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Large scale PV sites selection by combining GIS and Analytical Hierarchy Process. Case study: Eastern Morocco

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ABSTRACT

In this paper, a combination of Geographic Information System (GIS) and the Analytical Hierarchy Process (AHP) has been done to assess the capacity of Eastern Morocco to host large-scale Photovoltaic (PV) farms. For this reason, a GIS database with high spatial resolution has been built using data and layers provided from different governmental organizations. Besides, and in order to pursue high accuracy results, the Global Horizontal Irradiation (GHI) solar map used in this study was derived from a high-quality satellite map with a spatial resolution of 1km/pixel and twenty years of time coverage.

Results show that from the entire region's surface, the highly suitable sites to host PV farms make up 19%, while the unsuitable sites represent 15%. With those results our field of study can be very competitive -in comparison to neighboring countries like Spain-to attract investors in the field. Which will lead to an economical and sustainable development of the region by creating new jobs and producing green electricity.

1. Introduction

Morocco is a fossil fuel deficient country. It imports more than 96% of its energy needs from overseas [1]. However, it has a high potential of renewable energy sources that can cover a portion of its needs and export a part to Europe [2]. For this reason, Morocco launched an ambitious plan in 2008 called the National Renewable Energy & Efficiency strategy [3]. This strategy aims to produce 42% of the country's electricity from renewable sources: 14% solar, 14% wind, and 14% hydraulic [4].

Indeed, with an annual wind speed average ranging between 8 and 11 m/s in the North and 7 and 8.5 m/s in the south, the country's wind potential is considered as high [5,6]. This potential is well exploited, and the installed capacity has significantly increased from 915 MW at the end of 2009–2937 MW at the end of 2015 [7].

Regarding solar, the country launched the Moroccan Solar Plan (MSP). This project aims to produce 2000 MW of electricity from the sun by 2020 [8]. The Moroccan Agency for Solar Energy (MASEN) was created in parallel to bring the MSP's goal to fruition, and it set an objective to build five solar plants distributed on the country [9]. The MSP began with the inauguration of the first part of the Noor complex in Ouarzazate at the beginning of 2016. With a capacity of 160MWe and 3.5 h of storage, this plant is considered the largest in the world [10]. The second and the third part of Noor Complex are under construction and the complex final capacity will reach 500MWe (mainly from CSP) by 2018.

Because of the PV low LCOE and installation costs (in comparison to CSP) MASEN starts investing on large scale power plants based on this technology. Indeed, the 4th phase of Noor Complex will be a 72 MW plant, from PV technology with a total investment cost of 75 Million USD and an electricity price of 0.04.7 USD [11]. In the same direction, a part of Noor Midelt (the second power plant in the MSP in Eastern Morocco) will be dedicated to PV technology [81]. From this fact, we get the motivation to conduct this study and to highlight the most suitable sites to host PV power plants in Eastern Morocco.

The selection of suitable sites to host PV power plants is a very

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complex problem. It requires an optimal combination of different criteria, such as, the solar potential, the land availability, the presence of infrastructure, etc. To solve those problems, scientists and researchers generally use the Multi-Criteria Decision-Making techniques (MCDM) together with Geographic Information System (GIS) tools [12]. Several MCDM techniques are available in the literature, nevertheless, the most commonly used one in renewable energy sites assessment is the Analytical Hierarchy Process (AHP) [13].

This technique has been used by many authors to assess the capacity of their regions (or countries) to host wind power plants [14–17]. In the field of solar energy, Tahri et al. used a combination of GIS and AHP to find out the most suitable sites to host PV plants in southern Morocco [18]. Furthermore, Sanchez-Lorenzo et al. [19] and Aran Cariron et al. [20] used the same techniques to evaluate the capacity of Murcia and Granada, respectively, to host PV plants. In Turkey, Uyan used this combination to select the best sites to host PV farms in the region of Karapinar [21].

In this paper, we firstly developed a large GIS database -with high spatial resolution-by collecting data from different governmental organizations. Afterwards, four criteria and eight sub-criteria were chosen, and their weights were calculated using the AHP method. Finally, a GIS tool was used to create the final suitability map index. This map was clustered into five groups: “Highly Suitable,” “Moderately Suitable,” “Suitable,” “Marginally Suitable,” and “Unsuitable.”

Results show that Eastern Morocco can be considered as a good area to host large PV farms, with highly suitable sites accounting for 19% of the total region's surface. Those results are very important for MASEN and the local policymakers to develop new strategies and including other sites to host large PV plants. Besides, since Morocco has recently adopted a new regulation allowing private companies to build large renewable energy power plants [22] the results of this study can be of high interest to international investors, especially those working on the photovoltaic. This will undoubtedly contribute to the creation of new jobs and sustainable development, not only for the region, but for the country as well [23].

2. Methodology

2.1. The study area

The Eastern region of Morocco is located at the North-East of the country (Fig. 1), bordering Algeria for 500 km in the East and the Mediterranean Sea for 200 km in the North. The surface area of the region is 82800 km^2, which represents 11.7% of the country's area. The region has a very young population, and 61% of it are active. Furthermore, Eastern Morocco has an urbanization rate of 67%, and more than 80% of the population is concentrated in the northern

