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Sustainable siting of solar power installations in Mediterranean using a GIS/AHP approach

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This study aims to present and test a methodology for clarifying and prioritizing, the most suitable locations for siting solar power installations. By employing Geographical Information Systems and the Analytical Hierarchy Process (AHP), the recommended sustainable siting areas for solar power generation farms siting are identified, allowing the application of a spatial multi-criteria decision-making approach. The methodology identifies the available areas for solar farms siting, based on exclusion criteria defined from the current legislation. Furthermore, the available siting areas are evaluated and ranked through a multi-criteria analysis, considering also the relative importance of the selected criteria, through the AHP implementation performed by involved energy-related groups. The developed methodology employs different types of criteria, such as techno-economic and socio-environmental, it takes into account the distinct opinions of different stakeholders and it enables the evaluation of different scenarios. Finally, the methodology was applied for the case study of the Regional Unit of Rethymno, where the results, in terms of the potential maximum power that can be produced from the highest priority areas are 530 MWp for photovoltaics and 30 MW for Concentrated Solar Power systems.

1. Introduction

Renewable Energy Sources (RES) will continue to play a key role for the EU to meet its energy needs beyond 2020, as Member States have already agreed to a new RES target for 2030 [1]. These new targets concern a 40% cut in greenhouse gas emissions compared to 1990 levels [2] and at least a 32% share of RES consumption in the EU as a whole by 2030 [3]. Therefore, the growing concern for environmental issues and more specifically for the environmental impacts of the conventional electricity generation systems has opened up the dialogue for the RES exploitation in a rational and sustainable way.

The energy sector in Crete has unique characteristics, due to Crete's island nature, sensitive ecosystems and distance from the mainland. Furthermore, Crete has an off-grid electricity production system, where the supply of conventional energy resources occurs only via sea transportation [4]. Finally, the increasing energy demand, especially in the tourist season, as well as the European and national targets for RES promotion have led to an increasing interest in investments in Renewable Energy Technologies (RETs).

To meet this demand, the region of Crete, due to its position and the Mediterranean climate, can effectively accommodate the installation of RETs. The strong Mediterranean winds encourage the siting of wind farms, the solar potential is ideal for installations exploiting the solar radiation and the developed agricultural sector, due to Crete's mild climatic conditions, can launch the production of energy from biomass from agriculture residues.

However, in order to achieve a sustainable siting of RETs, together with the greatest possible exploitation of RES, the social and environmental implications accruing must be taken into consideration [5], such as conflicts of land use, preservation of the natural environment and sensitive ecosystems and social reactions. Photovoltaics (PVs) are usually connected with limited environmental impacts, allowing the direct conversion of solar radiation to electricity and avoiding Greenhouse Gases (GHGs) emissions. However, large-scale PV systems are linked to the significant area requirements for their operation, causing visual impacts, potential occupation of arable land and disturbance of the local ecosystem (flora and fauna); similarly, the Concentrated Solar Power (CSP) systems face analog problems [6].

In the literature, the problem of defining suitable locations for

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Abbreviations list

AHP	Analytical Hierarchy Process
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiance
ELECTRE	Elimination and Choice Translating Reality
GHI	Global Horizontal Irradiance
GIS	Geographic Information Systems
MCDM	Multi-Criteria Decision Making
OWA	Ordered Weighted Averaging
RES	Renewable Energy Sources
RET	Renewable Energy Technology
SFSPSD-RES	Specific Framework for Spatial Planning and Sustainable Development for the RES
TOPSIS	Technique for Order Preference by Similarity to Ideal Solutions

siting RETs is a common one, where researchers usually employ Multi-Criteria Decision-Making (MCDM) and Geographical Information Systems (GIS) tools to optimally combine the different evaluation and exclusion criteria. However, studies vary widely with respect to the energy technologies considered, the methodologies applied and the spatial scale of the area taken into consideration. In addition, different MCDM techniques are employed in RETs site assessment studies, such as the Analytical Hierarchy Process (AHP), the Elimination and choice Translating Reality (ELECTRE) method, the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), the Ordered Weighted Averaging (OWA) technique, as well as hybrid fuzzy-MCDM methodologies. AHP is the most commonly used MCDM technique in the literature for renewable energy site assessment, where the attributes' relative importance is assessed by ranking them against each other. However, studies incorporating the preferences of different RES-related stakeholders, producing realistic results, taking into account the specific characteristics and opinions in the study areas, are rare.

The aforementioned points demonstrate the need for the development of a well-structured, close to reality methodology for the sustainable siting of RETs regionally, taking also into account the distinct opinions of different local RETs siting stakeholders. Therefore, there is a need to prioritize dynamically the available locations for siting large-scale solar power installations, at a regional level, based on a wide selection of evaluation criteria. In the current paper, this methodology enables sustainable siting areas identification, by employing GIS and MCDM techniques. Finally, the adopted methodology was applied for the case study of the Regional Unit of Rethymno, where the scale of the area allowed for a more detailed and thorough analysis of all the data, which can affect the siting of solar power installations, taking into account the specific characteristics of the study area.

By using GIS, all the required information for siting RETs can be incorporated, allowing the analysis of spatial data and the production of dynamic maps. AHP allows the combination of different evaluation criteria. In addition, AHP allows the participation of different stakeholders of energy-related fields, by the implementation of pair-wise comparisons of the evaluation criteria, for their relative importance determination. With the experts' participation, the different preferences of the RETs siting stakeholders are incorporated, so that their distinct opinions reflect the complexity of this RETs siting problem, as an environmental-focused expert may favor a site, which is far away from areas of environmental interest, while an expert focused in the techno-economic aspect of the problem, may favor a site close to the road network and the electricity transmission lines. This methodology was tested during meetings and workshops with stakeholders of energy-related fields, such as the policymakers, the power supplier, the academia, the environmental groups and the engineers, in order to incorporate their opinions.

The aforementioned capabilities reinforce the developed methodology, for the minimization of the socio-environmental impacts and the maximization of the techno-economic potential. Therefore, the main aims of the current paper are:

- To *develop and test* a methodology for the facilitation of the solar farms siting.
- To *prioritize* the available siting areas for solar power installations siting, based on a wide range of evaluation criteria
- To *incorporate* the distinct opinions of different energy-related groups, on the site selection problem of the solar farms

2. State of the art

AHP methodology is quite common in the literature for defining the relative importance of the evaluation criteria, for the selection of suitable sites of solar installations. However, there is a gap in research, concerning the application of the AHP, incorporating the actual preferences of local stakeholders.

