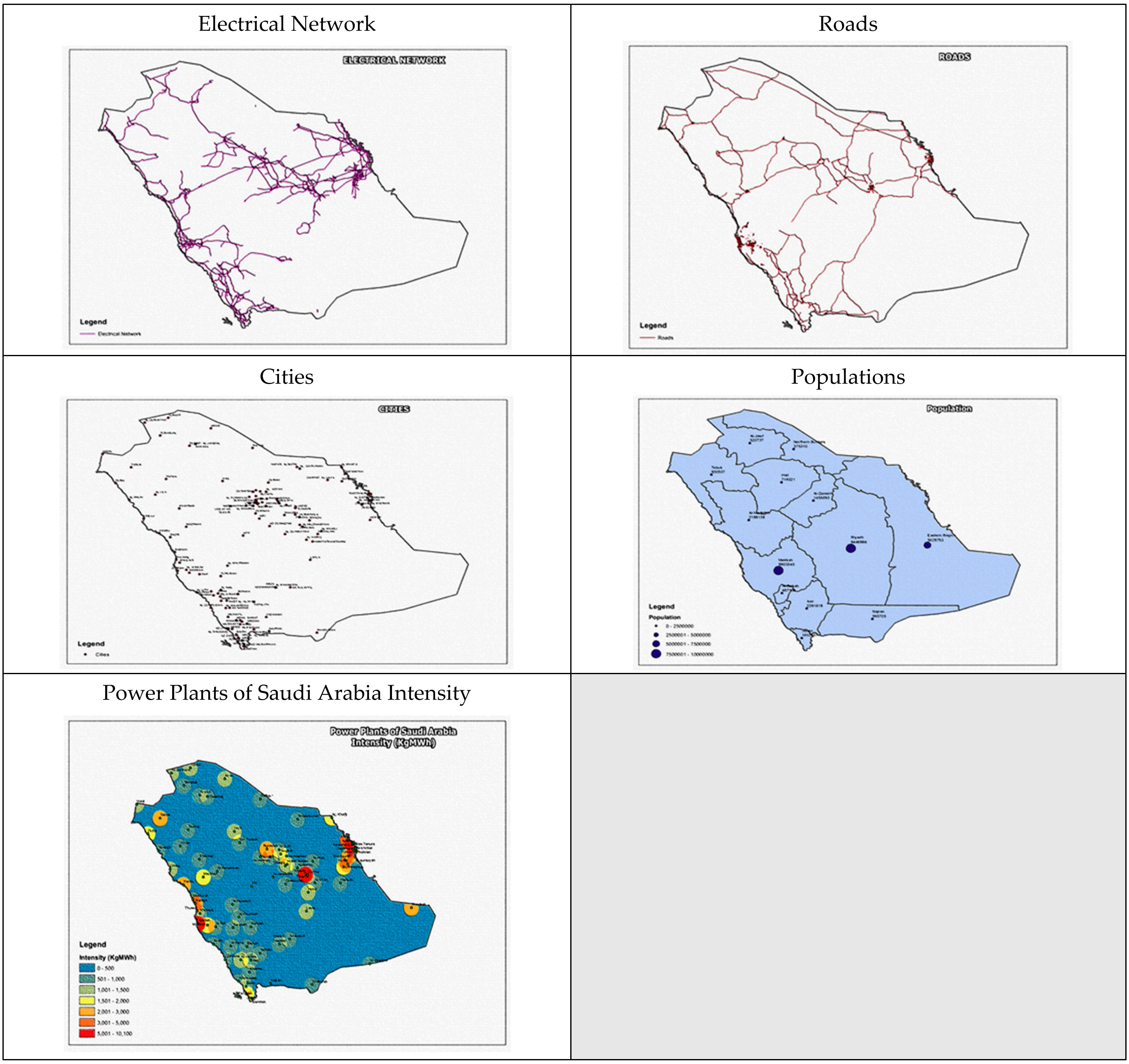

Figure 4. The generated GIS maps after applying the restriction factors.

