Solar Energy 166 (2018) 2–12

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

A GIS-AHP combination for the sites assessment of large-scale CSP plants with dry and wet cooling systems. Case study: Eastern Morocco

Ahmed Alami Merrouni[a,b,*], Fakhreddine Elwali Elalaoui[c], Abdellatif Ghennioui[b], Ahmed Mezrhab[a], Abdelhamid Mezrhab[c]

[a] Laboratory of mechanics and energy, Faculty of sciences, Mohammed 1st University, Oujda, Morocco
[b] Research Institute for Solar Energy and New Energies (IRESEN), Green Energy Park, Bengrir, Morocco
[c] Technologies of Geographical Information and Space Management's Team, GIS and Remote Sensing Centre, University Mohammed First, Oujda 60000, Morocco

ARTICLE INFO

Keywords:
CSP
AHP
GIS
Sites suitability analysis
Eastern Morocco

ABSTRACT

In this paper, we assessed the suitability of the Eastern region of Morocco to host large-scale Concentrating Solar Power (CSP) plants by combining Geographic Information System (GIS) and the Analytic Hierarchy Process (AHP). For this reason, a high spatial resolution GIS database is built using layers provided from different governmental organizations. Additionally, since the potential of the Direct Normal Irradiation (DNI) is the most important criterion for CSP site selection; a high-quality satellite solar map with a spatial resolution of 1 km^2/pixel and twenty years of time coverage was used.

Since CSP power plants need cooling systems for their power block cycle; the suitability of two cooling techniques (dry and wet) were evaluated for this region.

Results show that Eastern Morocco can be considered as a very good location for hosting CSP power plants. For the wet cooling systems, the highly suitable sites to host CSP plants represent 11.7% from the total area, while 5.5% is the proportion of the highly suitable sites for CSP plants with dry cooling systems.

1. Introduction

The development of CSP is promising because they can keep producing electricity after the sun sets or during cloudy periods of the day, thanks to the thermal energy storage. According to the IEA's road map (IEA, 2014), the electricity produced from CSP has strongly increased since 2010, and currently the global operational capacity is around 4728 MW (https://www.nrel.gov/csp/solarpaces/projects_by_status.cfm?status=Operational). The road map envisions that the installed capacity of CSP will reach 1000 GW by 2050, which will avoid 2.1 Gt of CO_2 emissions each year and contribute to 11% of the global electricity production.

Morocco is a deficient country regarding fossil fuels, but it has the potential to be a source of renewable energy, particularly solar and wind (Ouammi et al., 2012; Kousksou et al., 2015). This can cover a part of the country's energy needs and export to Europe as well (Boie et al., 2016). For this reason, the country launched an ambitious project to produce 42% of the electricity from renewable energy sources (14% from wind, 14% hydraulic and 14% solar) by 2020 (http://www.one.org.ma/).

Regarding solar energy, the Moroccan Solar Plan (MSP) was launched in 2009, and the Moroccan Agency for Solar Energy (MASEN) was created for the realization of this project. The objective of the MSP is to produce 2000 MW from solar energy, and five sites were selected to host the future solar plants (Tsikalakis et al., 2011). This plan started with the inauguration of the first part of the NOOR complex in Ouarzazate, with an electrical production of 160 MW and 3.5 h of storage (http://www.masen.org.ma).

The second phase of the MSP will be the construction of a 400 MW plant in Eastern Morocco. For this reason, we got the motivation to conduct this study with the objective to highlight the suitability of this region for hosting CSP power plants with different cooling techniques. To do so, maps with high spatial resolution, and a combination between Geographic Information System (GIS) tools and a Multi-Criteria Decision Making (MCDM) approach has been used.

The combination of GIS tools and MCDM techniques became a successful approach to solve the complex problem of site selection for solar plants. Many researchers use this technique to evaluate the capacity of their regions or countries to host green power plants. For instance, Tahri et al. (2015) assessed the suitability of southern Morocco to host large photovoltaic (PV) farms by using GIS tools and Analytical Hierarchy Process (AHP) – one of the MCDM techniques that will be discussed in detail in the next sections- and they found that 23% of the

* Corresponding author at: Laboratory of mechanics and energy, Faculty of sciences, Mohammed 1st University, Oujda, Morocco.
E-mail address: alami@iresen.org (A. Alami Merrouni).

https://doi.org/10.1016/j.solener.2018.03.038
Received 20 September 2017; Received in revised form 3 March 2018; Accepted 14 March 2018

study area is highly suitable to host those kinds of plants. Uyan (2013) used the same technique to evaluate the capacity of Karapinar region in Turkey to host PV plants, and 13.92% of the areas were highly suitable. Some other studies were conducted for southern Spain as well, and the rates of areas with high suitability were 3% for Murcia and 5% for Granada (Sánchez-Lozano et al., 2013; Carrión et al., 2008).

In the literature, the assessment of the suitable sites to host solar plants is mainly dedicated for photovoltaic technology, and only a few studies deal with CSP. Besides, most of the papers dealing with CSP, either investigate the integration on a specific site (Gastli et al., 2010), or do not specify the cooling technic to be used. Furthermore, water availability is rarely considered as a criterion during the site assessment analysis.

Knowing the fact that the DNI is the main criterion for the CSP sites assessment; the use of high quality DNI solar map is crucial. In the literature, most of the authors use low quality solar maps; for instance (Fluri, 2009) used a low-resolution satellite database (40 × 40 km/pixel), and (Ziuku et al., 2014) who created a DNI map by interpolating the ground measurement data.

In this paper, we used a combination of the AHP and GIS tools to find out the most suitable sites to host CSP plants in the Eastern region of Morocco. The used DNI solar map has a high spatial and temporal resolution (1 × 1 km/pixel and an average over 20 years). Additionally, the assessment of the suitability of our study area to host CSP power plants has been done for both cooling techniques dry and the wet.

In the first part of this paper we present and describe the GIS database used in this study. After that, the AHP method, the criteria definition and their weights are described. Finally, two maps showing the suitable sites to host CSP power plants with wet and dry cooling systems are presented and discussed.

Results show that 5.5% and 11.7% of the region's area, are highly suitable to host CSP plants with dry and the wet cooling systems respectively. While, the non-suitable sites represent 76.3% of the total areas. Those results can be of high interest, not only for MASEN or the Moroccan policy makers, but also for the international investors as well, since Morocco has recently adopted a new regulation allowing private companies to build large renewable energy power plants and inject the electricity produced into the national grid (www.mem.gov.ma). This will undoubtedly contribute to the creation of new jobs and sustainable development, not only for the region, but for the country as well (Sooriyaarachchi et al., 2015).

2. Methodology

2.1. Geographical location

The Eastern region of Morocco is located at the northeast 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 km2, which represents 11.7% of the country's area. The region has a very young population, and 61% are considered as power-labor. The region has an urbanization rate of 67%, and more than 80% of the population is concentrated in the northern part (www.hcp.ma). This region is well known with its high capacity to produce electricity from both CSP and PV power plants (Alami Merrouni et al., 2016a, 2016b; Ait Lahoussine et al., 2015; Alami Merrouni et al., 2017a, 2017b, 2017c).

2.2. The GIS database

The selection of the most suitable sites for the installation of large-scale CSP plants is very complex, and different parameters have to be taken into consideration during the analysis. Indeed, the solar potential alone is not sufficient; the land suitability and availability have to be taken into consideration as well. A CSP plant cannot be installed in a city, a forest, or a mountainous region (Schlecht and Meyer, 2012), and for economic reasons, it must be as close as possible to the infrastructure for the material transportation during the construction, as well as to the electrical grid to inject the produced electricity (http://www.endorsefp7.eu).

In this study, we primarily collected and built a GIS data set of the solar irradiation, accessibility, hydrology, and land availability of Eastern Morocco. Afterward, a constraints layer was created assembling all the unsuitable areas. Then, the criteria for two cooling scenarios (dry and wet) were defined, and the weight of each criterion was calculated using the AHP method for both scenarios. Finally, the sites suitability for the CSP plants installation was calculated by combining the GIS and the MCDM for the dry and wet cooling scenarios.