Authors usually employ a GIS tool for the exclusion of unsuitable siting locations and the production of suitability maps, while for the AHP implementation, the pair-wise comparisons of the evaluation criteria are conducted by the authors, based on their expertise or the literature and different scenarios are examined through a sensitivity analysis, not directly taking into account the stakeholders inputs ([7–11]). Aly et al. [12] used a GIS-based MCDM methodology for the identification and prioritization of the suitable locations for siting PV and CSP installations in Tanzania. For the definition of the relative importance of the selected evaluation criteria, the authors employed the AHP methodology, performing an extensive literature review for the implementation of the necessary pair-wise comparisons. An extensive literature review was also performed by Doorga et al. [13] for the evaluation criteria weights determination, using an AHP methodology, combined with a Weighted Linear Combination technique, for identifying potential solar farms sites in Mauritius. A similar approach was also employed by Asakereh et al. [14] for identifying suitable PV sites in Khuzestan province, Iran, but instead of assigning value scores to the classes of each selected criterion, they used fuzzy membership equations. Finally, Merrouni et al. [15] also employed a GIS-based AHP methodology to assess the suitability of the Eastern Morocco region to host CSP plants, while for the evaluation criteria relative importance definition, assumptions were made based on a literature review and discussions with experts. .

Besides AHP methodology, in the literature, other MCDM techniques are available for approaching the PV and CSP site selection problem including: ELECTRE, TOPSIS, OWA, Analytical Network Process, Boolean overlay operation. In addition, hybrid MCDM methods, incorporating fuzzy sets are also presented in the literature.

Sanchez-Lozano et al. [16] used the ELECTRE-TRI method for solar farms siting in the region of Murcia, Spain. Tavana et al. [17] introduced a fuzzy multi-criteria methodology for solar farm site selection in two Iranian regions, where GIS and MATLAB's fuzzy logic toolbox were employed. Mondino et al. [18] produced a synthetic index representing the ground-mounted PV plants carrying capability in North Italy, incorporating quantitative and qualitative criteria, with assigned weights produced by means of an Artificial

Neural Network analysis. Sindhu et al. [19] and Sanchez-Lozano et al. [20] applied a hybrid AHP-TOPSIS methodology for the evaluation of solar farms siting locations in India and Cartagena, Spain respectively, where AHP process was used for the criteria weights definition and TOPSIS methodology was applied for the assessment of the alternatives. In addition, the Boolean overlay was applied by Hott et al. [21] and Merrouni et al. [22] with no assignment of criteria weights in the case studies of Wyoming, USA and Eastern Morocco respectively. Moreover, Charabi and Gastli [23] performed a fuzzy multi-criteria analysis in GIS-environment for PV site suitability analysis in Oman, using OWA and AHP methodology, while a GIS-based OWA analysis was also performed by Firozjaei et al. [24] for determining optimal sites for solar power plants in Iran.

3. Methodology

The first step of the adopted GIS-based methodology constitutes of analyzing the current situation of the area investigated, locating all the required data that can affect the siting of solar power installations, such as: settlements, areas of environmental interest, areas and elements of cultural heritage, the main road network, the electricity transmission networks, the hydrographic network, land cover etc.

The next step constitutes of identifying the exclusion zones, where the siting of solar systems is not permitted, based on the national Specific Framework for the Spatial Planning and Sustainable Development for the RES (SFSPSD-RES) [25] and related legislation. After the identification of the exclusion zones and minimum allowable distances from neighbouring uses or activities, according to the national legislation plan, the legally available areas are derived. Moreover, a stricter socio-environmental scenario is also evaluated, taking into account the specific environmental characteristics of Crete.

Furthermore, the legally available areas and the available areas of the socio-environmental scenario are evaluated through a multi-criteria analysis process, based on criteria derived from the national legislation or the literature, such as solar potential, slope, elevation, distances from the main roads, the electricity transmission and hydrographic network, the areas of environmental interest and the visibility from most visited areas etc. Finally, a comprehensive literature review is performed, for the classification of each criterion to the selected criteria suitability scale (Table 1).

The next step consists of determining the relative importance of the selected evaluation criteria, through the criteria pair-wise comparisons, performed by involved groups (e.g. environmental groups, policy makers, academic community etc.) and the implementation of an AHP. Therefore, priority maps are produced, through a weighted sum aggregation of the selected criteria and the sustainable locations are determined, concerning the available siting areas of the socio-environmental scenario, with a high priority (greater than 60%), taking also into account area constraints for the solar power installations siting. Finally, a sensitivity analysis is performed, considering alternative scenarios for the criteria weights, for checking the sensitivity of the methodology's results.

The steps described above were applied for the identification of the sustainable solar installations siting areas in the Regional Unit of Rethymno (Fig. 1). In this study, ESRI's ArcGIS 10.3 was used, which is compatible with vector and raster data and offers the ability to geocode data in terms of images and access databases.

Table 1
Criteria suitability scale.

Priority scale	Score
Not Suitable	4
Less Suitable	3
Moderately Suitable	2
Suitable	1
Particularly Suitable	0

3.1. Exclusion criteria

For the exclusion criteria determination, two scenarios are examined, where the first corresponds to the legal exclusion areas for solar power installations siting and in the second scenario, additional socio-environmental constraints are added, taking into consideration the specific characteristics of the study area.

According to the legislation (SFSPSD-RES[1] [25] and Law 3851/2010[2] [26]), the solar energy installations are not permitted to be installed in:

1) World heritage areas, archaeological monuments and historical places of high importance, as well as in archaeological sites of zone A
2) Areas of absolute protection of nature, according to Specific Management Plans and Specific Environmental Studies
3) Centre of national forests, nature monuments, aesthetic forests
4) Other areas or zones currently falling under a special land-use regime, according to which siting of RES installations is not permitted as long as they are in force. Spatial, urban and regulatory land-use plans, that have been harmonized to the SFSPSD-RES [25] and have secured the maximum exploitation of the RES capacity, are only taken into consideration.

However, a second socio-environmental scenario is also considered where the exclusion areas are added:

- Sites of Community Importance (SCIs) of the NATURA 2000 network (RETs siting is permitted inside SCIs, as a means for the climate change mitigation, according to Law 3851/2010 [26])
- forests
- aesthetically and scientifically highly valued geotopes (with an additional 500 m buffer distance)
- rocky islets, as they are usually habitats of sensitive flora and fauna species
- settlements and traditional settlements are also excluded, as the studied large-scale installations require a large surface area to be occupied and therefore the visual impacts can be significant, in addition to the noise impacts they cause.