The decision matrix is generated as a form of B = (n × m), where n represents the number of the selected alternatives and m represents the number of the selected criteria listed in Section 2.2.1. Seventeen alternatives (cities) have accessible data and satisfied the purpose of this study. In Table 3, the entry values b_{ij} which represent the collected data value of the corresponding criterion i_{th} (row), at the alternative location j_{th} (column) are presented.

Table 3. The decision matrix.

	m1 ($Wh/m^2/d$)	m2 (C°)	m3 (%)	m4 (#)	m5 (°)	m6	m7 (Km)	m8 (people)	m9 (Km)	m10 (Km)	m11 (Kg)
Abha	6330	18.7	51.8	3	2	South	50	236,157	2	1	405,314,000
Al-Ahsa	6630	28.5	30.5	85	2	South	50	660,788	2	1	661,633,000
Al-Baha	5830	23.56	30.95	0	2	South	50	95,089	2	1	3,278,570
Arar	6620	22.16	26.1	33	2	South	50	167,057	2	1	173,546,300
Dammam	6620	26.82	49.2	13	2	South	50	903,312	2	1	26,974,200
Hail	6860	23.8	20.9	12	2	South	50	310,897	2	1	97,083,250
Jeddah	6740	28.2	82.1	30	2	South	50	3,430,697	2	1	5,563,960,870
Jizan	6910	30.1	69.84	45	2	South	50	127,743	2	1	313,196,200
Madinah	6950	29.7	19.7	18	2	South	50	1,100,093	2	1	157,041,430
Makkah	6720	31.4	37.1	6	2	South	50	1,534,731	2	1	95,244,410
Najran	6800	27	21.7	6	2	South	50	298,288	2	1	314,453,000
Qaisumah	6630	26.7	25.7	11	2	South	50	22,538	2	1	160,493,000
Qassim	6720	26.5	21.3	6	2	South	50	467,410	2	1	1,905,935,400
Riyadh	6840	27.9	25.2	28	2	South	50	5,188,286	2	1	1,954,276,620
Tabuk	6840	22.5	26.4	0	2	South	50	512,629	2	1	6,387,374,830
Taif	6720	23.9	35.7	2	2	South	50	579,970	2	1	481,743,000
Yenbo	6920	28.15	56.4	24	2	South	50	233,236	2	1	1,010,612,100

2.2.2. Criteria Weighting Using AHP Technique

To assess the plots of Figures 3 and 4 based on the criteria that have been mentioned in the Section 2.2.1, the weights of the criteria must be obtained. Thus, for this purpose, the analytical hierarchy process (AHP) technique that was created by Saaty [48] is used. The main concept behind this technique is to develop a comparison decision matrix that allows to compare each criterion with its pair, by applying certain calculations and procedures, to obtain consisted weights for each criterion. The following steps explains the required AHP procedure to obtain the criteria weights:

A. Pairwise comparison scaling:

Table 4 shows and describes the pairwise comparison scaling values of the criteria and the meaning of each value. The scale starts from 1 to 9, as Saaty suggested [48], which basically represents the relative importance for each criterion.

Table 4. The importance pairwise comparison scaling.

The Importance Scale (a_{ij}) of The Criteria	The Description
1	Criteria *i* and *j* are of equal importance
3	Criteria *i* is slightly more important than *j*
5	Criteria *i* is moderately more important than *j*
7	Criteria *i* is strongly more important than *j*
9	Criteria *i* is extremely more important than *j*
2, 4, 6, 8	Intermediate values

B. Pairwise comparison matrix (A):

The pairwise comparison matrix is generated as a form of a square matrix A = $(m \times m)$, where m represents the number of criteria. In the comparison process, the entry value a_{ij}, which represents the comparison value between the i_{th} (row) criterion relative to the jth (column) criterion, must achieve the condition in the following Equation (1). The comparison matrix was applied to all the criteria listed in Section 2.2.1 as shown in Table 5.

$$a_{ij} \times a_{ji} = 1 \quad (1)$$

Table 5. The pairwise comparison matrix.