2.2.1. Solar irradiation map

In order to assess the solar potential for a region or a country, it is crucial to develop a solar map with high accuracy. Several methods are available for the solar maps development. In the literature, some authors interpolate the solar irradiation data measured at ground level to create a solar map (Bachour and Perez-Astudillo, 2014; Alsamamra et al., 2009). Another technique is the use of the area solar radiation within the ArcGIS software's tools (Clifton and Boruff, 2010). Nevertheless, the most used technique is the analysis of satellite images (Janjai et al., 2013; Martins et al., 2007; Viana et al., 2011; Mahtta et al., 2014). This method provides solar irradiation data for long periods of time (10–20 years), and it covers a large area. Numerous databases provide solar data from the analysis of satellite images (NASA's SSE Release 6.0 (https://eosweb.larc.nasa.gov/sse/), PVGiS (http://solargis.info), and the clean power research SolarAnywhere's database (Perez et al., 2002). For more details about the satellite datasets refer to (Vernay et al., 2014).

In this study, we extracted the DNI solar map of Eastern Morocco from the IRESEN's server map portal (http://www.iresen.org/map-server/). This map was developed by the MINES ParisTech, the German Aerospace center (DLR), ARMINES, and TRASVALOR in the framework of Solar-Med Atlas project. The map has a high spatial resolution of 1 km and a long-term coverage of 20 years (1991–2010) (http://www.solar-med-atlas.org/solarmed-atlas/map.htm#t=dni).

The DNI map (Fig. 2) resource database was provided by Helioclim-3 within the SODA service. This source of data is considered as very acceptable for resource assessment. It has been reported in the literature, that under the Moroccan climate the DNI Bias is around 7.9% for the hourly DNI records for an average of two years (2012–2013) (Alami Merrouni et al., 2017a, 2017b, 2017c). Additionally, knowing the fact that the error decrease significantly while using long term measurements, we can say that the solar map used in this study is very accurate.

2.2.2. Infrastructure

Generally, a solar plant has to be accessible; it must be as close as possible to cities, roads, railways and electricity grid. Fig. 3 shows the complete road network, the railway network, the cities, and the power grid network of Eastern Morocco. Because of the fast-economic growth and the creation of new projects in the region (www.oriental.ma), the cities have a tendency to sprawl. For this reason, we decided to present the big cities by a buffer of 5 km and the small ones by a buffer of 2 km.

The road network was built based on topographic maps of the region and the transmission lines data were provided by the National Office of Electricity and Water (ONEE).

2.2.3. Vegetation

Fig. 4, shows the vegetation and the protected areas of Eastern Morocco. A protected area is defined by the International Union for the Conservation of Nature (IUCN) as "an area of land and/or sea especially dedicated to the protection and maintenance of biological diversity, and of natural and associated cultural resources, and managed through legal or other effective means" (Günther and Joemann, 2018). The vegetation data were provided by the Regional Directorates of Water and Forests (DREF) of the Eastern region of Morocco.

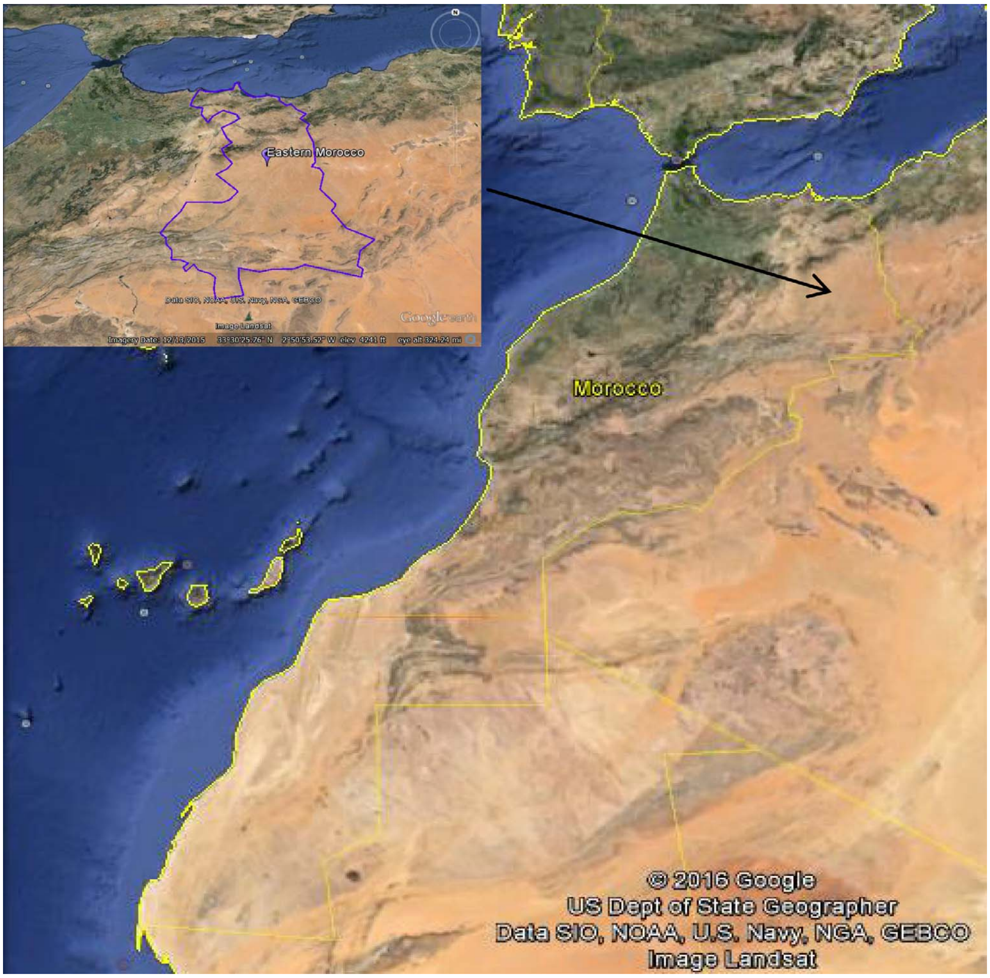

Fig. 1. The study area: Eastern Morocco.

2.2.4. *Slopes*

Solar power plants, especially CSP, are highly affected by the land slope. It is considered a major parameter for land assessment, since it highly affects the feasibility and the cost of any solar project (Bravo et al., 2007; Gastli et al., 2010). In this study, the slop gradient map (Fig. 5) was calculated using GIS software and the NASA Shuttle Radar Topographic Mission (SRTM) 30 m^2 digital elevation model for Eastern Morocco.

2.2.5. *Hydrology*

For CSP technology, the availability of water is crucial, as water plays a major role in the operation of the solar power plant. Indeed, water is used for the cleaning of the solar mirrors particularly in arid regions (like eastern Morocco), where dust presents a limiting efficiency factor for the electricity production (Sarver et al., 2013; Ghazi et al., 2014; Maghami et al., 2016; Urrejola et al., 2016; Alami Merrouni et al., 2017a, 2017b, 2017c).

Cleaning is not the most water-consuming factor in a CSP plant if the wet cooling option is used. In fact, according to (https://easac.eu) 90% of the water is used for the cooling and only 10% for the cleaning. This issue becomes less important for the dry cooling option (Qoaider and Liqreina, 2015; Liqreina and Qoaider, 2014). In this study, we will take into consideration both cooling options.

Fig. 6, presents the hydrological network of Eastern Morocco. This network contains the permanent waterways, the dams, and the underground water. The hydrological data were provided by the Hydrological Basin Agency of Moulouya (ABH-Moulouya).

2.3. *Analytical hierarchy process*

The selection of the most suitable sites to install solar power plants is a very complex issue. It requires identifying different alternatives, choosing between them, and finding the most suitable solution (Potić et al., 2016). Usually, to solve this type of problem, researchers and decision makers use the Multi-Criteria Decision Making (MCDM) methods (Ishizaka and Labib, 2011; Cristóbal and Ramón, 2012).

Several MCDM methods are present in the literature. However, researchers favor the use of the Analytical Hierarchy Process (AHP) to solve complex decisions with different criteria (Russo and Camanho, 2015; Dožić and Kalić, 2015).