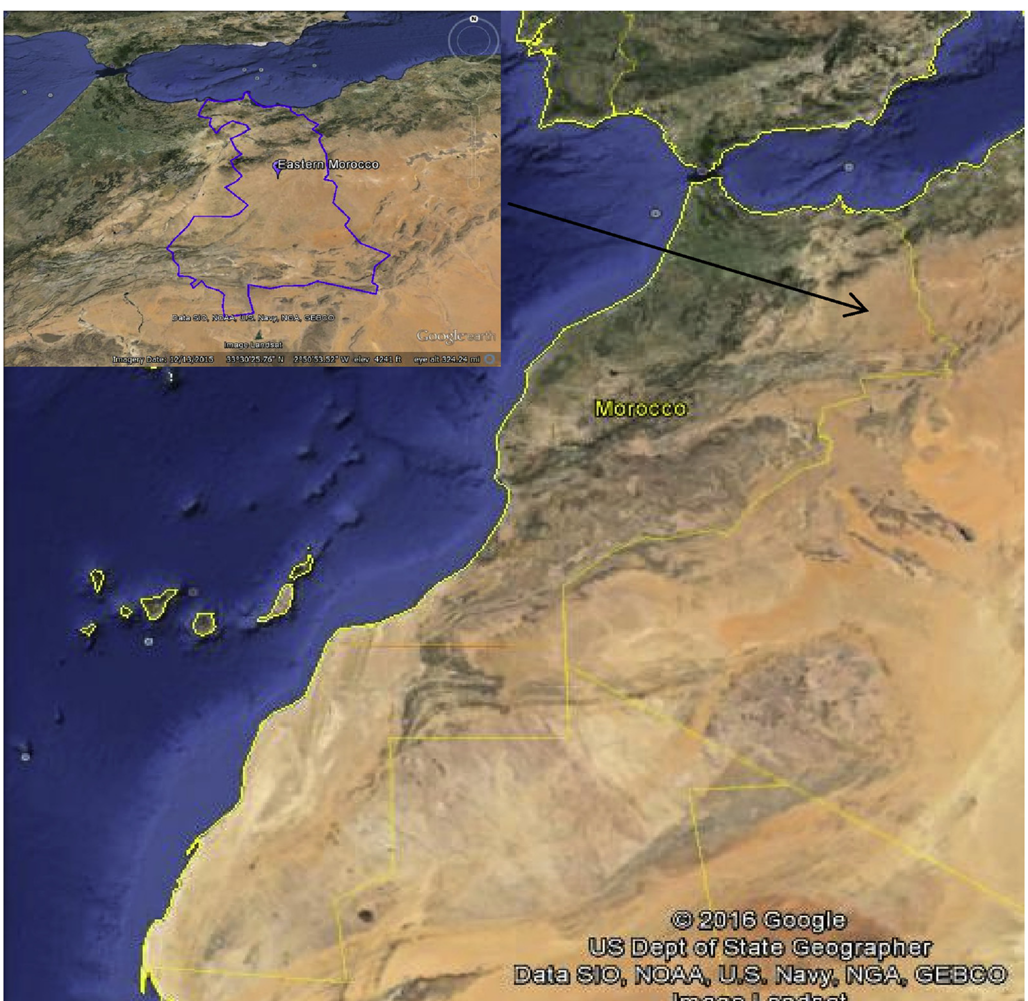

Fig. 1. Eastern Morocco: the study area.

Table 1
The criterions and the sub-criterions used on for the PV site suitability analysis in Eastern Morocco.

Goal	Criteria	Factors	Indicators
Select the most suitable sites to host PV power plant	Climate	Global Horizontal irradiation (kWh/m^2/a)	2175–2304
			2050–2175
			1925–2050
			1816–1925
	Orography	Slope (%)	<1
			1–2.5
			2.5–5
			>5
	Location	Distance from residential (km)	<1
			1–5
			5–20
			>20
		Distance from road and railway network (km)	<1.5
			1.5–5
			5–7.5
			>7.5
		Distance from Electricity grid (km)	<1
			1–5
			5–10
			>10
	Water resource	Distance from water ways (km)	>5
			5–10
			10–15
			>15
		Distance from dams (km)	<10
			10–15
			15–25
			>25
		Distance from groundwater (km)	On the underground water surface
			2.5 Km far away from the border of the surface
			5 Km far away from the border of the surface
			More than 5 Km from the board of the surface

part [79]. This region has demonstrated a good potential of electricity production from both solar technologies CSP and PV [89–92].

2.2. The analytical hierarchy process

As mentioned above, the selection of the most suitable locations to host Photovoltaic (PV) plants is a very complex problem. It requires identifying different alternatives, choosing between them, and finding the most suitable solution [24,25]. To resolve those problems, researchers and scientists commonly use the Multiple-Criteria Decision-Making methods (MCDM) [26].

Numerous MCDM techniques exist, but the Analytical Hierarchy Process (AHP) is the most used to solve complex decisions with different criteria [27,28].

The Analytical Hierarchy Process is a mathematical approach developed first by Satty [29]. It has the advantage of reducing complex decisions to a series of pairwise comparisons. It is also a valuable method to check the consistency of the decision and to reduce the bias in the decision-making analysis. At the beginning of each AHP process, the goal, alternatives, and criteria must be defined. Afterwards, a pairwise comparison matrix (M) can be generated.

If, n is the criteria's number, (M) will be a $(n \times n)$ matrix, where each entry p_{ij} of the matrix describes the importance of the i_{th} criterion to the j_{th} criterion. The relative importance of the two criteria is measured according to a numerical scale from 1 to 9 [30].

$$M = \begin{bmatrix} 1 & p & q \\ 1/p & 1 & r \\ 1/q & 1/r & 1 \end{bmatrix}$$

To calculate the weight of each criterion, we must normalize the matrix (M) by dividing the elements of each column by the sum of the elements of the same column. The average of the new matrix's rows gives the required relative criteria weights.

The AHP includes a good factor to check the consistency of the weights called the Consistency Ratio (CR). To calculate the CR we must primary calculate the Consistency Index (CI) using the formula:

$$CI = \frac{\lambda_{MAX} - N}{(N-1)}$$

where λ_{MAX} represents the eigenvalue of the pairwise comparison matrix and n is the number of the criteria. Finally, the CR is calculated by dividing the consistency index (CI) by the random consistency index (RI). The RI values for the appropriate n values are well known and collected in a table [31].