3.2. Evaluation criteria

The available siting areas of the two adopted scenarios are evaluated based on the criteria presenting in Table 2, while the classification of each criterion, to the adopted suitability scale, is conducted after a rigorous literature review.

Distance from the road network: This criterion can significantly influence the construction and maintenance costs of solar energy installations. A buffer distance of 100 m is frequently found in the literature for aesthetic and safety reasons ([9,10,14,27]). In addition, for the maximum distance from the road network, Carrion et al.

[1] The Specific Framework for Spatial Planning and Sustainable Development for the RES (SFSPSD-RES) was coordinated by the Hellenic Ministry of Environment, Physical Planning and Public Works in 2008 and introduced rules and criteria, in order to establish policies for the RES plants siting process.

[2] Law 3851 was coordinated in 2010, for the RES development acceleration, the simplification of the RES license procedures and the incorporation of the Directive 2009/28/EC in the Greek Law.

Fig. 1. Description of the methodology.

Table 2
Classification of the selected evaluation criteria to the five-class suitability scale.

Priority Scale	Score	Distance from the road network (m)	Distance from the high voltage lines (m)	Slope (%)	Elevation (m)	Slope directions	Land cover
Unsuitable	4	<100 and>4,000	>10,000	>28	>1,500	Northern	Permanent crops and forests
Less suitable	3	3,000–4,000	7,000–10,000	21–28	1,100 –1,500	Northeastern and Northwestern	Other agricultural areas
Moderately suitable	2	2,000–3,000	4,000–7,000	14–21	700-1,100	Eastern and Western	Low vegetation lands
Suitable	1	1,000–2,000	1,000–4,000	7–14	300–700	Southeastern and Southwestern	Urban areas and other land uses
Particularly suitable	0	100-1,000	<1,000	0–7	0–300	Southern	Barren areas with little or no vegetation

Priority Scale	Score	Visibility	Distance from the shoreline (m)	Distance from water bodies (m)	Solar potential ($kWh/m^2/year$)
Unsuitable	4	Areas visible from most-visited sites	<50	<100	<1,000
Less suitable	3	Invisible areas from archaeological sites	50–100	100–200	1,000–1,200
Moderately suitable	2	Invisible areas from archaeological sites and traditional settlements	100–150	200–300	1,200–1,400
Suitable	1	Invisible areas from archaeological sites, traditional settlements, monuments, beaches, marinas, camps and tourist accommodations	150–200	300–400	1,400–1,800
Particularly suitable	0	Invisible areas	>200	>400	>1,800

[28] set a 3,000 m distance, whereas Uyan [27] and Yushchenko et al. [11] set a distance of 5,000 m.

Distance from the electricity transmission lines: For large-scale solar energy installations siting, as the ones investigated in this study, the proximity to the electricity transmission lines is an important criterion for the installation's connection and reduction of the associated costs. This criterion was limited to the evaluation of the distance from the high voltage lines, whose spatial representation was available. From the literature review, the most frequent upper bound adopted for the highly suitable class is of 1 km distance from the electricity transmission lines ([10,11,28]), while for the unsuitable class is a 10 km distance ([10,27,28]).

Slope: Rough terrain with steep slopes incommodes the siting of large-scale solar energy installations. Therefore, extensive earthworks may be required for smoothing, as steep slopes make more difficult the right siting (with the optimum angle) of the PV panels. Carrion et al. [28] set the upper bound of the unsuitable slopes to 30%, Hott et al. [21] consider a constraint of 27%, Mondino et al. [18] of 15% and Sun et al. [29] of 7%.

Elevation: The elevation criterion is of both environmental and techno-economic significance, as in high altitude, rare flora and fauna species are encountered and the road and electricity transmission network are sparse [30].

Slope directions: As for the slope criterion, the criterion of slope directions is quite important for the efficiency of solar energy installations, while intense slope variation leads to a great fluctuation of these directions. From the literature review accrues that the most suitable aspect is the south-facing [7], so that the PV panels can receive the greatest amount of solar energy during the daytime. In addition, most studies consider suitable, the slope directions between 112.5° and 247.5°, namely the southeastern to southwestern slope directions ([8,21,31]).

Land cover: The land cover criterion is quite common in the literature because of the large areas that solar energy installations require for their siting. Most reviewed studies consider the agricultural areas as unsuitable areas for siting solar power installations, in order to preserve the agricultural production. In addition, it is usually suggested solar energy installations to be sited in low vegetated areas, as forest areas have to be preserved and the dense vegetation can reduce the efficiency of the installed systems [14]. SFSPSD-RES [25] suggests as priority areas for siting solar energy installations the barren and low productivity areas. Moreover, Tsoutsos et al. [30] suggest as suitable siting areas some urban land uses (inactive quarries, military areas, hospitals, industrial areas), with low aesthetic value and high energy needs.

Visibility from most-visited sites: The criterion concerning the distance from residential areas is also common in the literature. However, this criterion can be ambiguous for siting PV installations, as, from a technical point of view, siting near residential areas can reduce energy losses and connection costs. On the other hand, SFSPSD-RES [25] states that solar energy installations should preferably be invisible from most-visited areas. Therefore, it is suggested to investigate the visual impacts in residential areas and sites of cultural interest, for which buffer distances were not taken into consideration. Instead, a visibility analysis was conducted, studying the visibility from settlements, traditional settlements, archaeological sites, monuments, beaches, marinas, camps and tourist accommodations. The visibility analysis was conducted in ArcGIS 10.3, by employing the VIEWSHED analysis tool of the Spatial Analyst toolbox. After, defining the visible and invisible areas for each of the aforementioned sites, the criterion classification was produced (Table 2).

Distance from the shoreline: The reasoning behind selecting the evaluation criterion of the distance from the shoreline has multiple aspects, as technical, environmental and aesthetic reasons require its selection. According to the Greek legislation, the main purpose of the seashore, including a 50 m distance from the coast, is the free access to them. In addition, siting solar energy installations in proximity to the shoreline can cause visual impacts to tourist activities and saltiness can reduce the efficiency and lifespan of solar energy systems. Finally, the reasons for the preservation of the marine ecosystems from pollution incidents are also taken into account. Georgiou and Skarlatos [8] set a buffer distance of 200 m from the coastline and Tsoutsos et al. [30] define as particularly suitable, the areas located more than 200 m far from the seashore.

Distance from water bodies: Proportionally to the previous criterion, water bodies have to be protected, as they constitute sensitive ecosystems, where some materials of the PV systems can contaminate the aquifer, in case of abandonment [14]. However, Merrouni et al. [10] consider the need of proximity to water bodies, for cleaning purposes of the PV panels, especially in barren dusty areas, such as Saudi Arabia and cooling purposes of the CSP systems [12]. In this study, this criterion was set to be maximized, as the thermal contamination of the water bodies, in cases where water is used for cooling purposes of the CSP systems is also a serious environmental impact.