The AHP is a mathematical approach developed first by Satty in 1977 (Saaty, 1980). The advantage of this technique is the decrease of complex decisions to a series of pairwise comparisons. Moreover, it is a valuable method to check the consistency of the decision, thus reducing the bias in the decision-making progression (Saaty, 2012).

At the beginning of each AHP process we defined a goal and selected the alternatives and criteria. Afterwards, a pairwise comparison matrix (A) is generated. Let us assume that n is the number of criteria, then the matrix (A) will be a matrix where each entry a_{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 (Saaty, 1980).

$$A=\begin{pmatrix} 1 & a & b \\ 1/a & 1 & c \\ 1/b & 1/c & 1 \end{pmatrix}$$

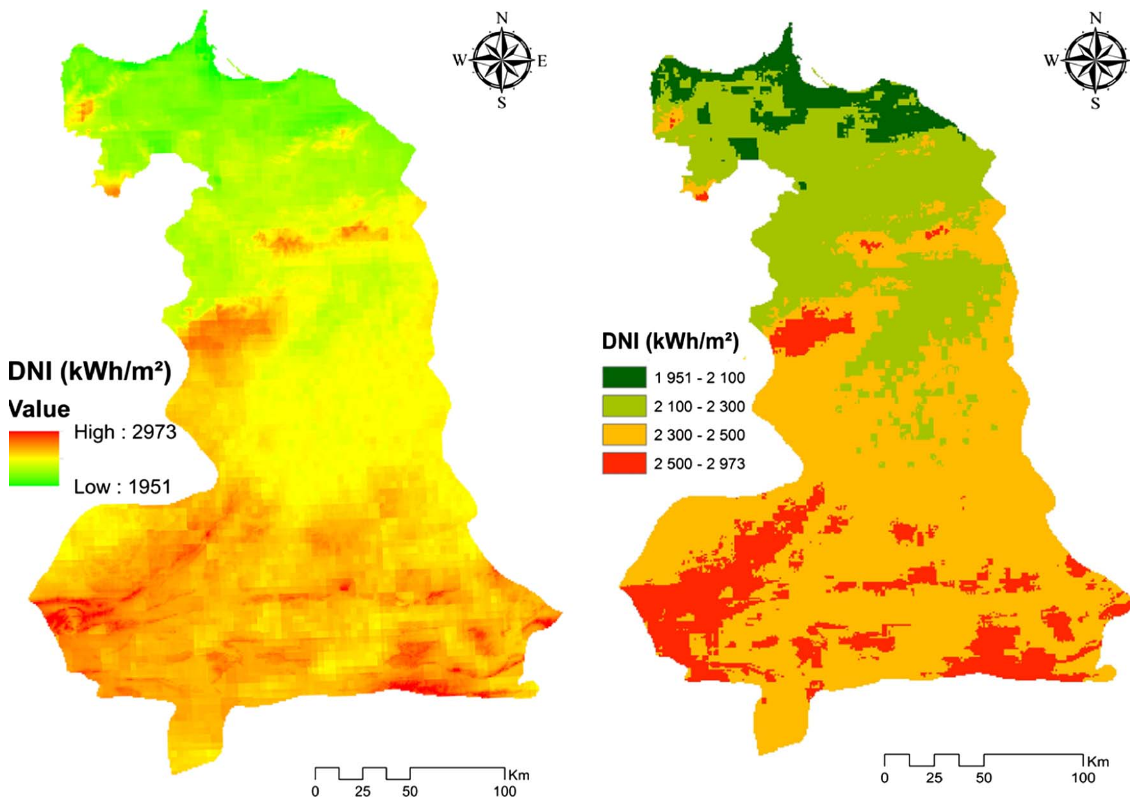

Fig. 2. On the left-hand side, the Direct Normal Irradiation (DNI) map of the Eastern region of Morocco over 20 years. On the right-hand side the discontinuous DNI classes selected as indicators for the AHP method.

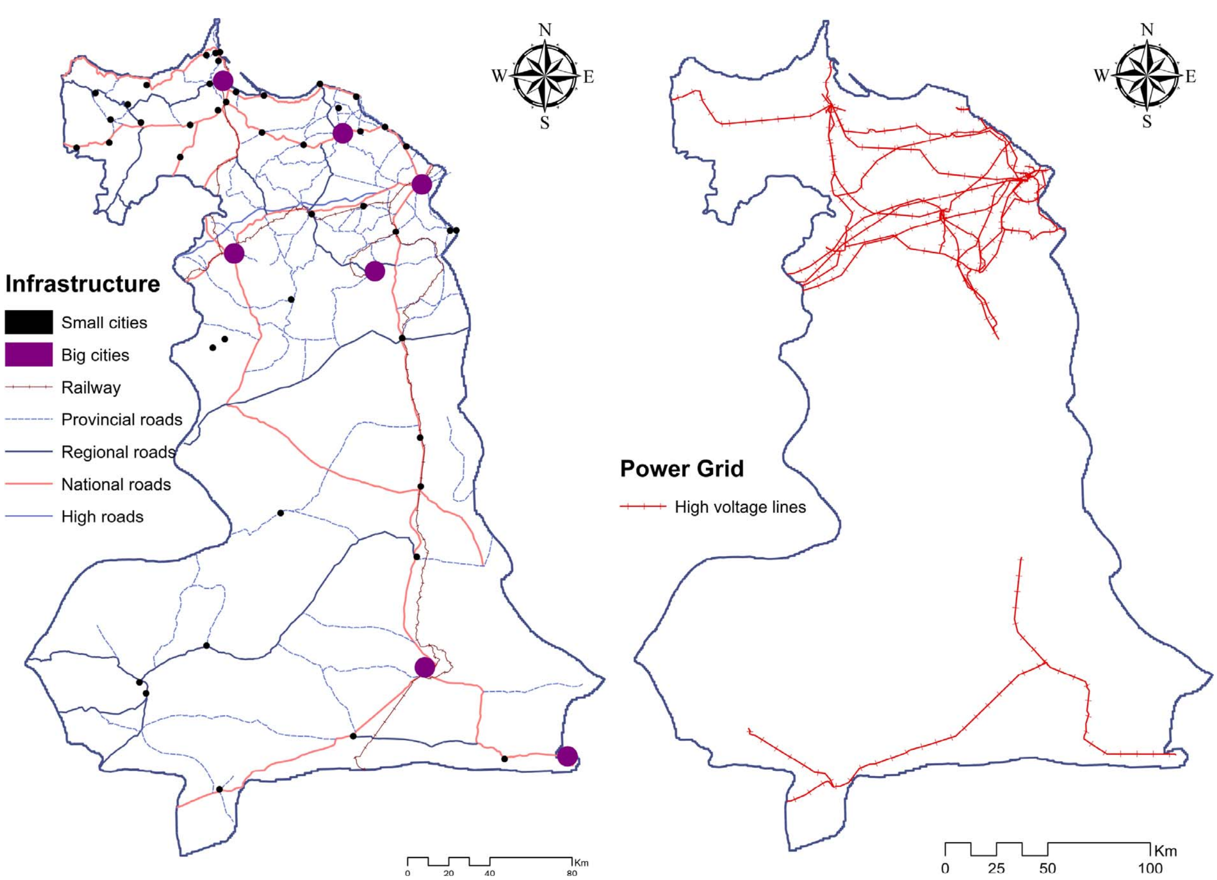

Fig. 3. On the left-hand side, the infrastructure map of Eastern Morocco including the complete road network, the cities and the railways. On the right-hand side, the complete power grid of Eastern Morocco.

