Chapter 4
Decision Criteria for Optimal Location of Solar Plants: Photovoltaic and Thermoelectric

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Abstract This chapter deals with the study and evaluation of decision criteria that should be considered for the optimal location of solar photovoltaic plants and solar thermal plants with high temperature and which are to be connected to the electricity distribution network. Criteria and subcriteria to be regarded will be of different nature, since environmental, geomorphologic, location, and strictly climatic criteria will all be considered, some of which are dependent on the technology being installed. Thus, we consider as possible alternatives the optimal locations and we will begin with a set of criteria, which must be evaluated for each of the possible alternatives for such a purpose, and includes both quantitative as well as qualitative information. As vaguely implied linguistic variables and numeric values have to be employed due to this disparity in the nature of the information, we will model the weights of the criteria by triangular fuzzy numbers. In order to reflect this and to carry out the extraction of knowledge a survey based on the fuzzy AHP methodology will be elaborated and sent to experts. In this way it will be possible to obtain the weights of the considered criteria for further evaluation of the alternatives.

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F. Cavallaro (ed.), *Assessment and Simulation Tools for Sustainable Energy Systems*, Green Energy and Technology 129,
DOI: 10.1007/978-1-4471-5143-2_4,

4.1 Introduction

At the end of the nineteenth century it began to be suspected that there were natural changes in the climatic conditions of the planet earth and the greenhouse effect was identified (Arrhenius 1896). The scientific community, through the Intergovernmental Panel on Climate Change (IPCC), alerted the world about the threat posed by this discovery and the effects it could have on climate change (Working Group I-II-III 1990a, b, c).

In response to the report by the IPCC, the United Nations set as a main goal to stabilize concentrations of greenhouse gases in the atmosphere (United Nations 1992). However, it was not until the development of the Kyoto Protocol (United Nations 1997) that they managed to limit net emissions of greenhouse gases from major developed countries. To achieve the objectives, a series of policies and measures were established, among which the increased use of renewable energies (RE) was highlighted.

Among the various issues to consider in carrying out the implementation of an installation of RE, its location must be highlighted since the investment required to undertake any installation is of such magnitude that a minimal error of planning can cause serious damage both economically and environmentally.

Nowadays, the decision criteria that are taken into account by an RE promoter seeking to establish an electricity generating plant in order to pour that power into the distribution grid are scarce and even at times null. Choosing a proper location is essential and for this type of generation plants the availability of land is not the most important factor. On occasions, plants of this type have been started to develop in areas that for various reasons (environmental, technical, etc.) their subsequent implementation has proved unfeasible. In such cases, if the area for its location had been discussed in a certain degree of depth and detail, it could have been claimed that the said area did not fulfill all the requirements for the development and implementation of an RE plant.

As the starting point in the search for a location for solar plants a number of restrictive criteria should be taken into account (Van Haaren and Fthenakis 2011). These permit to limit the area of study to those sites that fulfill the rules and guidelines in force, such as the compliance distance to existing infrastructure (road and rail networks); separation of the areas that involve risk of flooding (channels and watercourses); remoteness of guard bands of protected areas (high value landscape, archaeological, paleontological, etc.) Current regulations permit to define what are the restrictive criteria to be considered when implementing any infrastructure—not just for RE plants but also for any other area or sector (private building, construction, agriculture, etc.)

Although restrictive criteria allow to delimit the study area, it is necessary to consider another set of criteria that will influence the decision of selecting optimal sites (Charabi and Gastli 2011). The choice of such criteria is directly related to the type of infrastructure to be installed, i.e., they do not follow any rules in force but are factors that have a certain weight depending on the type of infrastructure to be made. Moreover, it is essential to distinguish among the various RE plants, those in which by their very nature require their location to be previously defined, from those other plants in which it is essential to carry out an assessment of all the criteria involved in the decision to place them in a great location.

It is possible to establish an RE classification based on the location of its facilities, and thus two groups can be distinguished: the first group would consist of those RE plants requiring a particular and clearly defined situation. Their location is mainly due to specific characteristics of the environment, with one or more criteria having a much greater importance than the rest. That group would include the RE such as biomass, biogas, biofuels, geothermal, energy from the seas and oceans and hydropower. The second group would be formed by those RE plants in which choosing the correct location is also a key issue, and this subject presents a greater uncertainly as a result of the criteria involved in the decision. There is not one single criterion or more criteria whose weight is so superior to the others so as to permit discarding the rest and not taking them into account. Among the RE plants of this second group, the solar photovoltaic and high temperature solar thermal (thermoelectric) plants stand out above the rest, and they will therefore be the RE plants to be analyzed in this chapter.