Solar potential: this criterion is a very important one, as it can individually exclude areas, where the solar potential is not adequate for siting solar energy installations. From the literature review, a value of 1,800 kWh/m^2 for the yearly average solar irradiance at ground level is considered ideal for solar energy installations siting ([10–12]). Many authors stress that PV technology works in the presence of both Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiation (DHI) unlike CSP technology which works only by using the DNI ([7,11,21]). Therefore, two different maps were constructed, concerning the yearly average Global Horizontal (GHI) and Direct Normal (DNI) Irradiance. In the context of solar potential estimation, in the literature, there are different methodologies employed. Some authors employ geostatistical methods, such as Kriging interpolation, for the solar potential estimation from surface meteorological stations' measurements ([14,22]), while others incorporate the area solar radiation extension of the ArcGIS Spatial Analyst toolbox ([7,9,18,23,29,31]). In this study, the Area Solar Radiation tool was used for the calculation of the GHI and DNI.

For the required parameters determination, data from the interactive maps of JRC's PV Geographical Information System (PVGIS) utility [32] and NASA's Surface Meteorology and Solar Energy utility [33] were used. By employing the PVGIS utility, it is possible to estimate the diffuse proportion of the solar irradiance, for different latitudes and longitudes. An average value of 0.30 was then introduced to ArcGIS's AREA SOLAR RADIATION tool for the ratio of diffuse to global radiation parameter definition. In addition, NASA's Surface Meteorology and Solar Energy utility [33] was also employed, for the transmissivity parameter determination, estimating an average value for the Insolation Clearness Index, representing the fraction of insolation at the top of the atmosphere which reaches the surface of the earth [34].

3.3. AHP implementation and sustainable siting areas

In order to apply the AHP, the first steps constitute of defining the problem and its goals, as well as the structure of the problem's hierarchy [35]. The goal and structure of this study's available siting areas prioritization problem are presented in Fig. 2. Subsequently, pair-wise comparisons of all criteria influencing the decision have to be conducted, based on Saaty's fundamental scale (Appendix, Table A1) and the priority vectors indicating the relative importance of different criteria are calculated.

The matrix of pair-wise comparisons $A = [c_{ij}]$ represents the intensity of the expert's preference between individual criteria, that affect the selection of one of the available alternatives. The

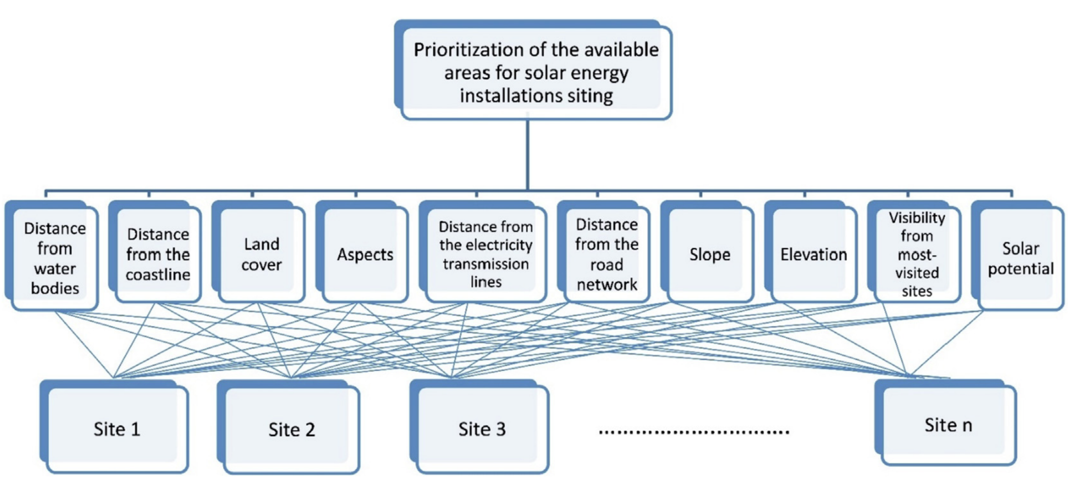

Fig. 2. Hierarchical structure of the siting areas prioritization problem.

judgment matrix is given below (5.1), for n criteria, where c_{ij} is the relative importance of the criterion C_i over the criterion C_j.

$$A = \begin{pmatrix} c_{11} & c_{12} & \cdots & c_{1(n-1)} & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2(n-1)} & c_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{n(n-1)} & c_{nn} \end{pmatrix} \tag{5.1}$$

The relative weights of criteria C_1, C_2 … C_n can be determined from matrix A, by normalizing it into a new matrix by dividing the elements of each column by the sum of the elements of the same column. The relative weights of the criteria are then computed by the row average of the new normalized matrix [37].

The advantage of this process is that it allows checking the consistency of the judgments made by the pair-wise comparisons. For a judgment to be consistent the following equation must be followed [38]:

$$c_{ij} = c_{ik} \times c_{kj} \; \forall \; i, j, k \tag{5.2}$$

However, assumption (5.2) is often violated in empirical decision situations, but Saaty argues that a reasonable level of inconsistency is expected and tolerated. To measure the degree of inconsistency of comparison matrices, Saaty introduced the Consistency Index (CI), measured as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5.3}$$

In Equation (5.3), n is the size of the matrix (n x n) and λ_{max} is the maximum eigenvalue of the comparison matrix. By solving the eigenvalue problem and determining the principal eigenvalue λ_{max}, the Consistency Ratio (CR) can be defined by the Equation:

$$CR = \frac{CI}{RI} \tag{5.4}$$

In Equation (5.4), CI corresponds to the Consistency Index calculated based on the Equation (5.3) and RI corresponds to Random Index values, which vary with the matrix size. A random matrix is one where the judgments have been entered randomly based on the Saaty's scale and therefore it is highly inconsistent.

Finally, as it was mentioned previously, a reasonable level of inconsistency is acceptable, therefore if $CR < 0.10$, the degree of consistency is considered satisfactory. Otherwise, consistency adjustment procedures proposed by Saaty can be performed, based on a maximum deviation approach [38].