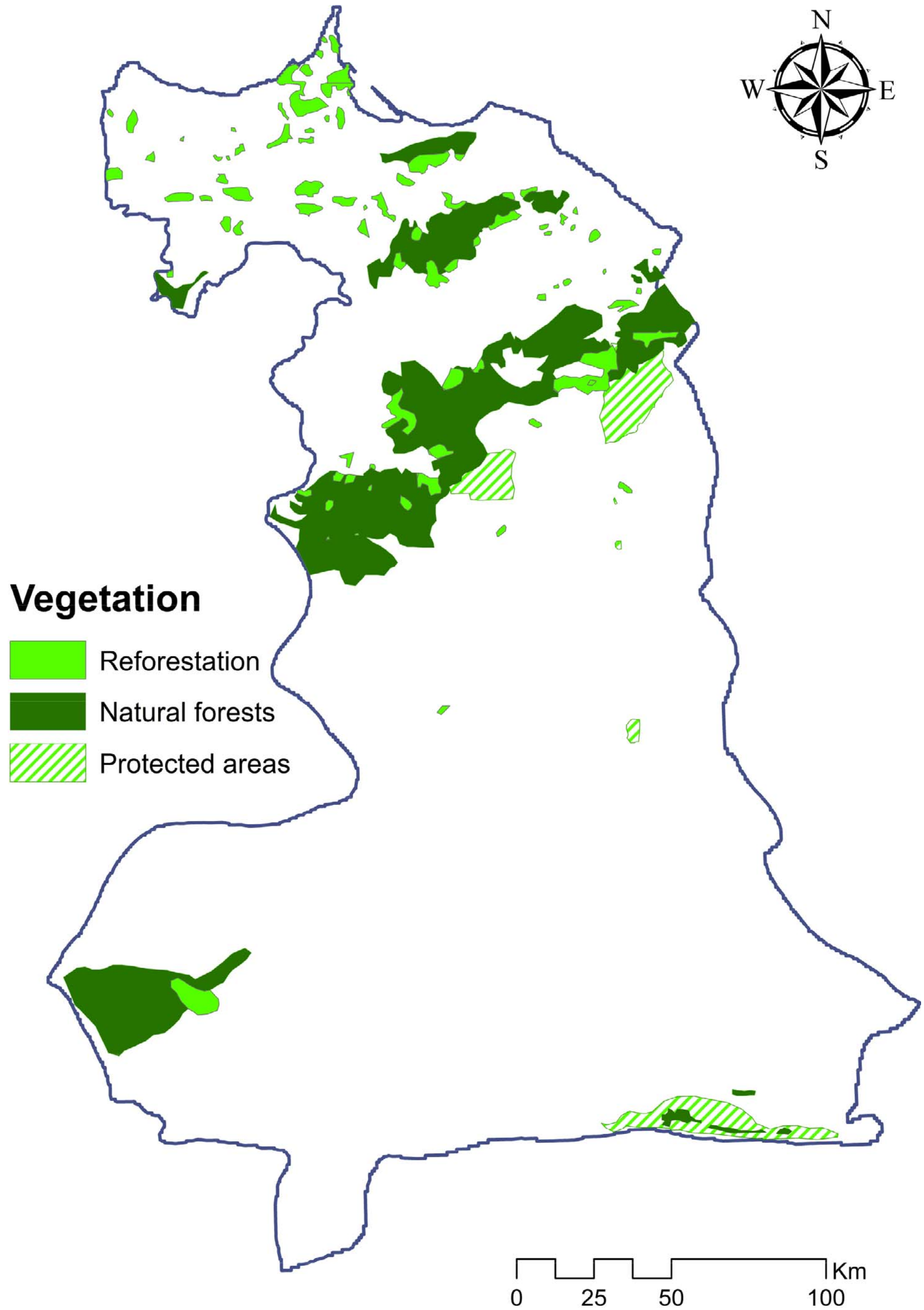

Fig. 4. The vegetation map of the Eastern region of Morocco.

To calculate the weight of each criterion we need to normalize the matrix (A) 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 criterion's weights.

After a certain number of pairwise comparisons, some inconsistency can arise. The AHP includes a parameter to control the consistency of the weight values called the Consistency Ratio (CR). To calculate the CR we must first calculate the consistency index (CI) using the formula:

$$CI = \frac{\lambda_{MAX}-N}{N_1}$$

where $\lambda_{\max}$ is the eigenvalue of the pairwise comparison matrix and N is the number of the criteria. At the end, the RC 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 (Saaty, 1980).

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

To obtain significant results with the AHP, the CR must be equal or less than 0.10 ($CR \le 0.10$), otherwise ($CR > 0.10$) there is an inconsistency, and the pairwise comparison values need to be adjusted.

2.4. Criteria description

Before defining the necessary criteria for the CSP plant site selection, let us start with the constraints analysis. As mentioned above, a mask of non-suitable sites has been built. This mask encloses:

- Buffer of road and railways network = 100 m.

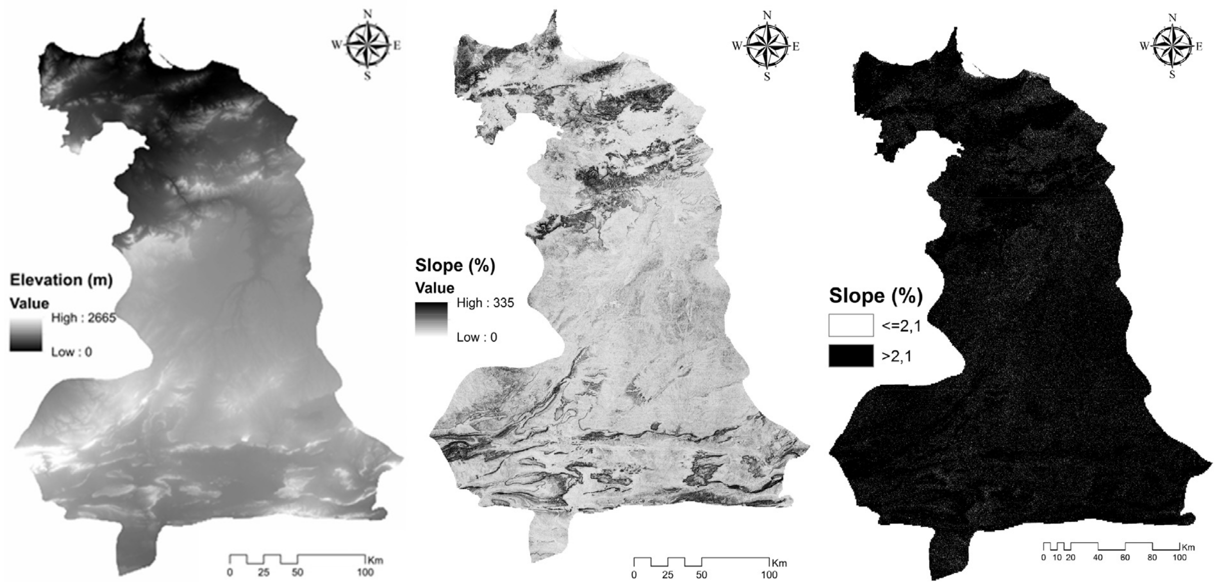

Fig. 5. The digital elevation model of Eastern Morocco (left). The slope gradient map of Eastern Morocco (middle). The areas with slopes above and under 2.1% (right).

- Buffer of the residential = 5 km and 2 km to the big and small cities respectively.
- Buffer of the vegetation and protected area = 500 m.
- Buffer of hydrology (Dams and waterways) = 500 m.

In a decision-making process, each criterion represents a measurable aspect of a judgment that makes it possible to characterize and quantify alternatives. In this study, the criteria were chosen based on previous case studies from the literature, as well as our own objectives. For this reason, and for each cooling scenario, four criteria (Climate, Orography, Location and Water resource) and eight factors were defined for the site selection process (Table 1).

2.4.1. Climate

The performance of the CSP power plants are not significantly affected by the temperature (Dierauf et al., 2013). Moreover, the CSP plants use the direct component of the solar irradiation (DNI) to produce the electricity because it can be concentrated.