	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11
m1	1.00	2.00	5.00	3.00	3.00	7.00	7.00	8.00	4.00	5.00	9.00
m2	0.50	1.00	4.00	2.00	2.00	6.00	6.00	7.00	3.00	4.00	8.00
m3	0.20	0.25	1.00	0.33	0.33	3.00	4.00	5.00	3.00	4.00	5.00
m4	0.33	0.50	3.00	1.00	1.00	4.00	5.00	6.00	5.00	6.00	7.00
m5	0.33	0.50	3.00	1.00	1.00	4.00	5.00	6.00	5.00	6.00	7.00
m6	0.14	0.17	0.33	0.25	0.25	1.00	1.00	2.00	0.50	0.33	3.00
m7	0.14	0.17	0.25	0.20	0.20	1.00	1.00	2.00	0.50	0.33	3.00
m8	0.13	0.14	0.20	0.17	0.17	0.50	0.50	1.00	0.25	0.33	2.00
m9	0.25	0.33	0.33	0.20	0.20	2.00	2.00	4.00	1.00	2.00	5.00
m10	0.20	0.25	0.25	0.17	0.17	3.00	3.00	3.00	0.50	1.00	4.00
m11	0.11	0.13	0.20	0.14	0.14	0.33	0.33	0.50	0.20	0.25	1.00
Sum	3.34	5.43	17.57	8.46	8.46	31.83	34.83	44.50	22.95	29.25	54.00

C. Comparison matrix normalization ($\overline{a_{ij}}$):

To establish a normalized pairwise comparison matrix A, it has to be done by dividing each entry value a_{ij} with the sum of the entry values in the belonging column as shown in Table 6 by using the following Equation (2):

$$\overline{a_{ij}} = \frac{a_{ij}}{\sum_{l=1}^{m} a_{lj}} \quad (2)$$

Table 6. The normalized pairwise comparison matrix.

	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11
m1	0.30	0.37	0.28	0.35	0.35	0.22	0.20	0.18	0.17	0.17	0.17
m2	0.15	0.18	0.23	0.24	0.24	0.19	0.17	0.16	0.13	0.14	0.15
m3	0.06	0.05	0.06	0.04	0.04	0.09	0.11	0.11	0.13	0.14	0.09
m4	0.10	0.09	0.17	0.12	0.12	0.13	0.14	0.13	0.22	0.21	0.13
m5	0.10	0.09	0.17	0.12	0.12	0.13	0.14	0.13	0.22	0.21	0.13
m6	0.04	0.03	0.02	0.03	0.03	0.03	0.03	0.04	0.02	0.01	0.06
m7	0.04	0.03	0.01	0.02	0.02	0.03	0.03	0.04	0.02	0.01	0.06
m8	0.04	0.03	0.01	0.02	0.02	0.02	0.01	0.02	0.01	0.01	0.04
m9	0.07	0.06	0.02	0.02	0.02	0.06	0.06	0.09	0.04	0.07	0.09
m10	0.06	0.05	0.01	0.02	0.02	0.09	0.09	0.07	0.02	0.03	0.07
m11	0.03	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02

D. Compute the overall weight vector (w_i):

The overall weight vector w_i can be calculated by taking the average for each row in the matrix as shown Table 7 by using the following Equation (3):

$$w_i = \frac{\sum_{l=1}^{m} \overline{a_{il}}}{m} \quad (3)$$

Table 7. The overall weight vector w_i.

m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11
0.25	0.18	0.08	0.14	0.14	0.03	0.03	0.02	0.06	0.05	0.02

E. Comparison matrix consistency verification:

Finally, to verify the consistency of the pairwise comparison matrix, the consistency ratio (CR) must be calculated. If CR < 0.1, the calculation consistency is acceptable to be used in the analysis, but if CR > 0.1, the procedure must be revised to find the reason of the inconsistency and correct it. CR is given in the following Equation (4):

$$CR = \frac{CI}{RI}, \tag{4}$$

where (RI) is the random index and (CI) is the consistency index and can be calculated by using the following Equation (5):

$$CI = \frac{\lambda_{max} - m}{m - 1}, \tag{5}$$

where λ_{max} is the maximum eigenvalue of the comparison matrix and m is the number of criteria in the comparison matrix. The λ_{max} is calculated as the average of the elements of the vector whose i_{th} element is the ratio of the i_{th} element of the vector ($A \cdot w_i$) to the corresponding element of the vector (w_i), as shown in Table 8.