For the AHP implementation, a survey was conducted, where local experts from different involved RES-related groups were asked to perform the necessary pair-wise comparisons of the selected criteria. These experts were selected in such a way, in order to evaluate the different preferences of the RETs siting stakeholders, so that their distinct opinions reflect the complexity of this RETs siting problem. In this study, the selected participants represent different stakeholders, such as the policymakers, the power supplier, the academia, the environmental groups and the engineers. One expert from each stakeholder, as well as two engineers, produce six completed judgment matrices. Subsequently, the participants' priority vectors were estimated, by applying the procedure described. In addition, as for the group of engineers, there are two participants, an average of the engineers' priority vectors was computed and then, an Aggregation of the Individual Priorities (AIP) was applied. AIP of the five priority vectors of the different stakeholders is implemented by a geometric mean method, based on the Equation:

$$P_g(C_J) = \left(\prod_{i=1}^{n} P_i(C_J) \right)^{\frac{1}{n}} \tag{5.5}$$

In Equation (5.5), $P_g(C_j)$ is the priority of the group of experts for the criterion j, $P_i(C_j)$ is the priority vector of an individual expert i, for the criterion j and n is the number of experts questioned. Aggregation of individual priorities is used in cases, where each individual of a group acts on his/her own interest, with different value systems [39], as it is considered in this study. Finally, the priority vectors accruing from the geometric mean method are normalized in order to ensure that:

$$\sum_{j=1}^{n} P_g(C_J) = 1 \tag{5.6}$$

After the estimation of the aggregated priority vectors for each criterion j, the weighted sum aggregation is employed, in order to determine the Overall Priority Index (OPI) for each cell of the study area, based on the Equation:

$$OPI_i = \sum_{j=1}^{n} w_j s_{ij} \tag{5.7}$$

In Equation (5.7), OPI_i corresponds to the Overall Priority Index of the cell i, w_j is the relative importance of the criterion j, s_{ij} is the score of the cell i over the criterion j and n is the total number of criteria. With the employment of the weighted sum aggregation, the priority maps of PV and CSP farms are produced, based on the fact that after the aggregation, each cell of the study area has a score between 0 and 4, where 0 corresponds to 100% priority and 4 corresponds to 0% priority. Finally, the priority maps are produced with the assistance of the RASTER CALCULATOR tool in ArcGIS 10.3.

3.4. Sustainable siting areas

By taking into account the available siting areas of the socio-environmental scenario, for solar energy installations siting, as described in Section 3.1 and the relative importance of the selected criteria from the aggregation of the individual priorities of the selected participants, two different priorities maps are produced, for large-scale PV and CSP farms respectively. After the construction of the priority maps, the sustainable siting areas for each solar energy installations are emerging, corresponding to a priority percentage greater than 60%. An additional area constraint was also introduced for the sustainable siting areas identification, corresponding to an area greater than 1,200 m^2 for PVs (power of 60 kW) and 400,000 m^2 for CSPs (power of 20 MW) [30].

The sustainable siting areas do not correspond to only high siting priority, but take into account the specific characteristics of the study area, through the employment of the additional socio-environmental constraints, apart from the legal exclusion areas and the siting feasibility, introducing the area constraints. Therefore, these areas can increase the potential for a sustainable siting, taking into account the three spectrums of sustainability (environment, society, economy).

3.5. Sensitivity analysis

In order to check the sensitivity of the assigned weights and the results obtained, a sensitivity analysis was carried out. For the sensitivity analysis implementation, different scenarios were employed, concerning the criteria weights. Apart from an equal-weighted scenario, techno-economic and socio-environmental

Table 3
Criteria relative importance in the different sensitivity analysis scenarios.

Evaluation Criteria	Criteria Relative Importance (%)			
	AHP	Equal-Weighted Scenario	Techno-Economic Scenario	Socio-Environmental Scenario
Distance from the coastline	16	10	0	20
Distance from water bodies	12	10	0	20
Distance from the electricity transmission lines	7	10	17	0
Distance from the road network	8	10	17	0
Slope directions	10	10	17	0
Land cover	12	10	0	20
Slope	8	10	17	0
Elevation	9	10	17	20
Visibility from most-visited sites	9	10	0	20
Solar potential	7	10	17	0

were employed. For example, in the techno-economic scenario, all techno-economic criteria were given equal weights and for the rest criteria, their relative importance was set to zero. Table 3 presents the relative importance of the selected criteria, in the different weight scenarios.

4. Results

The Regional Unit of Rethymno is divided in five municipalities and has a mountainous terrain; flatlands can be found to the northern and southern coastal areas. In addition, the scale of this area allowed for a more detailed and thorough analysis for the identification of the sustainable siting areas for solar power installations. Therefore, spatial data on individual tourist accommodations, tourist activities (camps, marinas) and regulatory and spatial land-use plans, as well as a visibility analysis from specific sites of the study area were accommodated, permitting the development of an integrated site selection approach. Consequently, it was considered that a wider study area, such as the whole island of Crete, would not have accommodated the desirable detailed analysis of all the data, which can affect the siting of solar power installations.

In the Regional Unit of Rethymno, four regulatory and spatial land-use plans are approved, but only the area 3 of the Urban Development Control Zone of Georgioupolis- Episkopi is taken into consideration, which contains the biotope's centre, where any construction is forbidden. As for the rest of the plans, they do not mention RES, so they are not taken into consideration.

Fig. 3(a) is constructed from the legally exclusion zones, where rivers, lakes and the road network are also excluded due to the physical constraints they evoke. With the definition of the additional exclusion zones, Fig. 3(b) is produced, presenting the available areas for siting PV and CSP installations in the Rethymno Regional Unit of the socio-environmental scenario.

Fig. 4 presents the sustainable siting areas for PV and CSP farms, based on the criteria relative importance derived from the AHP and Table 4 presents the municipality coverage by the sustainable siting areas for each solar energy technology. SFSPSD-RES [25] does not state any constraint concerning the maximum coverage per municipality by solar energy installations. Therefore, taking into account only the highest priority siting areas, corresponding to 80–100% priority, the potential maximum power, if the total of these areas is covered by solar energy installations, is estimated (Table 4). For the estimation of the potential maximum power, the technical factors taken into consideration are: 60kWp/1,200 m^2 for PVs and 20MW/400,000 m^2 for CSPs [30].

In Table 5, the results, in terms of the Regional Unit's coverage by the different priority classes, for PVs and CSPs siting are presented, in the different weight scenarios. In addition, the results of Table 5 concern the coverage of the Regional Unit of Rethymno by the available areas of the socio-environmental scenario (Section 3.1). As it can be seen from the Table, the greatest reduction in the coverage of the sustainable area, in relation to the one from the AHP (Figs. 5 and 6), accrues in the equally-weighted scenario, while a reduction is also observed in the techno-economic scenario for both PVs and CSPs siting.