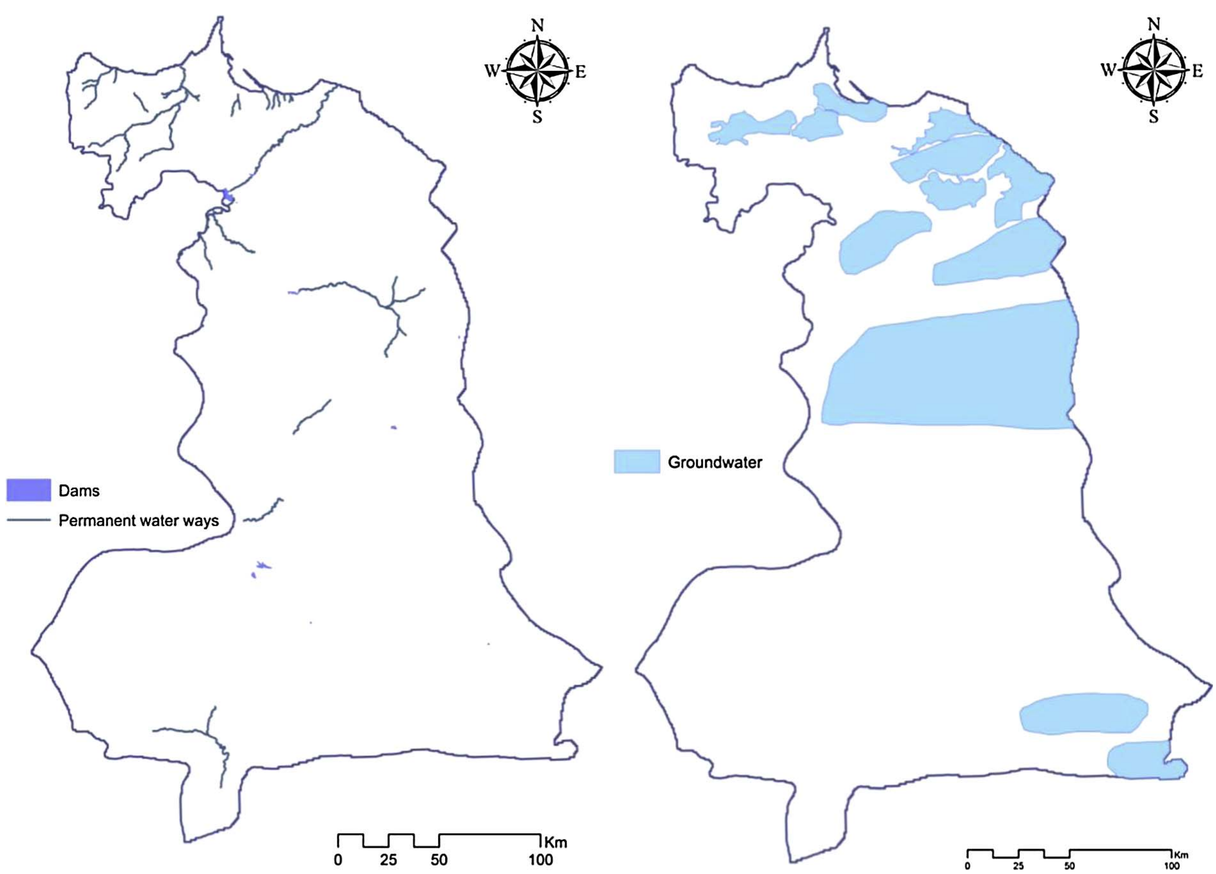

Fig. 6. The hydrological network of Eastern Morocco. Left: waterways and dams, right: Groundwater.

Table 1
The criteria and factors used in this study.

Goal	Criteria	Factors	Indicators
Select the most suitable sites to host CSP power plant	Climate	Direct normal irradiation ($kWh/m^2/a$)	2500–2973
			2300–2500
			2100–2300
			1951–2100
	Orography	Slope (%)	< 0.5
			0.5–1
			1–1.5
			1.5–2.1
	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 underground water (km)	on the underground surface
			2.5 km from the land surface
			5 km far away from the border of the surface
			> 5 km from the board of the surface

Table 2
Pairwise comparison matrix for the wet cooling scenario.

	Climate	Orography	Water resource	Location	Weight%	CR
Climate	1	3	5	9	57.6	0.042
Orography	0.3	1	3	5	25.6	
Water resource	0.2	0.3	1	3	11.7	
Location	0.1	0.2	0.3	1	5.1	

Table 3
Pairwise comparison matrix for the dry cooling scenario.

	Climate	Orography	Location	Water resource	Weight%	CR
Climate	1	3	5.5	9	58.8	0.025
Orography	0.3	1	2.5	6	25.5	
Location	0.2	0.4	1	2	10.4	
Water resource	0.1	0.2	0.5	1	5.3	

Table 4
Factors weight.

Factor	Weight (%)	
	Dry cooling	Wet cooling
Direct normal irradiation ($kWh/m^2/a$)	58.8	57.6
Slope (%)	25.5	25.6
Distance to residential (km)	4.8	2.3
Distance to Electricity grid (km)	3.3	1.6
Distance to road and railway network (km)	2.3	1.1
Distance to waterways (km)	3.3	7.3
Distance to dams (km)	1.5	3.3
Distance to ground water (km)	0.5	1.2

Because on economic considerations, the minimum DNI value required for a region to host CSP plants is 1800 kW h/m^2/a (Breter and Knies, 2009). In Spain, the DNI value is between 2000 and 2100 kW h/m^2/a, while in South Africa this value can reach 2900 kW h/m^2/a (Eaton, 2013). In this study, the climate criterion is represented by the DNI value, because it is the climatic factor that directly influences the feasibility of a CSP project. This criterion was divided into four subcriteria based on the amount of the DNI in the region, as well as other countries solar potential in order to ensure that the selected sites will be competitive in the solar market. We need to mention that no exclusion criteria have been affected to the DNI, because, in our field of study the values are everywhere above 1800 kW h/m^2/a (Fig. 1).

2.4.2. Orography

As mentioned above, the CSP power plants, especially parabolic trough technology, requires a flat land. According to the German Aerospace Center (DLR), the threshold of a CSP project should be 2.1% (Schilings et al., 2012). The slope orientation does not significantly affect the site selection, as opposed to PV, which must be oriented to the south in the northern hemisphere and to the north in the southern hemisphere. For this purpose, the orography criterion in this paper is represented by the land slope.

2.4.3. Location

The best location for any power plant is one close to the road network for the transportation of the materials and workers. It must also be near the electricity grid (high voltage lines) to inject the electricity produced. Moreover, since the power plant needs workers, it must be somewhat close to residential areas (rural and urban). In this paper, the location criterion was divided into three factors: "distance to residential", "distance to road and railway network" and "distance to the grid network."

2.4.4. Water resource

Even if the water availability is crucial for solar power plants, especially in arid regions, very few studies on the literature deal with this factor. Two options of the power block cooling exist: dry and wet. In this paper, we are investigating the suitability of Eastern Morocco to host CSP plants with both cooling techniques. The water resource criterion is divided to three factors: distance to waterways, distance to dams, and distance to groundwater.

3. Results and discussion

In this study, a combination of the Multi-Criteria Decision Making (MCDM) and Geographic Information System (GIS) tool has been used to evaluate the suitability of Eastern Morocco to host CSP power plants. Two different CSP technologies with two cooling scenarios (wet and dry) were investigated. The pairwise comparison matrices of the two scenarios are presented in Tables 2 and 3.