Table 8. The maximum eigenvalue of the comparison matrix λ_{max}.

m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11	λ_{max}
12.21	12.32	12.28	12.64	12.64	11.38	11.25	11.33	11.45	11.20	11.56	**11.84**

In Equation (4), the random index (RI) according to Saaty [48], changes subject to the number of the criteria as shown in Table 9.

Table 9. The random index.

m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11	m12
0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54

2.2.3. Technique for Order Preference by Similarity to Ideal Solution

In Section 2.2.2 the criteria weights have been obtained, the next step is to evaluate the alternatives to find the optimum location to host the PV system plant. The technique for order preference by similarity to ideal solution (TOPSIS), which was created by Hwang and Yoon [49], is applied. The fundamental concept of this technique is to find an alternative whose distance from the positive ideal solution is the shortest while the distance from the negative ideal solution is the longest. The computational steps of the TOPSIS method are the following:

A. Performance matrix creation and normalization ($\overline{b_{ij}}$):

Table 3. The decision matrix B is used as a performance matrix for TOPSIS. To establish a normalized performance matrix $\overline{B}$, each entry value x_{ij} is divided with the sum of the squared entry values, under the squared root, in the same column as shown in Table 10 by using the following Equation (6):

$$\overline{b_{ij}} = \frac{b_{ij}}{\sqrt{\sum_{i=1}^{n} b_{ij}^2}}. \tag{6}$$

Table 10. The performance matrix normalization. * Blank control.

	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11
Abha	0.23	0.17	0.30	0.03	0.24	*	0.24	0.04	0.24	0.24	0.04
Al-Ahsa	0.24	0.26	0.18	0.73	0.24	*	0.24	0.10	0.24	0.24	0.07
Al-Baha	0.21	0.22	0.18	0.00	0.24	*	0.24	0.01	0.24	0.24	0.00
Arar	0.24	0.20	0.15	0.28	0.24	*	0.24	0.02	0.24	0.24	0.02
Dammam	0.24	0.25	0.29	0.11	0.24	*	0.24	0.14	0.24	0.24	0.00

Table 10. *Cont.*

	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11
Hail	0.25	0.22	0.12	0.10	0.24	*	0.24	0.05	0.24	0.24	0.01
Jeddah	0.24	0.26	0.48	0.26	0.24	*	0.24	0.51	0.24	0.24	0.62
Jizan	0.25	0.28	0.41	0.39	0.24	*	0.24	0.02	0.24	0.24	0.03
Madinah	0.25	0.27	0.12	0.16	0.24	*	0.24	0.16	0.24	0.24	0.02
Makkah	0.24	0.29	0.22	0.05	0.24	*	0.24	0.23	0.24	0.24	0.01
Najran	0.25	0.25	0.13	0.05	0.24	*	0.24	0.04	0.24	0.24	0.03
Qaisumah	0.24	0.25	0.15	0.09	0.24	*	0.24	0.00	0.24	0.24	0.02
Qassim	0.24	0.24	0.13	0.05	0.24	*	0.24	0.07	0.24	0.24	0.21
Riyadh	0.25	0.26	0.15	0.24	0.24	*	0.24	0.78	0.24	0.24	0.22
Tabuk	0.25	0.21	0.16	0.00	0.24	*	0.24	0.08	0.24	0.24	0.71
Taif	0.24	0.22	0.21	0.02	0.24	*	0.24	0.09	0.24	0.24	0.05
Yenbo	0.25	0.26	0.33	0.21	0.24	*	0.24	0.03	0.24	0.24	0.11

B. Weighted normalized performance matrix ($\overline{B} \times w_i$):

The weighted normalized performance matrix is calculated by multiplying the weight vector w_i by the normalized performance matrix $\overline{B}$ as per the following Equation (7), and the results are shown in Table 11.

$$Z = \overline{B} \times w_i \tag{7}$$

Table 11. The weighted normalized performance matrix. * Blank control.