In addition, the results are about the same for the AHP and socio-environmental scenario, as the priority vectors derived from the AHP, emphasize in the socio-environmental criteria, giving them greater importance in relation to the techno-economic criteria. Therefore, high priority areas derived from the AHP have a lower priority in the techno-economic scenario, where only techno-economic criteria are taken into consideration. This is another element that indicates the RETs siting problem complexity, where the relative importance of the selected evaluation criteria can lead to different results regarding suitability.

5. Conclusions and discussion

The main characteristic of this RETs siting problem is its complexity, as different and often contradictive criteria have to be taken into consideration, in order to find the most suitable siting areas. For example, an environmental criterion for solar energy installations siting, such as the distance from areas of environmental interest, whose aim is to be maximized, in some cases may contradict with the criterion of the distance from the road network, which is a techno-economic criterion aimed to be minimized. Therefore, the key objective of the RETs site selection studies is to find the most suitable locations, for the minimization of the impacts on the natural and human environment and the maximization of the economic and technical potential.

This study dealt with the solar power installations siting problem, by employing GIS and the AHP. Therefore, a dynamic methodology was developed, for finding the sustainable siting areas to host PV and CSP farms. The adopted methodology was applied in the case study of the Regional Unit of Rethymno and enabled:

- the identification of the legally available siting areas, after reviewing the related legislation
- the evaluation of the available siting locations, based on techno-economic and socio-environmental criteria
- the classification of each evaluation criterion into a five-class priority scale, after a rigorous literature review
- the determination of the criteria relative importance, by implementing the AHP, where local experts from different involved RES-related groups were asked to perform the necessary pair-wise comparisons of the selected criteria

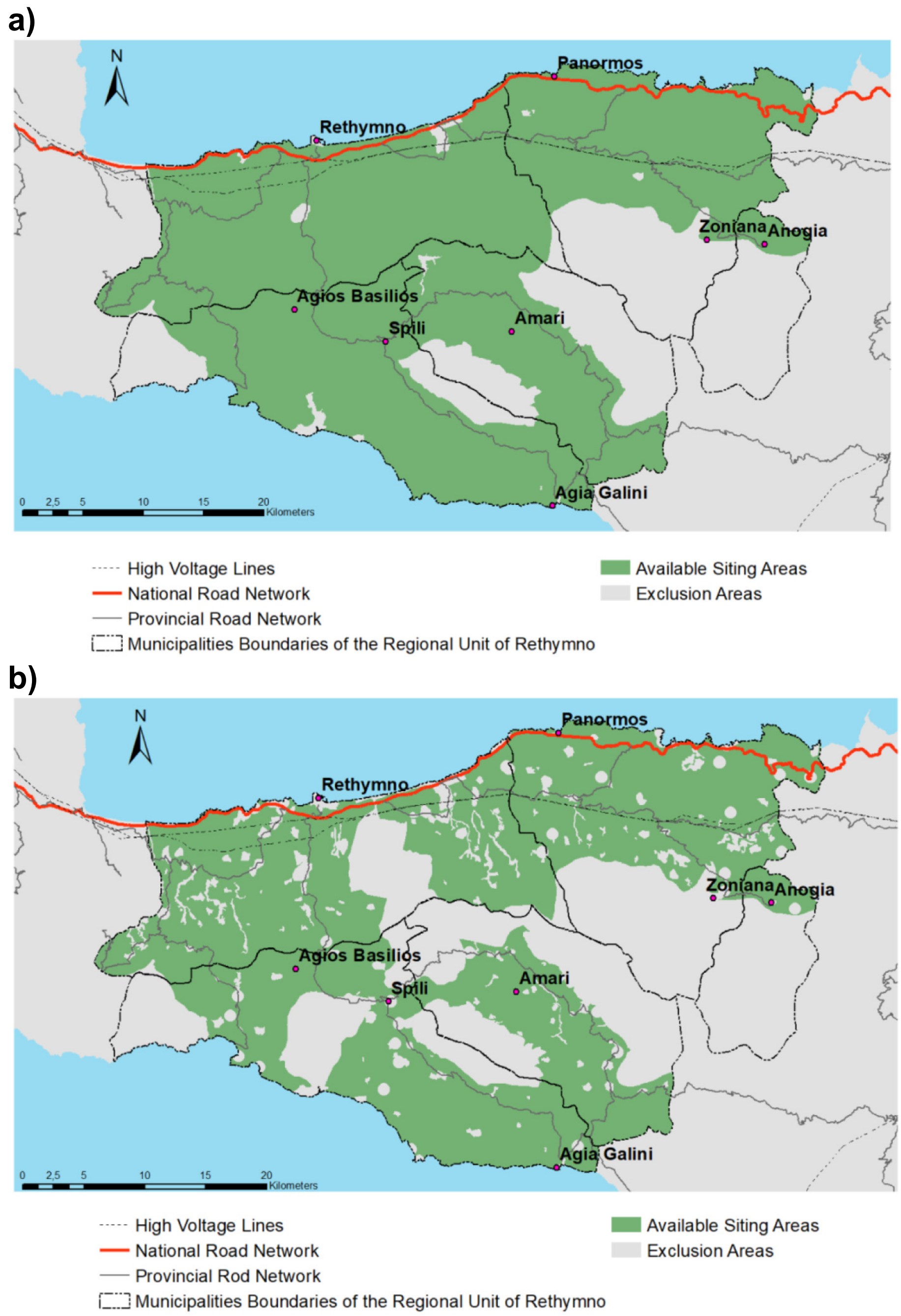

Fig. 3. Legally available (a) and available siting areas of the socio-environmental scenario (b).

- the identification of the sustainable siting areas, after the production of priority maps with a weighted sum aggregation of the selected criteria
- the sensitivity evaluation of the methodology's results, by employing different scenarios for the criteria weights

The results from the adopted methodology, for the Regional Unit of Rethymno, in terms of the coverage from the highest priority sustainable siting areas (80–100%) are 2.88% for PV farms and 0.17% for CSP farms. In addition, the results of the adopted methodology, in terms of the potential maximum power from the highest priority areas are 530 MW for PVs and 30 MW for CSPs.