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

It is worth mentioning that, in order to obtain significant results with the AHP technique, the CR must be equal to or less than 10%, otherwise, the pairwise comparisons values have to be recalculated.

2.3. The criteria definition

Before the installation of any solar power plant in a region or a country, a prefeasibility study must be conducted taking into consideration the solar potential and the land occupation. Generally, the selected site to host the solar plant must be well irradiated, accessible, and flat. Moreover, for environmental interest, it should not be in a forest, an agricultural area, or a protected area. The combination of these parameters is very complex, and researchers

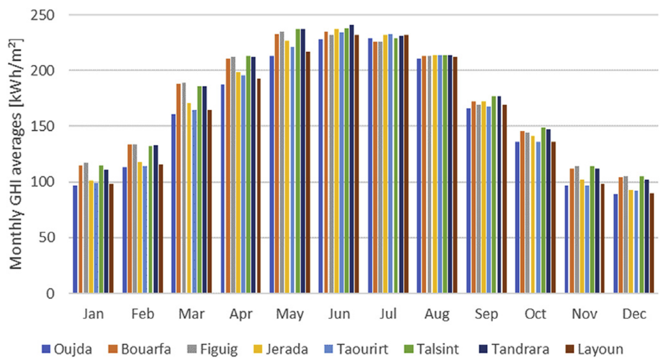

Fig. 2. The Global Horizontal Irradiation (GHI) monthly averages.

usually use a combination of a MCDM method and GIS tools to solve this kind of problems.

In this study, a combination of GIS tools and the Analytical Hierarchy Process technique was used to assess the suitability of Eastern Morocco to host large-scale photovoltaic (PV) power plants. For this reason, four criteria (climate, orography, water resources, and location) and eight sub-criteria were defined to resolve this problem (see Table 1).

In a decision-making process, the criterion represents a measurable aspect of a judgment that makes it possible to characterize and quantify alternatives [32]. Those criteria were carefully chosen based on the literature and the discussion with local and external experts in the field. The specificities of the region were taken into consideration, as well, in the criteria's selection.

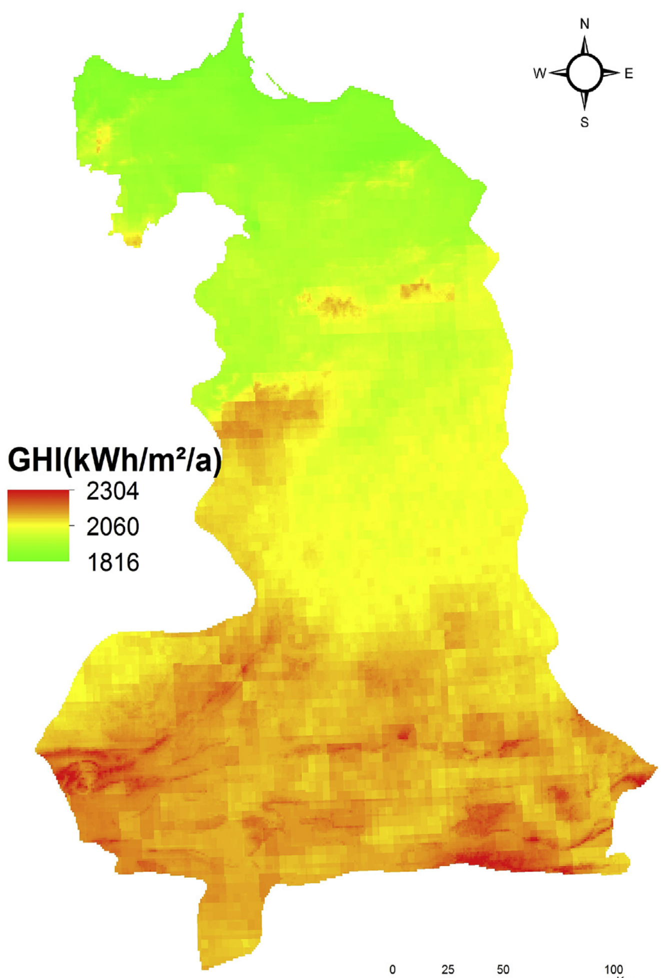

Fig. 3. The Global Horizontal Irradiation (GHI) map of Eastern Morocco over twenty years.

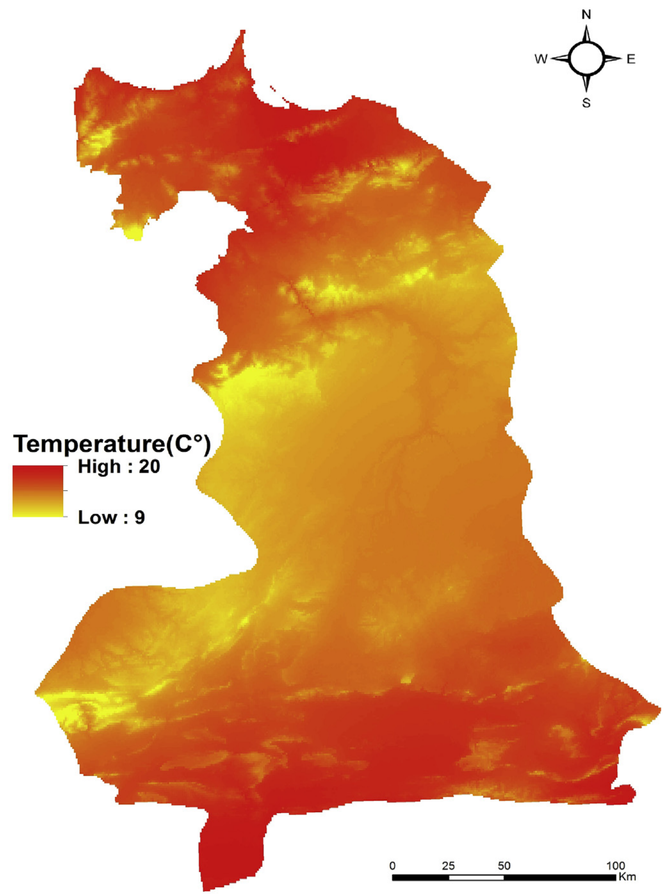

Fig. 4. Map of average temperature values of Eastern Morocco over fifty years.