	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11
Abha	0.055	0.029	0.024	0.004	0.033	*	0.007	0.001	0.013	0.011	0.000659
Al-Ahsa	0.058	0.045	0.014	0.099	0.033	*	0.007	0.002	0.013	0.011	0.001075
Al-Baha	0.051	0.037	0.015	0.000	0.033	*	0.007	0.000	0.013	0.011	0.000005
Arar	0.058	0.035	0.012	0.039	0.033	*	0.007	0.000	0.013	0.011	0.000282
Dammam	0.058	0.042	0.023	0.015	0.033	*	0.007	0.003	0.013	0.011	0.000044
Hail	0.060	0.037	0.010	0.014	0.033	*	0.007	0.001	0.013	0.011	0.000158
Jeddah	0.059	0.044	0.039	0.035	0.033	*	0.007	0.010	0.013	0.011	0.009044
Jizan	0.061	0.047	0.033	0.053	0.033	*	0.007	0.000	0.013	0.011	0.000509
Madinah	0.061	0.047	0.009	0.021	0.033	*	0.007	0.003	0.013	0.011	0.000255
Makkah	0.059	0.049	0.017	0.007	0.033	*	0.007	0.005	0.013	0.011	0.000155
Najran	0.060	0.042	0.010	0.007	0.033	*	0.007	0.001	0.013	0.011	0.000511
Qaisumah	0.058	0.042	0.012	0.013	0.033	*	0.007	0.000	0.013	0.011	0.000261
Qassim	0.059	0.042	0.010	0.007	0.033	*	0.007	0.001	0.013	0.011	0.003098
Riyadh	0.060	0.044	0.012	0.033	0.033	*	0.007	0.015	0.013	0.011	0.003177
Tabuk	0.060	0.035	0.012	0.000	0.033	*	0.007	0.002	0.013	0.011	0.010383
Taif	0.059	0.038	0.017	0.002	0.033	*	0.007	0.002	0.013	0.011	0.000783
Yenbo	0.061	0.044	0.027	0.028	0.033	*	0.007	0.001	0.013	0.011	0.001643

C. Determining the positive and negative ideal solutions (${z_j}^+$ & ${z_j}^-$):

To find the positive ideal solution in the jth (column), find the maximum cell value in the same column of the matrix Z. To find the negative ideal solution in the jth (column) find the minimum cell value z_{ij} in the same column of the matrix Z. Note that this is only true for the beneficial criteria while for the non-beneficial criteria the opposite procedure is to be followed. The desired positive and negative ideal solution are shown in Table 12.

Table 12. The positive and negative ideal solutions. * Blank control.

	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11
${z_j}^+$	0.0609	0.0294	0.0093	0.0000	0.0329	*	0.0069	0.0152	0.0129	0.0111	0.0104
${z_j}^-$	0.0511	0.0494	0.0387	0.0993	0.0329	*	0.0069	0.0001	0.0129	0.0111	0.0000053

D. Finding the Euclidean distance from positive and negative ideal solutions ($S_i{}^+$ & $S_i{}^-$):

This can simply be found through calculating the measurement of the alternatives with respect to $z_j{}^+$ and $z_j{}^-$, as shown in Table 13, by applying Equations (8) and (9):

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(z_{ij} - z_l^+\right)^2}, \quad (8)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(z_{ij} - z_l^-\right)^2}. \quad (9)$$

Table 13. The Euclidean distance from positive and negative ideal solutions.

	Abha	Al-Ahsa	Al-Baha	Arar	Dammam	Hail	Jeddah	Jizan	Madinah
S_{I^+}	0.02	0.10	0.02	0.04	0.03	0.02	0.05	0.06	0.03
S_{I^-}	0.10	0.10	0.11	0.08	0.09	0.09	0.08	0.08	0.09
	Makkah	**Najran**	**Qaisumah**	**Qassim**	**Riyadh**	**Tabuk**	**Taif**	**Yenbo**	
S_{I^+}	0.03	0.02	0.03	0.02	0.4	0.02	0.02	0.04	
S_{I^-}	0.10	0.10	0.09	0.10	0.08	0.11	0.10	0.08	

E. Calculating the Performance score (P_i):

The performance score can be found throughout the calculation of the relative proximity of each alternative to the positive and negative ideal solutions, by dividing the negative ideal solution over the positive and negative ideal solutions, as shown in Table 14, by using the following Equation (10):

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (10)$$

Table 14. The performance scores.