In addition, from the implemented sensitivity analysis, a reduction was observed in the sustainable siting areas of the techno-economic scenario, in relation to the coverage derived from the AHP. Moreover, it must be noted that the priority vectors derived from the AHP, emphasize in the socio-environmental criteria, giving them greater importance in relation to the techno-economic criteria. Therefore, the main advantages of the adopted methodology are that:

- it takes into account the three spectrums of sustainable development to ensure both the environmental and landscape preservation and the feasibility of the investment

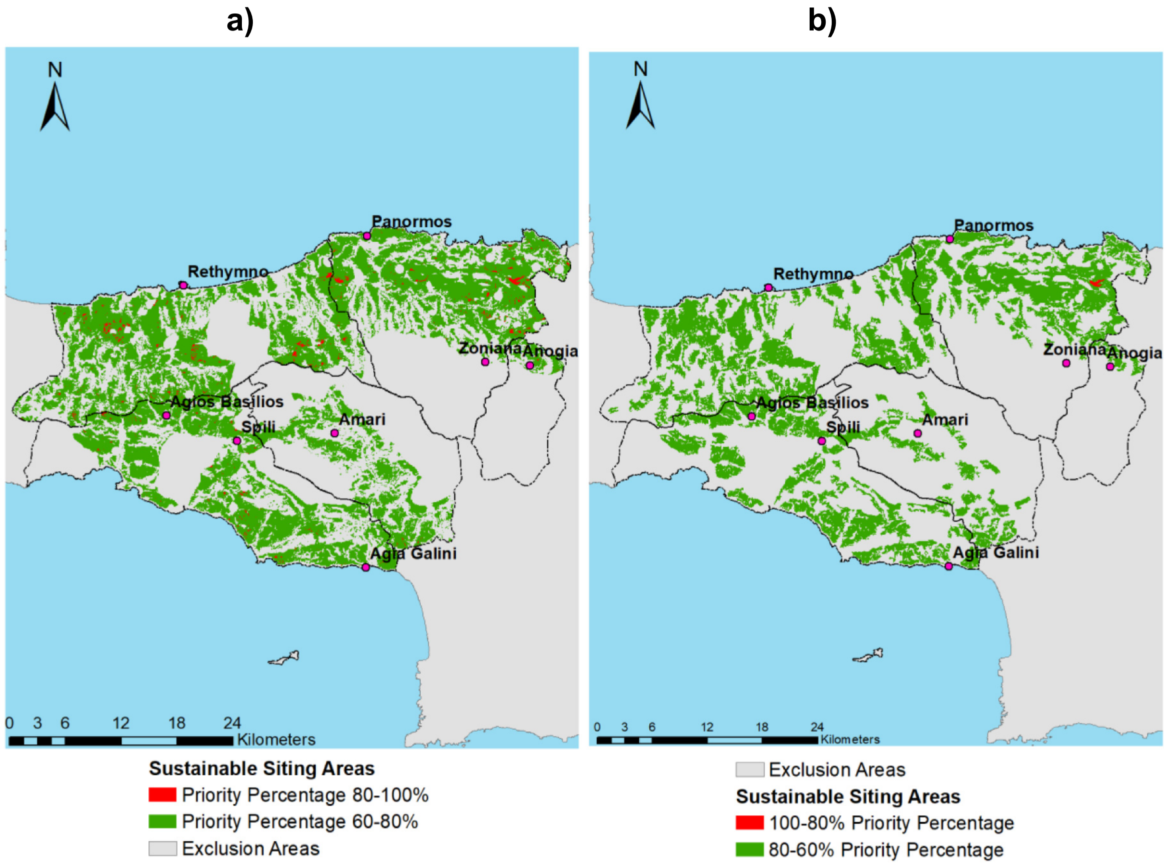

Fig. 4. Sustainable siting areas for PV (a) and CSP (b) farms respectively, based on the criteria weights derived from the AHP.

Table 4
Municipality coverage by the sustainable siting areas and calculation of the carrying capacity.

Municipality	Municipality Coverage (%)		Potential maximum power (MW)			
	Areas with priority 80−100%		Areas with priority 60–80%		Areas with priority 80−100%	
	PVs	CSPs	PVs	CSPs	PVs	CSPs
Agios Vasilios	0.49	–	42.31	31.59	88	0
Amari	0.06	–	22.82	13.84	9	0
Anogia	0.05	–	7.88	4.92	3	0
Mylopotamos	1.08	0.17	41.16	32.49	197	30
Rethymno	1.19	–	48.86	38.42	234	0

- it takes into account the complexity of the RETs siting, by incorporating the distinct opinions of different RES-related involved groups
- it enables the creation of alternative scenarios, for the exclusion criteria selection and the evaluation criteria importance and the visualization of the results for each scenario.

Further research can also be performed in the methodology development, for the RETs sustainable siting areas identification and its application in the Regional Unit of Rethymno. More evaluation criteria can be incorporated, more stakeholders can participate in the survey for the criteria weights determination and more RETs can be studied. Therefore, economic evaluation criteria can be employed for the economic potential determination and investors in the RES field can participate in the survey, for their input in the

Table 5
The coverage of the Regional Unit of Rethymno in the different sensitivity analysis scenarios.

Priority (%)	Coverage of the Regional Unit of Rethymno (%)							
	PV Farms				CSP Farms			
	AHP	Equal-Weighted Scenario	Techno-Economic Scenario	Socio-Environmental Scenario	AHP	Equal-Weighted Scenario	Techno-Economic Scenario	Socio-Environmental Scenario
100–80	0.71	0.25	3.16	2.73	0.29	0.05	1.13	2.73
80–60	37.79	26.67	29.22	29.41	31.98	19.02	22.54	29.41
60–40	22.21	32.99	25.05	26.28	28.20	39.14	29.30	26.28
40–20	0.12	0.91	3.42	2.40	0.35	2.61	7.21	2.40
20–0	0.00	0.00	0.10	0.00	0.00	0.00	0.77	0.00
Sustainable Siting Areas	38.50	26.92	32.39	32.15	32.27	19.07	23.68	32.14