2.3.1. Climate

For PV power plants, the two major climatic factors affecting the performance of the modules are the solar irradiance and the temperature [33]. Indeed, the more solar irradiation is received, the better the electricity production will be. Consequently, to accurately select the suitable sites for PV plants, the use of high-resolution solar maps is a necessity.

Table 2
Coordinates of the stations used to calculate the daily ambient temperature distribution and the measurements periods.

Station	Latitude	Longitude	Elevation (m)	Measurements period
Bouarfa	32.52	−1.92	1202	01/01/2012–31/07/2013
				01/03/2015–30/04/2016
Feguig	32.12	−1.22	910	01/01/2012–19/04/2016
Jerada	34.2	−2.09	1015	01/01/2012–31/07/2013
				01/03/2015–30/04/2016
Layoun	34.58	−2.5	612	01/01/2012–12/05/2016
Oujda	32.15	−1.56	619	01/01/2012–31/07/2013
				01/03/2015–31/03/2016
Taourirt	34.39	−2.89	415	01/01/2012–31/07/2013
				01/03/2015–31/03/2016
Talsint	32.53	−3.45	1340	01/01/2012–12/05/2016
Tandrara	33.05	−1.99	1441	01/01/2012–31/12/2014

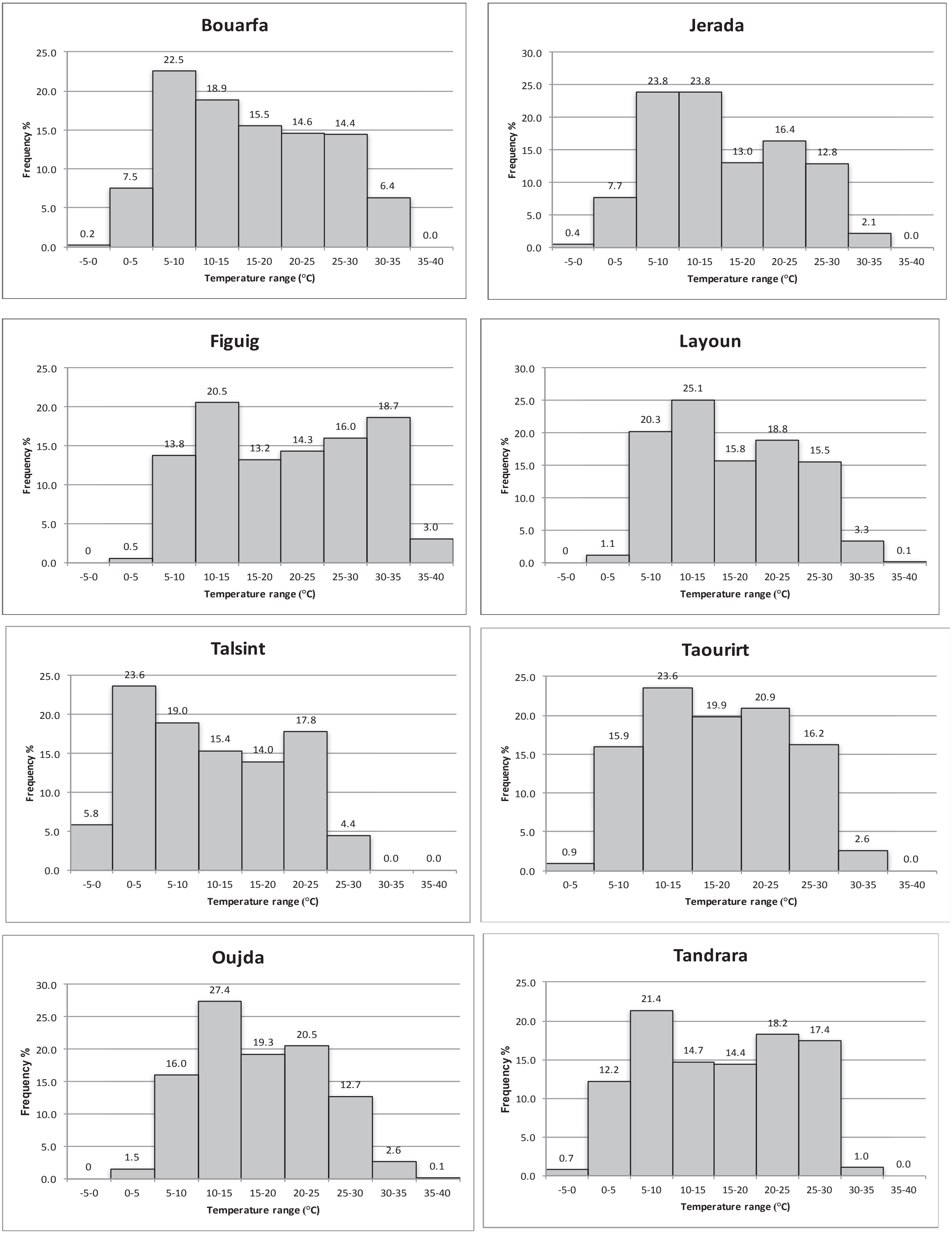

Fig. 5. Frequency distribution of the daily temperature average measured at eight stations well dispersed on the field of study.