Those matrices were calculated using the Analytical Hierarchy

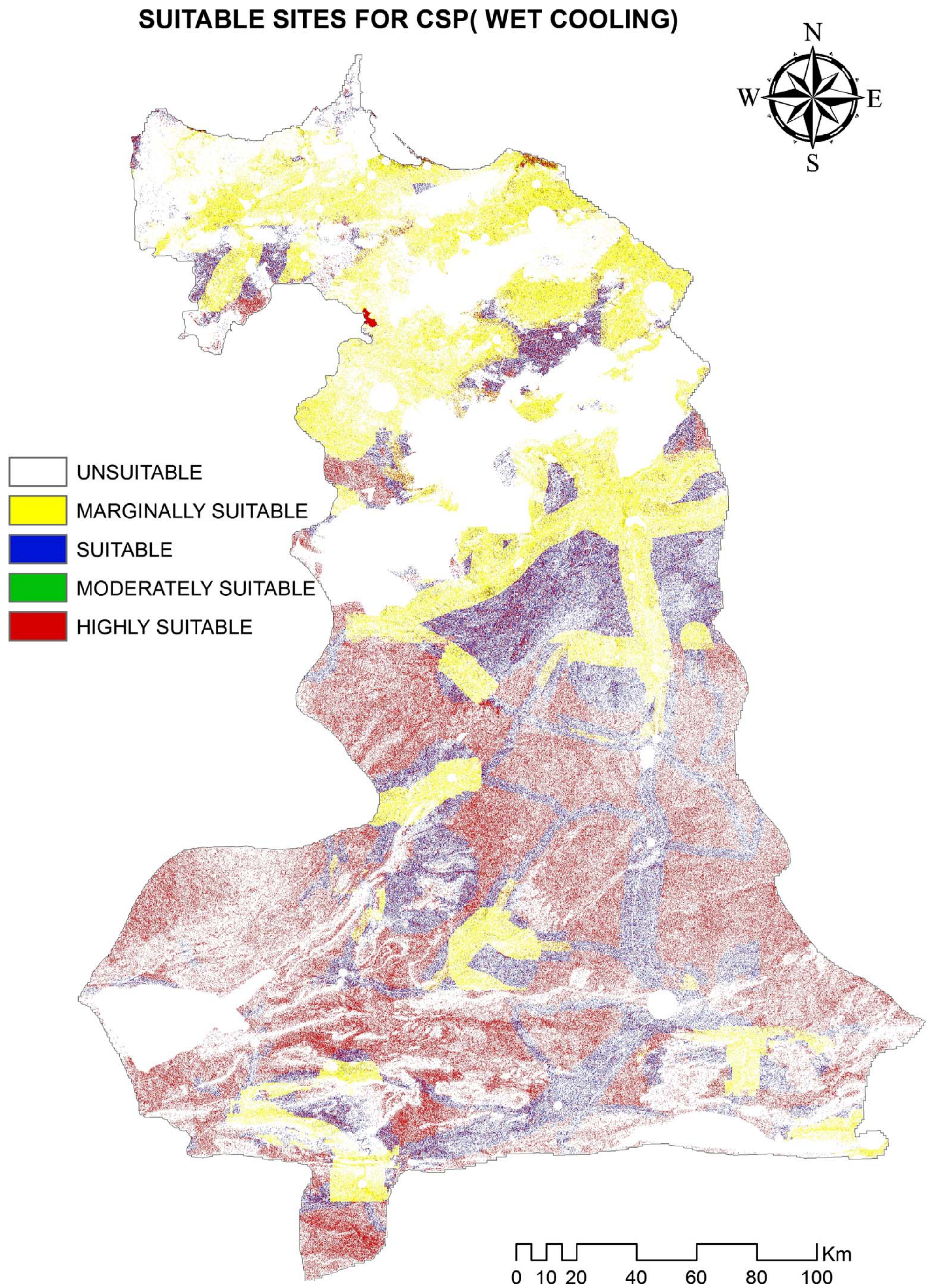

Fig. 7. The sites suitability map for the installation of CSP power plants with wet cooling technique in Eastern Morocco.

Process (AHP). The hierarchical decision data were made based on the literature and our assumption after discussing the specifics of the region with experts in the field. In Fact, for both cooling technologies the most important criterion is the climate/DNI, which is considered 3 times important than the orography, the second important site selection criteria in our case. The main difference between the two technologies is the importance of the water resource. This criterion is considered 5 times less important than the DNI if the wet cooling scenario is selected and 9 times in the case of the dry cooling.

For both cooling scenarios, the Consistency Ratio (CR) is less than 10% (4.2% for the wet and 2.5% for the dry), which make the results of our pairwise comparisons acceptable and the values consistent.

From the AHP weight analysis, the climate, or in other words, the Direct Normal Irradiation (DNI) is the most important criterion for both CSP plant technologies. The solar potential is directly connected to the electricity production. Thus, the target site for CSP installation must be well irradiated in order to be competitive in the electricity market. The weights are of 58.8% for the dry cooling and 57.6% for the wet cooling.

The Orography criterion comes in second, with a weight of 25.6% for the wet cooling and 25.5% for the dry cooling. This is reasonable because the presence of the slopes is a limiting factor in the site selection, and it increases the investment costs for building a CSP plant significantly.

The difference between the two CSP plant technologies appears when assessing water availability and location. Obviously, when the dry cooling option is selected, the water consumption will decrease significantly. Hence, the presence of a water resource close to the potential installation site becomes less significant if compared to the accessibility.

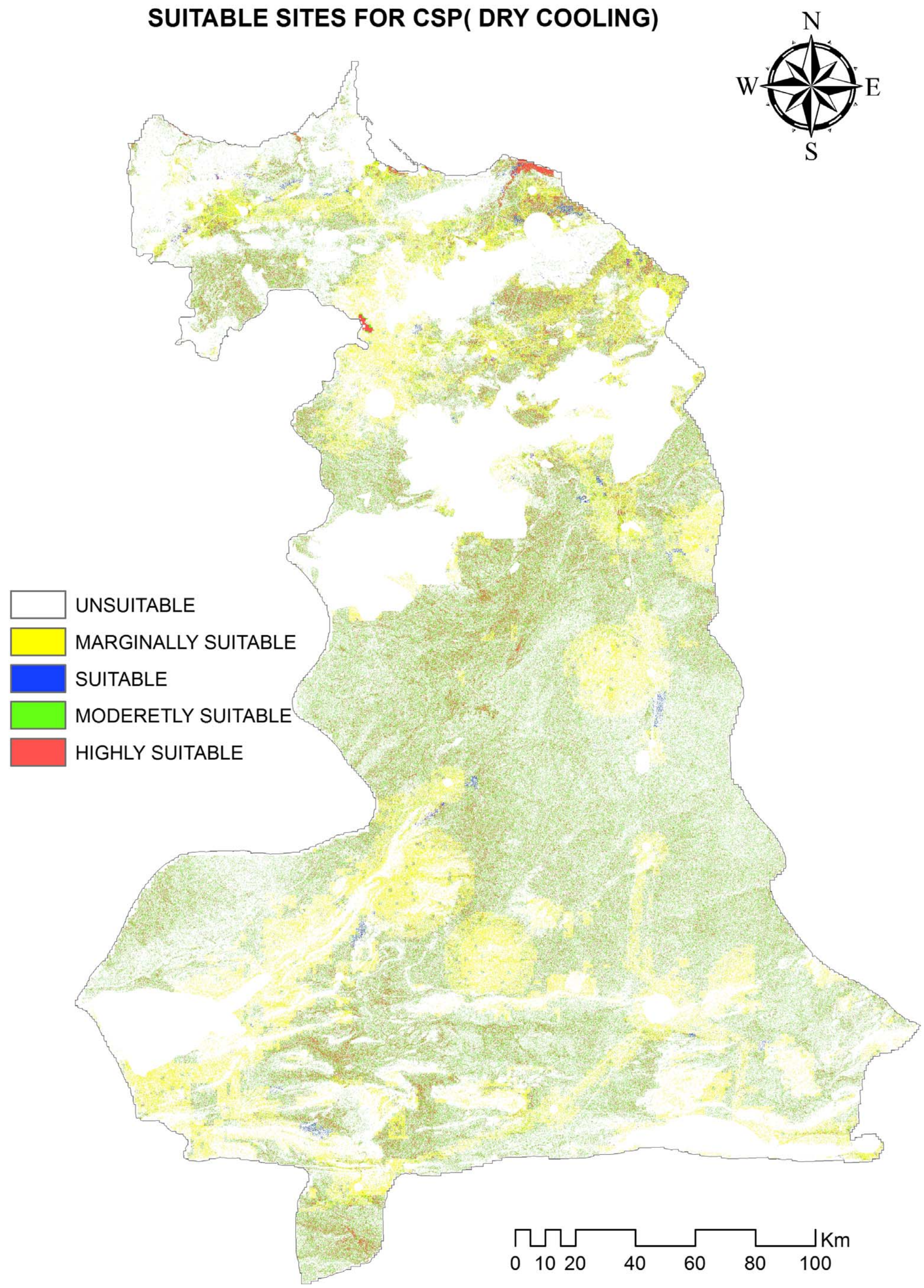

Fig. 8. The sites suitability map for the installation of CSP power plants with dry cooling technique in Eastern Morocco.