When the correct location for a solar photovoltaic or solar thermal plant is selected, there are a number of criteria which, depending on the type of installation, will have a greater or lesser importance. Thus, the crossing of criteria between these two technologies offers many variants and carrying out a thorough analysis can be of considerable interest.

Therefore, this chapter deals with the study and evaluation of decision criteria that influence the location of solar photovoltaic and thermoelectric plants, in order to obtain their weights or important coefficients. These take into account the information provided by experts and will be developed under the following headings and the methodology applied.

4.2 Decision Criteria for the Optimal Location of Solar Power Plants

In this chapter the criteria that must be taken into account when implementing solar photovoltaic and solar thermal energy plants will be discussed, these are diverse and thematic relating to the environment, and geomorphology, climatology or location. Such thematics allow to classify the criteria in a criteria tree (shown in Fig. 4.1).

Each of the above criteria is briefly described:

- C_1: *Agrological capacity* (*Classes*): Suitability of land for agricultural development, if a zone has excellent agrological capacity, it will not be ideal to host the facility, and vice versa.

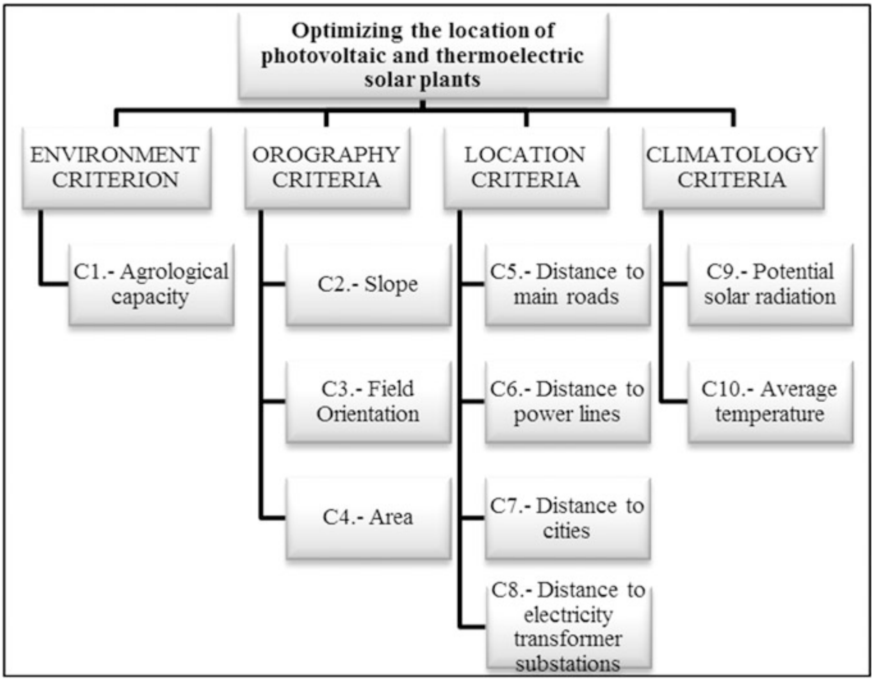

Fig. 4.1 Criteria tree for optimizing the location of solar photovoltaic and thermoelectric plants

- C_2: *Slope* (%): Land slope, the higher percentage of having a surface inclination, the worse aptitude to hold a solar plant.
- C_3: *Field Orientation* (*Cardinal points*): Position or direction of the ground to a cardinal point.
- C_4: *Area* (m^2): surface contained within a perimeter of land that can accommodate an RE plant.
- C_5: *Distance to main roads* (m): Space or interval between the nearest road and the different possible sites.
- C_6: *Distance to power lines* (m): Space or interval between the nearest power line and the different possible sites.
- C_7: *Distance to cities* (m): Space or interval between cities (cities or towns) and the different possible sites.
- C_8: *Distance to electricity transformer substations* (m): Space or interval between transformer substations of electric power and the different possible sites.
- C_9: *Potential solar radiation* (kJ m^2/day): This corresponds to the amount of solar energy a ground surface receives over a period of time (day).
- C_{10}: *Average temperature* (°C): Average temperatures measured on the ground in the course of one year.