	Abha	Al-Ahsa	Al-Baha	Arar	Dammam	Hail	Jeddah	Jizan	Madinah
P_i	0.81	0.51	0.82	0.65	0.76	0.80	0.63	0.56	0.74
	Makkah	**Najran**	**Qaisumah**	**Qassim**	**Riyadh**	**Tabuk**	**Taif**	**Yenbo**	
P_i	0.78	0.81	0.78	0.82	0.69	0.87	0.83	0.67	

3. Results and Discussion

Once the criteria have been identified, the integrated MCDM-GIS methodology is applied to weight those criteria, to eliminate the restricted locations, and to evaluate the remaining alternatives locations based on the data availability. The AHP technique is used to weight the identified criteria that were mentioned in Section 2.2.1. The given weights, as shown in Figure 5, are consistent and acceptable since the consistency ratio CR was 0.08, a resulting value of Equation (4).

It is obvious that, the climate and the orography criteria have the highest weight over the location and environmental criteria so that solar irradiation, air temperature and humidity, land slope and land aspects have a direct impact of the power production and modules performance of the PV system. TOPSIS technique has been applied to evaluate the 17 alternatives locations with those which were mentioned in Section 2.2.3. The evaluation procedure was accomplished based on the weighted criteria. The performance score for each alternative demonstrated on a scale range (0–1), which is defined in Equation (10), is presented in Figure 6 where Tabuk has the highest score. The results show that the region of Saudi Arabia is very promising to host PV system facilities. All the alternatives locations got evaluation scores above 50% based on the identified weighted criteria.

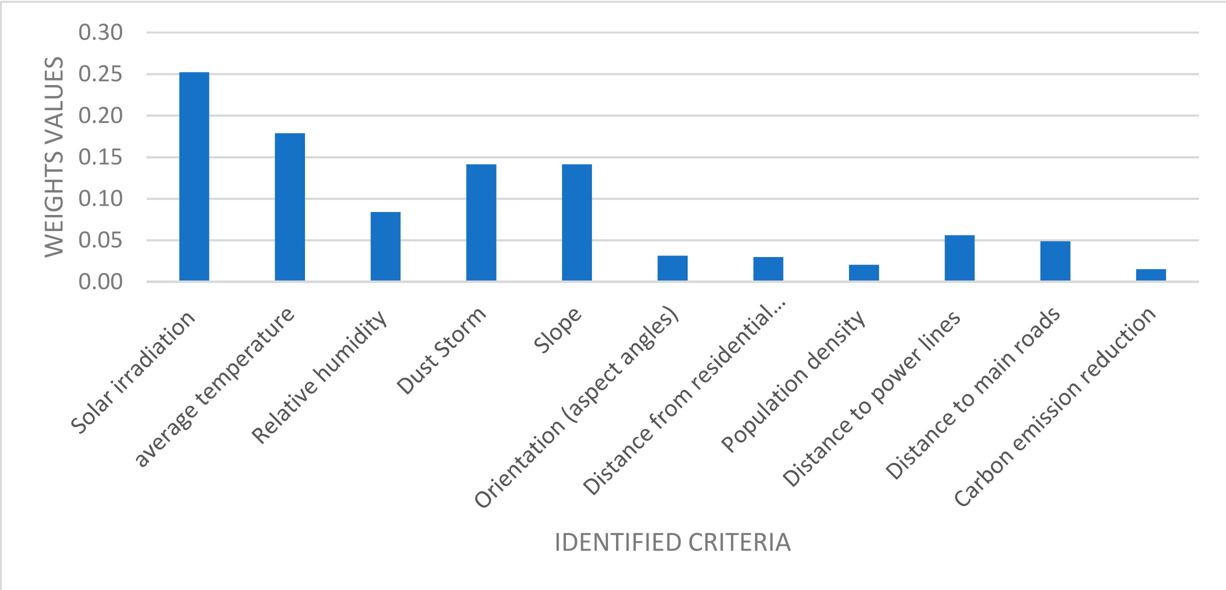

Figure 5. The weights values given to each criterion.