For the dry cooling technique, the weight of the water resource is 5.3%, while, for the wet cooling technique, it is 11.7%. The location weights are of 5.1% and 10.4% for the wet and dry cooling scenarios, respectively.

Regarding the factors, the same AHP process has been repeated and the weights are presented on the Table 4.

For sustainability reasons, the water resource to be used in a power plant must be from a renewable source (waterways or dams). For instance, the NOOR1 solar complex in Ouarzazate (south of Morocco) uses the water pumped from the Eddahbi dam, located 12 km from the plant (www.afdb.org). That is why the ground water factor has the lowest weight for both cooling techniques.

The calculations for the dry cooling scenario give the weights of 58.8% for the DNI, 25.5% for the slope, 4.8% for the distance from residential areas, 3.3% for the distance from the grid, 2.3% for the distance from the road network, 3.3% for the distances from waterways, 1.5% for the distance from dams, and 0.5% for the distance from underground water.

The weights for the wet cooling factors are of 57.6%, 25.6%, 2.3%, 1.6%, 1.1%, 7.3%, 3.3% and 1.2% for each factor in the order mentioned above.

Using a GIS tool, those evaluation criteria were used to create suitability maps for the implementation of CSP power plants for Eastern Morocco. The final suitability index maps are grouped into five classes: unsuitable, marginally suitable, suitable, moderately suitable and highly suitable (Figs. 7 and 8).

Table 5
Summary of the planimetric surfaces and the suitability indexes for Eastern Morocco.

Suitability	Planimetric Area (km^2)		Percentage	
	Dry	Wet	Dry%	Wet%
Unsuitable	52,107	52,107	76.3	76.3
Marginally suitable	3881	5284	5.7	7.7
Suitable	112	2874	0.2	4.2
Moderately suitable	8451	24	12.4	0.04
Highly suitable	3743	8006	5.5	11.7
Total	68,295	68,295	100	100

As a result, and according to the GIS calculations, Eastern Morocco can be considered as a good location for hosting CSP plants with both cooling techniques. In fact, for the wet cooling scenario, 11.7% of the total area is highly suitable, 4.2% suitable, and 7.7% marginally suitable to host solar plants.

Regarding the dry cooling, 5.7% from the total area is marginally suitable, 12.4% moderately suitable, and 5.5% is highly suitable. The unsuitable areas, or in other words, the constraint mask, represents 76.3% of the surface of Eastern Morocco. The results are summarized in Table 5.

4. Conclusions

The objective of this paper is to assess the most suitable sites to host CSP power plants in Eastern Morocco by combining Multi-Criteria Decision Making and Geographical Information System tools. For this reason, four criterions and eight sub-criterions were selected. Their weights were calculated, and suitability maps have been created for CSP plants with both dry and wet cooling technics. In the literature, very few studies deal with the integration of CSP, especially for Morocco, which has an ambitious project to produce 2000 MW from solar Energy. This project has begun with the inauguration of the NOOR1 complex, the largest CSP power plant in the world. In order to promote and push forward the investments in CSP, the same method can be applied to different regions in Morocco (or in other countries) by selecting similar criterions and weights, as well as, including the water availability and the cooling technics in the assessment.

The results show that Eastern Morocco can be considered as a good location to host CSP power plants with a proportion of 11.7% and 5.5% for the wet and the dry cooling, respectively. The Non-suitable areas represent 76.3% of the total areas.

Knowing the fact that Eastern Morocco will host the second solar complex in the Moroccan Solar Plan and the new regulation adopted by the country on the liberalization of the electricity market, the results of this study can be considered as highly important, as it provides the policymakers as well as local and international investors with an idea of the potential of Eastern Morocco to host CSP plants. This will encourage and boost the investments in solar energy in this region. Thus, creating new jobs and a sustainable development, not only for the region, but also for the whole country.

Acknowledgment

Authors would like to warmly Acknowledge the “ONEE”, the “DREF”, and the “ABH-Moulouya” for sharing the GIS layers used in this study.

References

Alami Merrouni, A., Amrani, A., Mezrhab, A., 2017a. Electricity production from large scale PV plants: benchmarking the potential of Morocco against California, US. Energy Proc. 119, 346–355.

Ait Lahoussine, O.H., Alami Merrouni, A., Moussaoui, M.A., Mezrhab, A., 2015. Electricity yield analysis of a 50 MW solar tower plant under Moroccan climate. In: Proc. ICEIT (International Conference, Electrical and Information Technologies) 2015 Conf. Marrakech, Morocco, pp. 252–256. http://dx.doi.org/10.1109/EITech. 2015. 7162978.

Alami Merrouni, A., Ait Lahoussine, O.H., Moussaoui, M.A., Mezrhab, A., 2016a. Analysis and comparison of different Heat Transfer Fluids for a 1 MWe parabolic trough collector. In: Proc. ICEIT (International Conference, Electrical and Information Technologies) 2016 Conf. Tangiers, Morocco, pp. 510–515. http://dx.doi.org/10. 1109/EITech. 2016.7519653.

Alami Merrouni, A., Mezrhab, A., Ghennioui, A., Naimi, Z., 2017b. Measurement, comparison and monitoring of solar mirror's specular reflectivity using two different Reflectometers. Energy Proc. 119, 433–445.

Alami Merrouni, A., Mezrhab, A., Moussaoui, M.A., Ait Lahoussine, O.H., 2016b. Integration of PV in the Moroccan buildings: simulation of a small roof system installed in Eastern Morocco. Int. J. Renew. Energy Res. 6, 306–314.

Alami Merrouni, A., Ghennioui, A., Wolfertstetter, F., Mezrhab, A., 2017. The uncertainty of the HelioClim-3 DNI data under Moroccan climate. In: AIP Conference Proceedings, vol. 1850, No. 1, AIP Publishing, pp. 140002.

Alsamamra, H., Ruiz-Arias, J.A., Pozo-Vázquez, D., Tovar-Pescador, J., 2009. A comparative study of ordinary and residual kriging techniques for mapping global solar radiation over southern Spain. Agric. For. Meteorol. 149, 1343–1357.

Bachour, D., Perez-Astudillo, D., 2014. Ground-measurement GHI Map for Qatar. Energy Proc. 49, 2297–2302.

Boie, I., Kost, C., Bohn, S., Agsten, M., Bretschneider, P., Snigovyi, O., Pudlik, M., Ragwitz, M., Schlegl, T., Westermann, D., 2016. Opportunities and challenges of high renewable energy deployment and electricity exchange for North Africa and Europe e Scenarios for power sector and transmission infrastructure in 2030 and 2050. Renew. Energy 87, 130–144.

Bravo, J.D., Casals, X.G., Pascua, I.P., 2007. GIS approach to the definition of capacity and generation ceilings of renewable energy technologies. Energy Pol. 35, 4879–4892.

Breter, C., Knies, G., 2009. Global energy supply potential of concentrating solar power. In: Proc. SolarPACES Conf., Berlin, Germany..

Carrión, J.A., Estrella, A.E., Dols, F.A., Toro, M.Z., Rodríguez, M., Ridao, A.R., 2008. Environmental decision-support systems for evaluating the carrying capacity of land areas: optimal site selection for grid-connected photovoltaic power plants. Renew. Sust. Energy Rev. 12, 2358–2380.

Clifton, J., Boruff, B.J., 2010. Assessing the potential for concentrated solar power development in rural Australia. Energy Pol. 38, 5272–5280.

Cristóbal, S., Ramón, J., 2012. Multi criteria analysis in the renewable energy industry. http://dx.doi.org/10.1007/978-1-4471-2346-0.

Dierauf, T., Growitz, A., Kurtz, S., Cruz, J.L.B., Riley, E., Hansen, C., 2013. Weather-Corrected Performance Ratio. Tech. Rep. NREL/TP-5200-57991. National Renewable Energy Laboratory, Golden CO.