4.3 Methodology

To solve the location problem, a multicriteria decision method MCDM (Chen and Hwang 1992; Hwang and Yoon 1981; Keeney and Raiffa 1976; Luce and Raiffa 1957) can be used to choose the best alternative A_i, $i = 1,2,\ldots,n$ with $n \geq 2$ a number of criteria C_j, $j = 1,2,\ldots,m$ with $m \geq 2$ are considered, and experts E_k, $k = 1,2,\ldots,r$ with $r \geq 2$; considering that both n and r are finite.

Specifically, an MCDM called Analytic Hierarchy Process (AHP) will be applied, which is detailed below.

The AHP method

The AHP method was proposed by Saaty in (Saaty 1980) and it is based on the idea that a decision making problem with multiple criteria can be solved by the ranking of the proposed problems, i.e., it consists of an alternative selection method based on a number of criteria which are often in conflict.

The main feature of the AHP method is that the decision problem is modeled using a hierarchy whose apex is the main objective of the problem, and the possible alternatives to evaluate are situated at the base, the intermediate levels correspond to the criteria/subcriteria based on which a decision is made (Fig. 4.2).

At each level of the hierarchy, comparisons are carried out between pairs of elements of that level, based on the importance or contribution of each element of the upper level to which they are linked.

The target in the case under study is the optimal location of sites for solar photovoltaic and thermoelectric plants, and specifically in determining the weight or coefficient of importance of the intermediate levels of the hierarchy, i.e., the criteria that influence the decision (see Fig. 4.1).

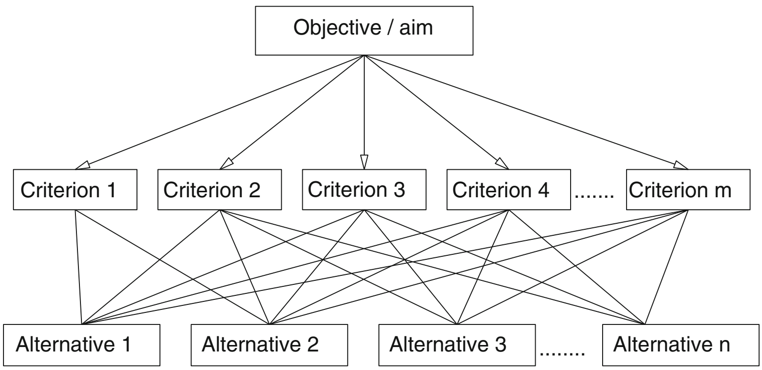

Fig. 4.2 AHP Hierarchy process

4.4 Survey of Experts

To carry out the extraction of knowledge from the experts a pseudo-delphi technique will be used in which the members involved in the decision are independent of each other, i.e., they do not interact in the moment of extraction of knowledge. For that purpose, a questionnaire similar to that made by García-Cascales et al. (2012) was developed, which was given to experts with the aim of reducing uncertainly and imprecision of the proposed problem.

The group of experts involved in the decision process for photovoltaic solar plants was composed of a doctor engineer (expert E_1) specialized in solar photovoltaic technology; a doctor in physics (expert E_2) with more than 10 years experience in solar photovoltaic technology; and a promoter of RE plants (Expert E_3) with more than 5 years of experience in the industry.

The group of experts involved in the decision process of thermoelectric solar plants consisted of three doctor engineers (experts E_1, E_2, *and* E_3) and a doctor in physics (expert E_4) with more than 10 years experience in the RE sector, all of them specialized in solar photovoltaic and thermoelectric technologies.

The survey is divided into two parts:

1. The decision problem is explained indicating what the goal to achieve is (optimal location of sites of solar photovoltaic and thermoelectric); the methodology used; and the criteria that influence the decision making process. Thus, the basic elements of the decision problem are described through a hierarchical structure, as shown in the criteria tree (see Fig. 4.1).
2. It is based on the hierarchical structure described and its purpose is to gather data to obtain the weight or coefficient of importance of criteria.