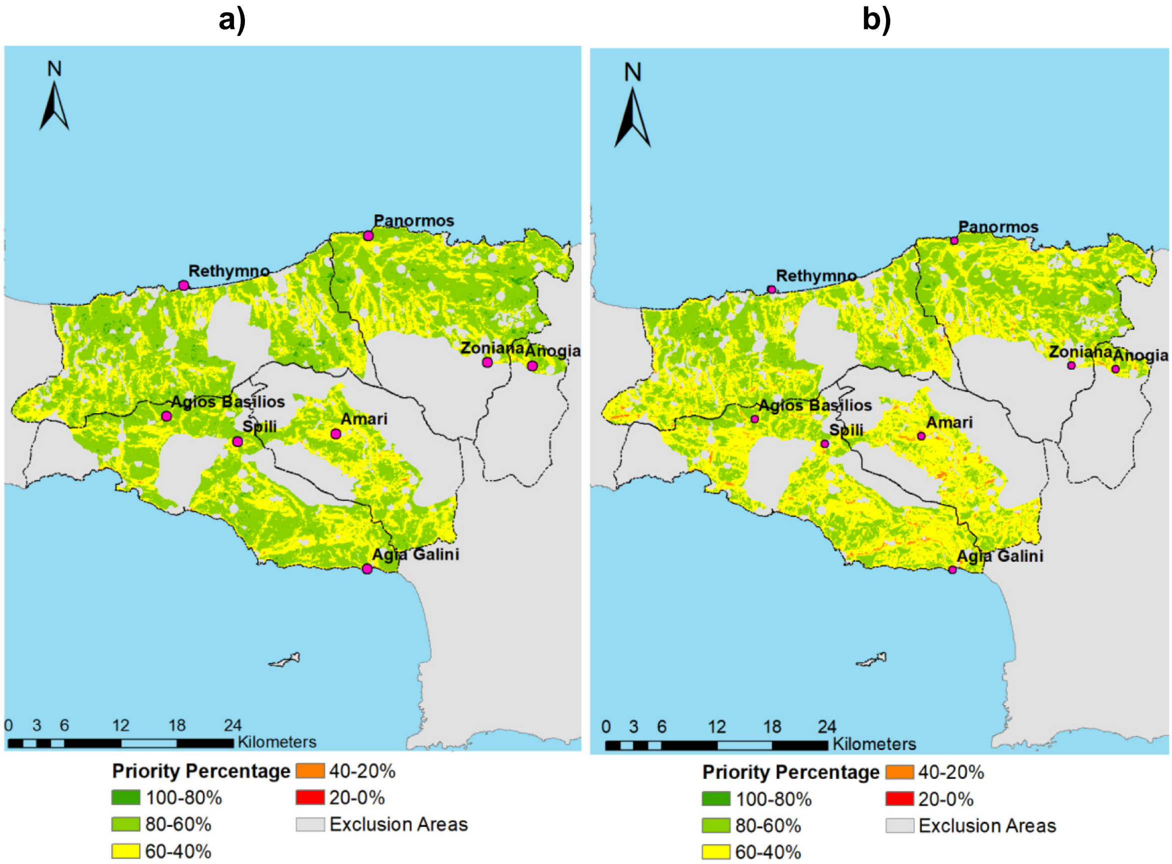

Fig. 5. Priority maps for large-scale PV farms, based on the criteria weights derived from the AHP (a) and the equally-weighted scenario (b).

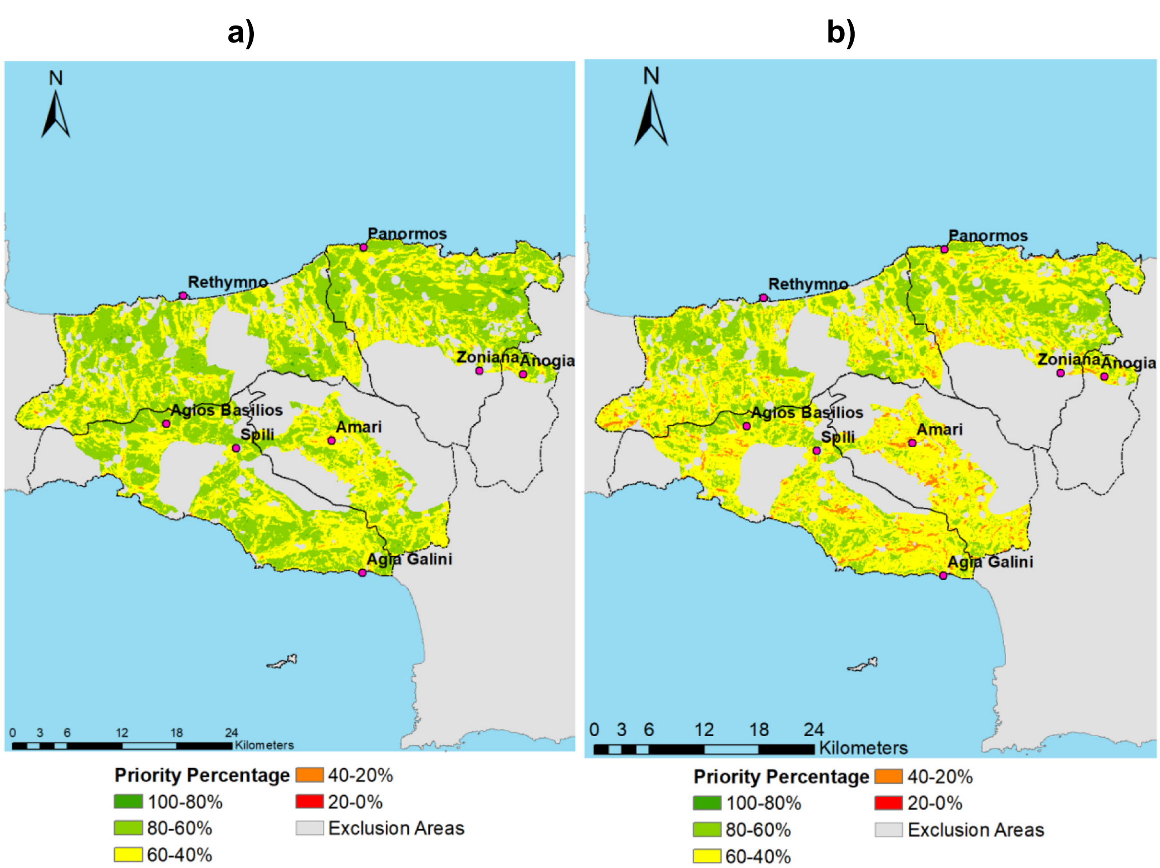

Fig. 6. Priority maps for CSP farms, based on the criteria weights derived from the AHP (a) and the equally-weighted scenario (b).

criteria relative importance.

Finally, the developed methodology is based on the quality and quantity of the available data for collection. In this study, a special effort was made for the collection of the necessary data from official authorities and scientific studies. However, as discussed in previous Sections, a spatial representation of the medium voltage lines of the Regional Unit of Rethymno was not available to us by the competent authority. In addition, forest maps and spatial data on the high productivity agricultural areas were not published yet for the Regional Unit of Rethymno. Therefore, data from the historical CORINE database were employed, concerning the forest and agricultural areas of the region. However, despite these limitations, the methodology developed is dynamic, allowing for the continuous update of the collected data, which can, in turn, lead to the employment of additional evaluation criteria.

Appendix

Table A.1 The fundamental scale according to Saaty (1980) [36].

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is favored very strongly and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed

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