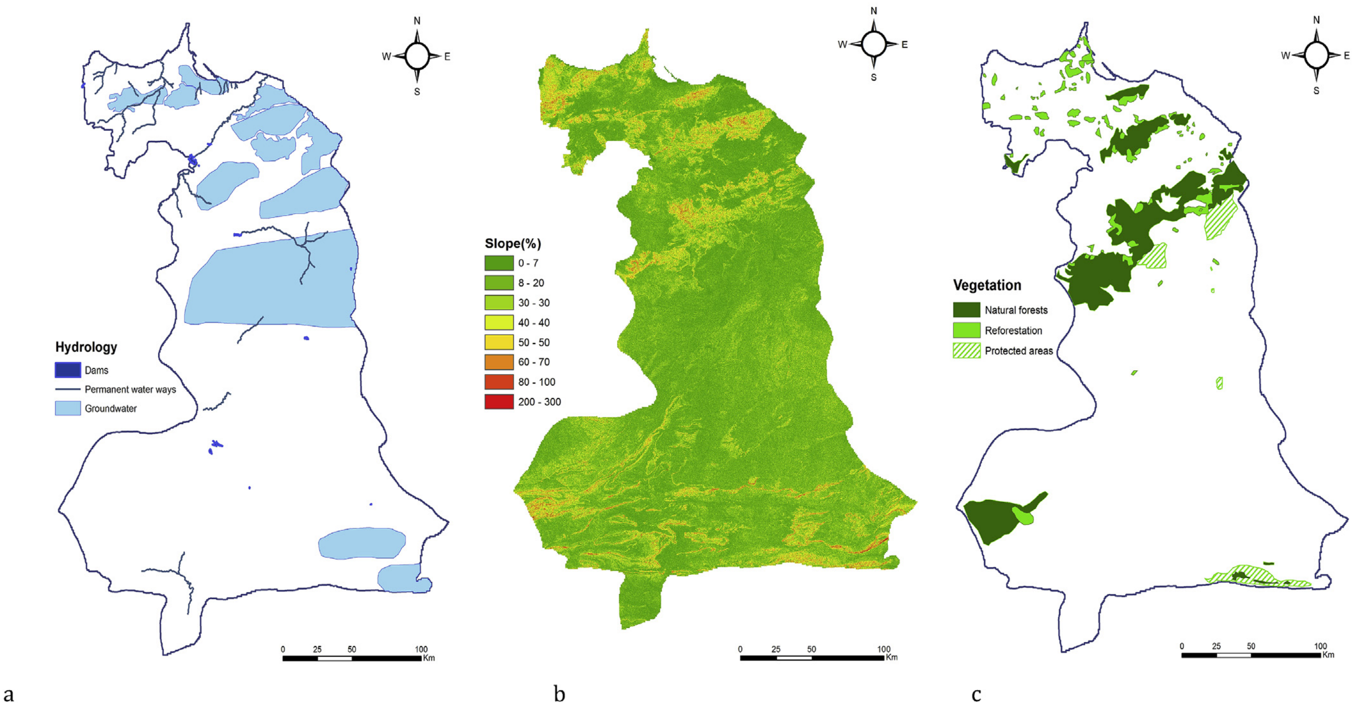

Fig. 6. (a) groundwater, (b) slope (c) vegetation, of the Eastern region of Morocco.

From the three components of solar irradiation, the amount of the Global Horizontal Irradiation (GHI) must be evaluated for the installation of PV plants. As for Concentrating Solar Power plants (CSP), the Direct Normal Irradiation (DNI) should be assessed because it is the one that can be concentrated.

Plenty of methods for calculating solar irradiance are available in the literature. Some authors use numerical methods to estimate the solar potential [34–38]. Others interpolate the solar irradiation measured at ground level to generate the solar Maps [39,40,80]. Alternatively, some authors use the advantage of the Area Solar Radiation tool within the ArcGIS software to generate their solar maps [41,42]. However, the most common method is the analysis of satellite images [43–48,82,83]. The advantage of this method is the long-term data existence (up to 20 years) and the coverage of a large area. Furthermore, several satellite databases (priced and open access) provide solar data. We cite, for instance, NASA's SSE Release 6.0 [49], GEOMODEL Solar from PVGIS [50], and the Satel-Light database that covers Europe and North Africa [51]. A review of