The survey consists of a block of 3 questions:

- Q1: Do you believe that the ten criteria considered have the same weight?

If the answer is yes, $w_i = w_{j=1/n} \times \sqrt{i,j}$ it will not be necessary to apply any MCDM to obtain the weights of the criteria as these will have the same value. Otherwise, i.e., if experts consider that not all the criteria have equal importance, the second question in the survey will be posed:

- Q2: List the criteria in descending importance.

According to the experts, the order of importance of the criteria for the two types of RE plants for analysis is shown in Table 4.1.

Once the orders of importance provided by each of the experts have been obtained, then the third question will be asked:

- Q3: Compare the criterion considered as having the greatest order of importance with respect to that considered second and successively, using the following tags, (II), (M+), (+I), (Mu + I), (Ex + I) according to the meanings in Table 4.2.

Table 4.1 Order of importance of the criteria for each of the experts

Solar photovoltaic energy	
E_1	$C_8 > C_6 > C_4 > C_{10} > C_2 > C_3 > C_9 > C_5 > C_7 > C_1$
E_2	$C_7 > C_2 = C_3 > C_5 = C_{10} > C_6 = C_8 > C_1 = C_4 > C_9$
E_3	$C_9 > C_6 > C_4 > C_2 > C_8 > C_5 > C_{10} > C_3 > C_7 > C_1$
Solar thermoelectric energy	
E_1	$C_9 > C_3 > C_2 > C_{10} > C_4 > C_6 > C_8 > C_7 > C_5 > C_1$
E_2	$C_8 > C_6 > C_2 > C_4 > C_3 > C_9 > C_{10} > C_5 > C_7 > C1$
E_3	$C_4 > C_1 > C_6 > C_8 > C_5 > C_9 > C_2 > C_3 > C_7 > C_{10}$
E_4	$C_5 = C_7 = C_{10} > C_1 = C_2 > C_4 = C_6 = C_8 > C_3 = C_9$

Table 4.2 Scale of valuation in the pair-wise comparison process (Saaty 1980)

Labels	Verbal judgments of preferences between criterion i and criterion j	Triangular fuzzy scale and reciprocals
(II)	C_i and C_j are equally important	(1,1,1)/(1,1,1)
(M + I)	C_i is slightly more/less important than C_j	(2,3,4)/(1/4,1/3,1/2)
(+I)	C_i is strongly more/less important than C_j	(4,5,6)/(1/6,1/5,1/4)
(Mu + I)	C_i is very strongly more/less important than C_j	(6,7,8)/(1/8,1/7,1/6)
(Ex + I)	C_i is extremely more/less important than C_j	(8,9,9)/(1/9,1/9,1/8)

4.4.1 Configuration Data

The information provided by the experts is qualitative in character or is very vague since it has been obtained through linguistic terms This means that the data obtained should be set and modeled so that further handling is feasible and easy.

Among the various options for representing information and because, on the one hand the data is grouped perfectly, and on the other, handling is simple and effective, fuzzy numbers will be chosen to represent information (Delgado et al. 1992; Herrera et al. 2009). In the particular case study, the data provided shall be represented by triangular fuzzy numbers (Zadeh 1965; Klir and Yuan 1995; Dubois and Prade 1980).

4.4.2 Calculating the Weights of the Criteria

The weights of the criteria will be determined by pair-wise comparison among criteria. As a result of the data collection process used, a total of $(n-1)$ comparisons will be required. Tags that have been used and their meanings are shown in Table 4.2.

The process will run pair-wise comparison between criteria for the case of photovoltaic solar sites and for expert 1 as an example; the value pairs are shown in Fig. 4.3.

	C_8	C_6	C_4	C_{10}	C_2	C_3	C_9	C_5	C_7	C_1
C_8	(II)	(M + I)	(+I)	(+I)	(Mu + I)	(Mu + I)	(Mu + I)	(Ex + I)	(Ex + I)	(Ex + I)

Fig. 4.3 Values given by E_1 for location of solar photovoltaic plants

Triangular fuzzy numbers expressed according to Table 4.2 prove to be as shown in Fig. 4.4.

According to Garcia-Cascales and Lamata (2011) and by expression (4.1) the weights for the example shown will be obtained (see Fig. 4.5).