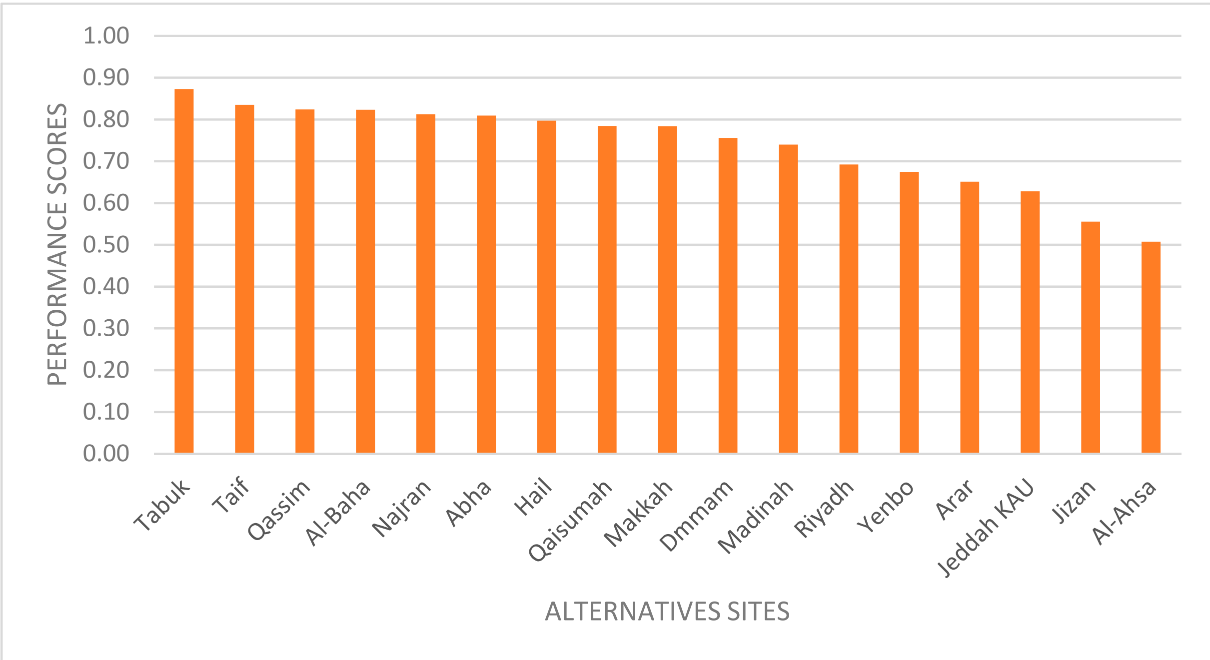

Figure 6. The performance score for each alternative by Rank.

Regions such as Tabuk, Taif, Qassim, Al-Baha, Najran, Abha and Hail are considered to be the most suitable locations since their scores are above or equal 80%. However, there are three cities that scores below 65%, which are Jeddah, Jizan, and Al-Ahsa. That means 82% of the alternative locations can be classified as suitable locations to host PV system facilities since they got performance scores above 65%. Finally, the distribution of the locations is demonstrated on the map shown in Figure 7.