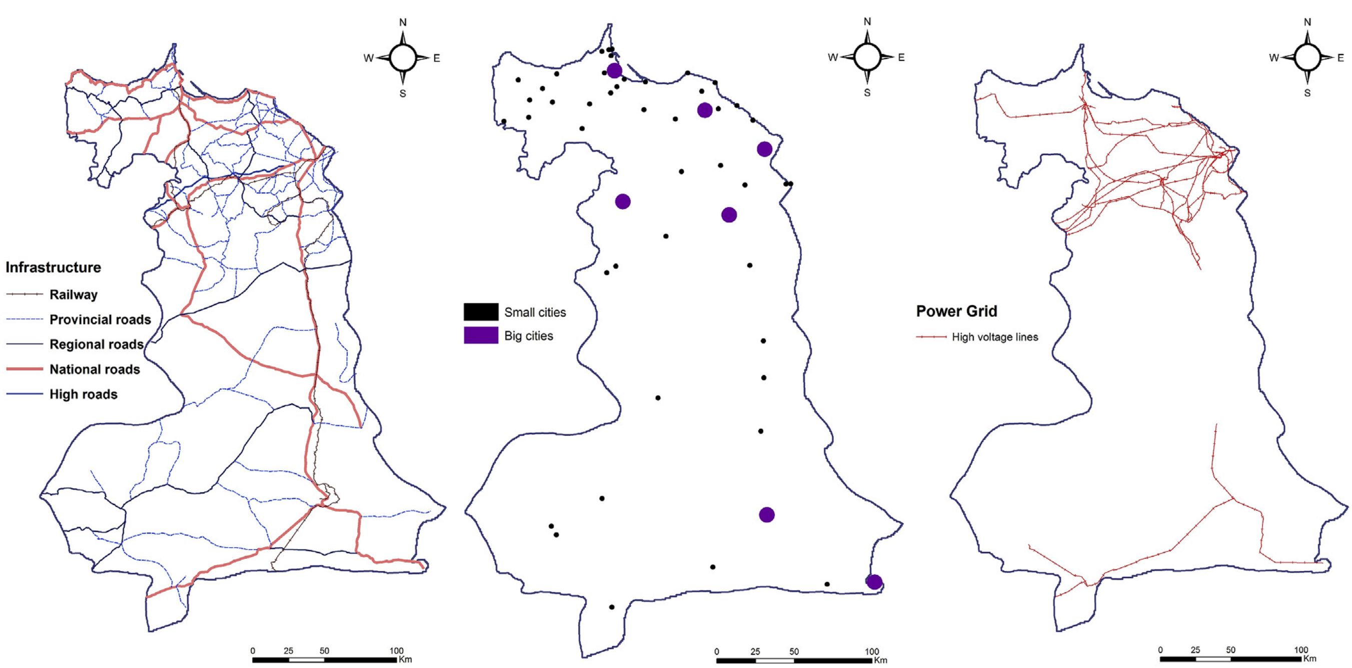

Fig. 7. The Infrastructure, the cities and the power grid network of the Eastern region of Morocco.

Fig. 8. Picture of heavy soiled PV panels on the Gran Canaria Island western Morocco [78].

the existing satellite datasets, the details about the time and the land coverage, as well as the accessibility is gathered by Vernay et al. [52].

In this study, we used a high accuracy GHI solar map of Eastern Morocco. This map was extracted from the IRESEN's server map portal [53], and it was developed in the frame of Solar-Med-Atlas project by MINES ParisTech, the German Aerospace center (DLR), ARMINES, and TRASVALOR. The GHI map (Fig. 3) has a high spatial resolution of 1 km and a long-term coverage of 20 years (1991–2010). Besides it takes into consideration the slope's orientation [54].

With an annual GHI values between 1816 and 2304 kWh/m^2/a, Eastern Morocco can be considered as a highly irradiated region. With this potential, the region can be very competitive in the PV market, knowing that Qatar, Spain, and Germany have annual GHI potentials of 2134, 1659, and 1066 kWh/m^2/a respectively [61].

To have a more detailed idea about the GHI values, Fig. 2 presents the GHI monthly averages of 8 sites well distributes on area of study. Those values are extracted from Ref. [53]. As it can be seen, the highest values are recorded during spring and summer, while, the lowest ones are measured during winter and fall. Nevertheless, for all the year, the monthly irradiation rang distribution, is between 100 and 250 kWh/m^2 which can be considered as good.

In this study, the solar irradiation criterion was divided into four sub-criteria based on the GHI values:

- ➢ 1816–1925 kWh/m^2/a
- ➢ 1925–2050 kWh/m^2/a
- ➢ 2050–2175 kWh/m^2/a
- ➢ 2175–2304 kWh/m^2/a

As mentioned above, the temperature is the second most dominant factor for PV systems regarding climate. It highly affects the performance of the PV modules and, consequently, their power

Table 4
The factors weight.

Factor	Weight (%)
Global Horizontal irradiation (kWh/m^2/a)	59.00
Slope (%)	23.50
Distance to waterways (km)	7.67
Distance to dams (km)	3.07
Distance to groundwater (km)	1.06
Distance to residential (Km)	2.62
Distance to Electricity grid (km)	1.82
Distance to road and railway network (km)	1.25

production. Usually, the PV panel's manufacturers provide the module specifications based on standard conditions (irradiation = 1000 W/m^2, 1.5 AM and a temperature of 25 °C). But, in regions with high ambient temperatures (above 30 °C), those characteristics are significantly affected [55–59]. Indeed, high temperature values affect the cells temperature, which causes a drop in the electricity production and the systems performance ratio [84,85]. Furthermore, high temperature values affect the modules lifetime and durability. This phenomenon can appear in the form of thermal stress at the cells interconnectors level and at the modules Encapsulant [86,87]. Therefore, the assessment of the ambient temperature of Eastern Morocco is crucial.

Fig. 4, represents a map of the average ambient temperature of our field of study over 50 years. This map is extracted from the temperature data published by WorldClim-Global climate data [60]. As the figure shows, the temperature values vary between 9 and 20 °C. With those conditions, Eastern Morocco's temperature is very acceptable, and it does not affect the PV modules performances.

For the sake of precision and in order to further investigate the temperature ranges of this region, a frequency distribution of average daily measurements from eight well-distributed stations in the area has been calculated. Table 2, summarizes the stations coordinates and the measurement periods and (Fig. 5) shows the temperatures distributions.

For almost all the stations, the days with temperature values above 30 °C are very infrequent. Therefore, the ambient temperature does not represent a significant limiting factor for PV power plants in Eastern Morocco. Consequently, it was decided that the climate criterion will be represented by the amount of Global Horizontal Irradiation (GHI) only.

2.3.2. Orography

Solar power plants are highly affected by land elevation. The presence of slopes affects the feasibility of solar projects and increases investment costs [62,63]. According to the International Renewable Energy Agency (IRENA), there is no unified threshold for the sloped area that has to be extracted [64]. In the literature, we find different slopes thresholds. For CSP, the German Aerospace center (DLR) excluded any land with a slope higher than 2.1% [65]. This threshold was used by IRENA for CSP as well in a report about Africa [66]. Regarding the PV farms, many slope thresholds are present in literature, 3% [67] and 5% [68].