Dožić, S., Kalić, M., 2015. Comparison of two MCDM Methodologies in Aircraft type Selection Problem. Transp. Res. Procedia 10, 910–919.

EASAC Policy Report: Concentrating Solar Power: its potential contribution to a sustainable energy future, 2011. < https://easac.eu/ > (last accessed March 1, 2018).

Eaton, A., 2013. DNI values in SA are amongst the best in the world. < http://newenergyupdate.com/csp-today/markets/dni-values-sa-are-amongst-best-world > (last accessed March 1, 2018).

Fluri, T.P., 2009. The potential of concentrating solar power in South Africa. Energy Pol. 37, 5075–5080.

Gastli, A., Charabi, Y., Zekri, S., 2010. GIS-based assessment of combined CSP electric power and seawater desalination plant for Duqum-Oman. Renew. Sust. Energy Rev. 14, 821–827.

Ghazi, S., Sayigh, A., Kenneth, I., 2014. Dust effect on flat surfaces – a review paper. Renew. Sust. Energy Rev. 33, 742–751.

Günther, M., Joemann, M., Site Assessment. enerMENA CSP teaching materials. < http://www.energyscience.org/bibliotheque/cours/1361457716Chapter%2014%20%20site.pdf > (last accessed March 1, 2018).

Ishizaka, A., Labib, A., 2011. Review of the main developments in the analytic hierarchy process. Exp. Syst. Appl. 38, 14336–14345.

Janjai, S., Masiri, I., Laksanaboonsong, J., 2013. Satellite-derived solar resource maps for Myanmar. Renew. Energy 53, 132–140.

Kousksou, T., Allouhi, A., Belattar, M., Jamil, A., El Rhafiki, T., Arid, A., Zeraouli, Y., 2015. Renewable energy potential and national policy directions for sustainable development in Morocco. Renew. Sust. Energy Rev. 47, 46–57.

Liqreina, A., Qoaider, L., 2014. Dry cooling of concentrating solar power (CSP) plants, an economic competitive option for the desert regions of the MENA region. Sol. Energy 103, 417–424.

Maghami, M.R., Hizam, H., Gomes, C., Radzi, M.A., Rezadad, M.I., Hajighorbani, S., 2016. Power loss due to soiling on solar panel: a review. Renew. Sust. Energy Rev. 59, 1307–1316.

Mahtta, R., Joshi, P.K., Jindal, A.K., 2014. Solar power potential mapping in India using remote sensing inputs and environmental parameters. Renew. Energy 71, 255–262.

Martins, F.R., Pereira, E.B., Abreu, S.L., 2007. Satellite-derived solar resource maps for Brazil under SWERA project. Sol. Energy 81, 517–528.

Ouammi, A., Zejli, D., Dagdougui, H., Benchrifa, R., 2012. Artificial neural network analysis of Moroccan solar potential. Renew. Sust. Energy Rev. 16, 4876–4889.

Perez, R., Ineichen, P., Moore, K., Kmiecik, M., Chain, C., George, R., Vignola, F., 2002. A new operational model for satellite-derived irradiances: description and validation. Sol. Energy 73, 307–317.

Potić, I., Golić, R., Joksimović, T., 2016. Analysis of insolation potential of Knjaževac Municipality (Serbia) using multi-criteria approach. Renew. Sust. Energy Rev. 56, 235–245.

Qoaider, L., Liqreina, A., 2015. Optimization of dry cooled parabolic trough (CSP) plants for the desert regions of the Middle East and North Africa (MENA). Sol. Energy 122, 976–985.
Russo, R.de.F.S.M., Camanho, R., 2015. Criteria in AHP: a systematic review of literature. Procedia Comput. Sci. 55, 1123–1132.
Saaty, T.L., 2012. Decision Making for Leaders. RWS Publications.
Saaty, T.L., 1980. The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill.
Sánchez-Lozano, M., Teruel-Solano, J., Soto-Elvira, P.L., García-Cascales, M.S., 2013. Geographical Information Systems (GIS) and Multi-Criteria Decision Making (MCDM) methods for the evaluation of solar farms locations: Case study in south-eastern Spain. Renew. Sust. Energy Rev. 24, 544–556.
Sarver, T., Al-Qaraghuli, A., Kazmerski, L.L., 2013. A Comprehensive review of the impact of dust on the use of solar energy: history, investigations, results, literature, and mitigation approaches. Renew. Sust. Energy Rev. 22, 698–733.
Schilings, C., Wandrer, T., Huld, T., 2012. "CSP-GIS" for Morocco. < http://www.endorse-fp7.eu/sites/www.endorse-fp7.eu/files/docs/ENDORSE_WP405_deliverable_v1.1.pdf > (last accessed March 1, 2018).
Schlecht, M., Meyer, R., 2012. Site selection and feasibility analysis for concentrating solar power (CSP) systems. Concentrating Sol. Power Technol. 91–119.
Sooriyaarachchi, T.M., Tsai, I.-T., El Khatib, S., Farid, A.M., Mezher, T., 2015. Job creation potentials and skill requirements in, PV, CSP, wind, water-to-energy and energy efficiency value chains. Renew. Sust. Energy Rev. 52, 653–668.
Tahri, M., Hakdaoui, M., Maanan, M., 2015. The evaluation of solar farm locations applying geographic information system and multi-criteria decision- making methods: case study in southern Morocco. Renew. Sust. Energy Rev. 51, 1354–1362.
Tsikalakis, A., Tomtsi, T., Hatziargyriou, N.D., Poullikkas, A., Malamatenios, Ch., Giakoumelos, E., Jaouad, O.C., Chenak, A., Fayek, A., Matar, T., Yasin, A., 2011. Review of best practices of solar electricity resources applications in selected Middle East and North Africa (MENA) countries. Renew. Sust. Energy Rev. 15, 2838–2849.
Urrejola, E., Antonanzas, J., Ayala, P., Salgado, M., Ramírez-Sagner, G., Cortés, C., Pino, A., Escobar, R., 2016. Effect of soiling and sunlight exposure on the performance ratio of photovoltaic technologies in Santiago, Chile. Energy Convers. Manage. 114, 338–347.
Uyan, M., 2013. GIS-based solar farms site selection using analytic hierarchy process (AHP) in Karapinar region, Konya/Turkey. Renew. Sust. Energy Rev. 28, 11–17.
Vernay, C., Pitaval, S., Blanc, P., 2014. Review of satellite-based surface solar irradiation databases for the engineering, the financing and the operating of photovoltaic systems. Energy Proc. 57, 1383–1391.
Viana, T.S., Rüther, R., Martins, F.R., Pereira, E.B., 2011. Assessing the potential of concentrating solar photovoltaic generation in Brazil with satellite-derived direct normal irradiation. Sol. Energy 85, 486–495.
Ziuku, S., Seyitini, L., Mapurisa, B., Chikodzi, D., van Kuijk, K., 2014. Potential of concentrated solar power (CSP) in Zimbabwe. Energy Sustain. Develop. 23, 220–227.

Web sites

https://eosweb.larc.nasa.gov/sse/ (last accessed March 1, 2018).
https://solargis.info/ (last accessed March 1, 2018).
http://www.solar-med-atlas.org/solarmed-atlas/map.htm#t=dni (last accessed March 1, 2018).
http://www.oriental.ma/fr/Page-16/les-grands-projets (last accessed March 1, 2018).
IEA, Technology Roadmap, Solar Thermal Electricity, 2014.
https://www.nrel.gov/csp/solarpaces/projects_by_status.cfm?status=Operational (last accessed March 1, 2018).
Rapport d'activités 2012, Morocco. http://www.one.org.ma/ (last accessed March 1, 2018).
IRESEN map server. http://www.iresen.org/mapserver/ (last accessed March 1, 2018).
http://www.hcp.ma/regionoriental/docs/ETUDESREGIONALES/ORIENTALatoutspotentialites.pdf (last accessed March 1, 2018).
https://www.afdb.org/fileadmin/uploads/afdb/Documents/Environmental-and-Social-Assessments/Morocco_-_Ouarzazate_Solar_Power_Station_Project_II_-_ESIA_Summary.pdf (last accessed March 1, 2018).