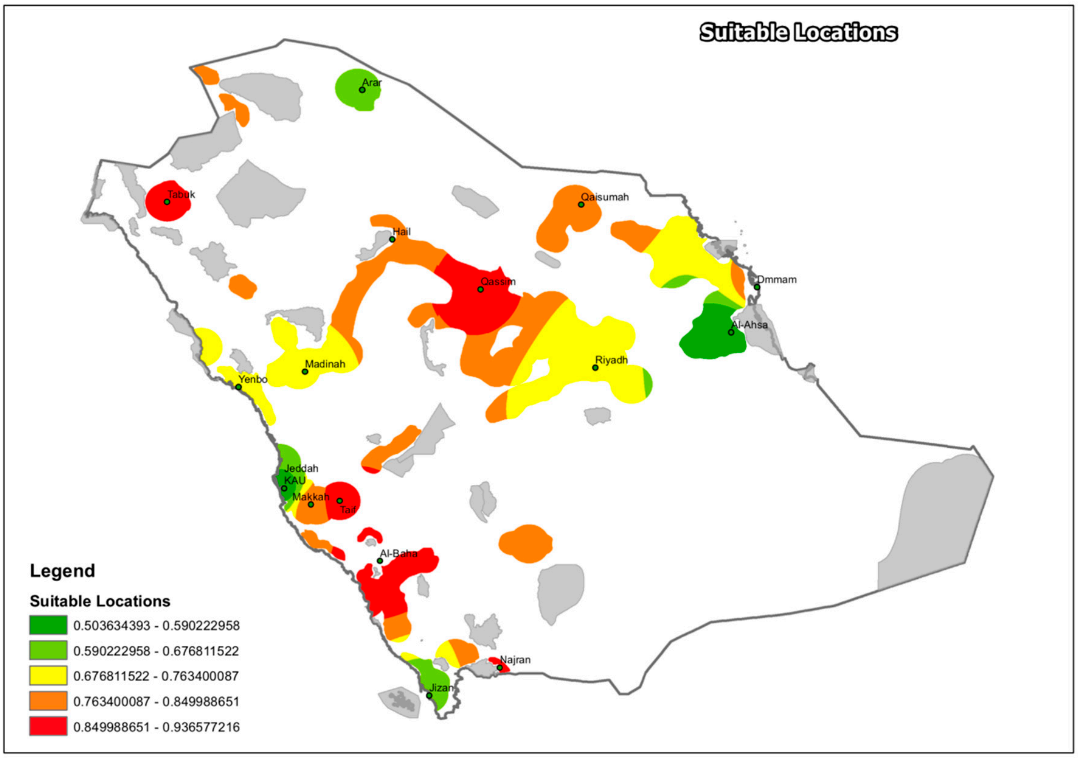

Figure 7. Suitable locations to harvest solar PV system in Saudi Arabia.

4. Conclusions

In this paper, the potential sites to host the PV system facility in Saudi Arabia were examined throughout the application of MCDM techniques integrated with the GIS software tool. The identification of the criteria was comprehensive and included as much criteria as possible, such as climate, location, orography, and environmental criteria with a total of 11 sub-criteria. The weights given to each sub-criterion by using the AHP technique were acceptable since the results of the consistency ratio were less than 0.1. Sub-criteria such as solar irradiation, average temperature, dust storm and slope were given accumulative weights of 71%, which were much higher than the remaining sub-criteria, which is due to their direct technical impact on the power output and the performance of the modules of the PV system. The TOPSIS technique was used to evaluate the alternatives location for the first time in Saudi Arabia. Seventeen sites were analyzed based on the weighted criteria and results of the performance score for each alternative site was optimistic. All of the candidate sites got scores above 50%, out of which seven sites got scores above 80%. The Tabuk site was selected to be the optimum location among all the other alternatives since it got the highest score of 87%. In conclusion, the Tabuk site is the best location to host the Large-Scale PV system grid connected to the network of Saudi Arabia. In the early planning and feasibility study, there are limitations to gathering data and time is needed to evaluate where the suitable location to implement Renewable Energy could be, and this study helps to decide the suitable location for PV site in an early stage. Existing and available GIS information could provide a fundamental data before taking measurements of each region and give a basic direction for the feasibility study. In this article, 17 cities were considered to implement a PV system facility and choose seven sites for a suitable place. It implies that in a practical case, it saves time and budget to select a suitable site for PV implementation. In addition, attention should be given based on local experts' assistance, and more and different criteria should be considered as well. In a future study, the potential technical impact and economic assessment will be investigated for the selected regions after integrating large-scale PV solar system to the electric grid in Saudi Arabia with real network parameters.

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