Table 3
The pairwise comparison matrix, the weight of each criterion and the consistency ratio.

	Climate	Orography	Water resource	Location	Weights	CR
Climate	1	3	5	9	0.590	0.01832
Orography	0.33	1	2.5	4	0.235	
Water resource	0.2	0.4	1	2.5	0.118	
Location	0.11	0.25	0.4	1	0.057	

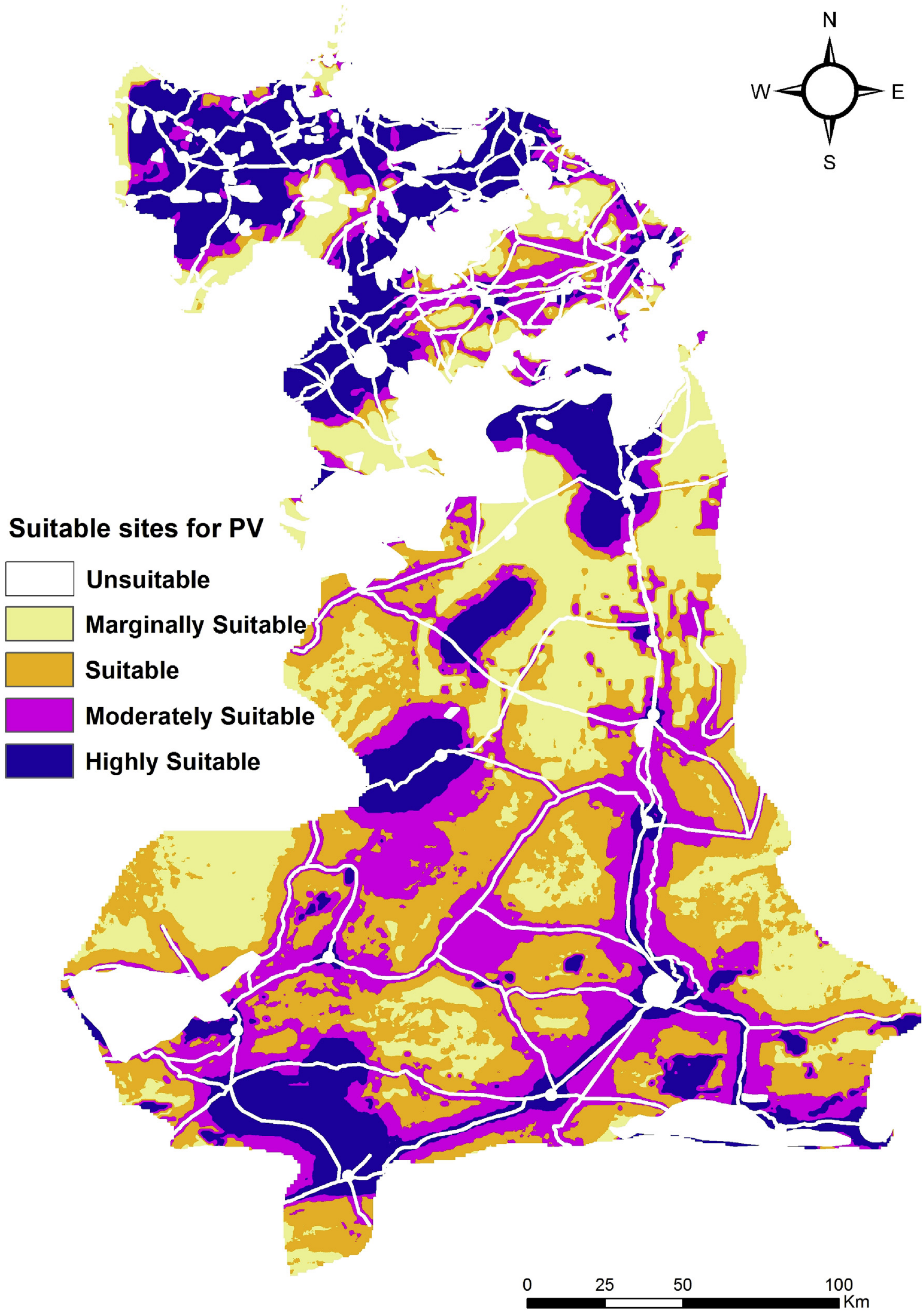

Fig. 9. Sites suitability map for large PV farms installation in the Eastern region of Morocco.

In this study, all the slopes higher than 5% were excluded. This choice has been done in order to be sure that the selected sites will be relatively flat, thus, will not require high investment costs and they will be competitive to other neighboring regions and courtiers.

The slopes map (Fig. 6b) was calculated from the NASA Shuttle Radar Topographic Mission (SRTM) 30 m × 30 m digital elevation model for Eastern Morocco.

2.3.3. Location

The location of a solar plant is important in the site selection. Generally, a solar power plant must be accessible, i.e. close to the road network for modules and equipment transportation during and after the construction phase. Moreover, it has to be close enough to residential areas and to the electrical grid to supply the electricity produced.

In this study the location criterion was divided into three sub-criteria: distance from residential areas, distance from the road network, and the distance from the electrical grid.

The electricity transmission lines layer was provided by "the National office of electricity and water (ONEE)," while the cities and the road network layers were prepared based on a high-precision topographical map of the region (Fig. 7).

2.3.4. Water resource

All solar plants need water during their operation. For Concentrating Solar Power (CSP) plants, the water is used for cleaning the solar field, as well as, for the cooling cycles [69,70]. PV plants, however, require water only for the modules and the systems cleaning.

In arid regions, the presence of dust and aerosols (Fig. 8) can cause a huge diminishment of the plants electrical production [71–75]. Indeed, soiling is considered a high limiting efficiency factor in the operation of solar plants. According to [76], the PV system efficiency dropped by 65.8% after 6 months of exposition in Saudi Arabia. Furthermore, Mastec et al. reported a decrease of 13% in the power production after only one month of exposition in India [77].

Even though the presence of water resource is an important criterion in the power plants site selection; very few studies in the literature taken it into consideration. In this study, the criterion of the water resource was split on three sub-criteria: distance from waterways, distance from the dams, and distance from groundwater (Fig. 6a). The hydrological database used in this study is provided by "Hydrological Basin Agency of Moulouya (ABH-Moulouya)".

2.4. The constraints definition

A constraint layer represents a mask of the whole unsuitable areas for hosting photovoltaic farms. A PV farm cannot be installed in a mountain, a forest, a city, or a waterway, all of which must be excluded in the site suitability analysis.

In this study, the constraint layer is represented by a map

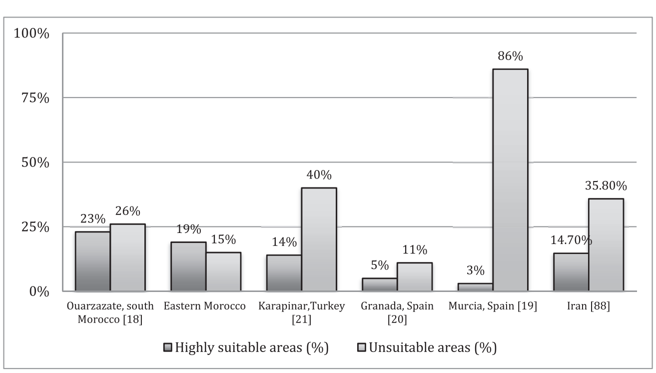

Fig. 10. Comparison of the capacity of Eastern Morocco to host large PV farms with neighbor countries [88].

including a buffer of 100 m for the road and railways network, a buffer of 500 m for the vegetation, a buffer of 500 m for hydrology (dams and waterways), and a buffer of 5 km and 2 km for residential areas in big and small cities, respectively. The vegetation layer, Fig. 6c, was provided by "the "Regional Directorates of Water and Forests (DREF)" of the Eastern region of Morocco.

3. Results and discussion

The purpose of this study is to assess the capacity of the Eastern region of Morocco to host large photovoltaic (PV) farms. To do so, a combination of a Multiple-Criteria Decision-Making (MCDM) technique and a Geographic Information System (GIS) tool was used.

The pairwise comparison matrix is calculated using the Analytical Hierarchy Process (AHP) and is shown on Table 3. The hierarchical decision data were made based on the literature and our assumption after discussions with local and international specialists in the field regarding the specificity of the region. The results of the pairwise comparisons of this study are very acceptable and the values are very consistent, since the Consistency Ratio (CR) equals 1.8% way less than 10%.

From the AHP weight analysis in Table 3, we can see that the climate criterion is the most dominant with a weight of 59%. This is completely true because the electricity production is directly linked to the amount of solar irradiation (GHI in the case of the PV farms). Therefore, to be competitive in the solar market, the suitable sites for hosting PV farms must be located in well-irradiated places.

The orography is the second most important criterion in the AHP analysis. This is reasonable because the presence of slopes significantly increases the investment costs during the PV farm construction. In this study, we chose relatively small slope elevation (in comparison with [18]) in order to ensure that the sites with high capacity/suitability to host PV plants will be relatively flat, consequently, requiring smaller investment costs and ensuring that a competitive PV farm is built there. The weight of the orography is of 23.5%.

As discussed above, in arid regions (like Eastern Morocco) the presence of water is crucial for PV farms due to the presence of dust. Cleaning the PV modules can be very expensive and water consuming, that's why the installation of a power plant close to a water resource is important. Therefore, the water resource criterion comes in the third place with a weight of 11.8%, while the location's weight is 5.7%.

Table 4, represents the factors weight calculation. The weights were calculated by repeating the same AHP process. The calculations returned a weight of 59% for the GHI, 23.5% for the slopes, 7.67% for the distance from the waterways, 3.07% for the distance from the dams, 1.06% to the distance from groundwater, 2.62% for the distance to residential, 1.82% to the distance from the electrical grid and 1.25% to the distance from the roads and railway network.

The final suitability map (Fig. 9) was created using a GIS tool and it was grouped into five classes: Unsuitable, Marginally Suitable, Suitable, Moderately Suitable and Highly Suitable.

The results of the GIS calculations show that Eastern Morocco can be considered a highly suitable host for large PV power plants. Indeed, from the total area of Eastern Morocco, 19% of the land is highly suitable, 20% marginally suitable, 23% suitable and 23% moderately suitable. The constraint map, or in other words, the unsuitable areas represent 15% of the total surface of the region.

4. Conclusion

In this paper, we assessed the capacity of the Eastern Region of Morocco to host large Photovoltaic farms by combining a Multi-

Criteria Decision-Making technique and a Geographical Information System tools. This region is considered a target region in the solar investment market, since it will host the second solar complex fixed in the Moroccan Solar Plan. The results show that this region can be considered highly suitable to host large PV farms.

The highly suitable sites represent 19% of the entire region's surface. The percentage of marginally suitable, suitable, and moderately suitable areas are 20%, 23% and 23% respectively, while the unsuitable sites represent 15%.

The results can be considered as very encouraging for investors in solar industry -especially on PV– in comparison to other close regions in the area Fig. 10. We believe that the results of this study will boost the investments on solar energy in the region, which will lead to the creation of new jobs as well as a sustainable development to the country.

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