The above matrix was obtained by performing a normalizing operation using the following expression:

$$\left(w_{c_{ia}}, w_{c_{ib}}, w_{c_{ic}}\right) = \left[\frac{c_{ia}}{\sum_{i=1}^{n} c_{ic}}, \frac{c_{ib}}{\sum_{i=1}^{n} c_{ib}}, \frac{c_{ic}}{\sum_{i=1}^{n} c_{ia}}\right] \tag{4.1}$$

4.5 Result of the Weights of the Criteria

Analogously to the procedure developed to obtain the weights of the criteria for expert E_1 in the location problem for solar photovoltaic installations, it will be extended to the other experts in this decision problem (Table 4.3) and for the location problem of solar thermoelectric plants (Table 4.4).

	C_8	C_6	C_4	C_{10}	C_2	C_3	C_9	C_5	C_7	C_1
C_8	(1,1,1)	(2,3,4)	(4,5,6)	(4,5,6)	(6,7,8)	(6,7,8)	(6,7,8)	(8,9,9)	(8,9,9)	(8,9,9)

Fig. 4.4 Matrix of decision making for E_1 for location of solar photovoltaic plants

Fig. 4.5 Weight criteria E_1 for location of solar photovoltaic plants

$$\begin{matrix} C_8 \\ C_6 \\ C_4 \\ C_{10} \\ C_2 \\ C_3 \\ C_9 \\ C_5 \\ C_7 \\ C_1 \end{matrix}
\overset{C_8}{\begin{bmatrix} (1,1,1) \\ (1/4, 1/3, 1/2) \\ (1/6, 1/5, 1/4) \\ (1/6, 1/5, 1/4) \\ (1/8, 1/7, 1/6) \\ (1/8, 1/7, 1/6) \\ (1/8, 1/7, 1/6) \\ (1/9, 1/9, 1/8) \\ (1/9, 1/9, 1/8) \\ (1/9, 1/9, 1/8) \end{bmatrix}}
= \begin{bmatrix} (0.348, 0.401, 0.436) \\ (0.087, 0.134, 0.218) \\ (0.058, 0.080, 0.109) \\ (0.058, 0.080, 0.109) \\ (0.043, 0.057, 0.073) \\ (0.043, 0.057, 0.073) \\ (0.043, 0.057, 0.073) \\ (0.039, 0.045, 0.055) \\ (0.039, 0.045, 0.055) \\ (0.039, 0.045, 0.055) \end{bmatrix}$$

$$(2.292, 2.495, 2.875)$$

Table 4.3 Weights of the criteria for location of solar photovoltaic plants

	Expert 1			Expert 2			Expert 3		
C_1	[0.039,	0.045,	0.055]	[0.050,	0.054,	0.062]	[0.026,	0.027,	0.032]
C_2	[0.043,	0.057,	0.073]	[0.057,	0.069,	0.082]	[0.039,	0.049,	0.063]
C_3	[0.043,	0.057,	0.073]	[0.057,	0.069,	0.082]	[0.026,	0.027,	0.032]
C_4	[0.058,	0.080,	0.109]	[0.050,	0.054,	0.062]	[0.235,	0.247,	0.254]
C_5	[0.039,	0.045,	0.055]	[0.050,	0.054,	0.062]	[0.039,	0.049,	0.063]
C_6	[0.087,	0.134,	0.218]	[0.050,	0.054,	0.062]	[0.235,	0.247,	0.254]
C_7	[0.039,	0.045,	0.055]	[0.453,	0.485,	0.493]	[0.026,	0.027,	0.032]
C_8	[0.348,	0.401,	0.436]	[0.050,	0.054,	0.062]	[0.039,	0.049,	0.063]
C_9	[0.043,	0.057,	0.073]	[0.050,	0.054,	0.062]	[0.235,	0.247,	0.254]
C_{10}	[0.058,	0.080,	0.109]	[0.050,	0.054,	0.062]	[0.026,	0.027,	0.032]

In order to unify the weights of the obtained criteria a homogeneous aggregation will be carried out, i.e., all experts are equally important in the decision, as a measure of aggregation the arithmetic average will be used (expression 4.2).

$$(\bar{X}_{ia}, \bar{X}_{ib}, \bar{X}_{ic}) = \left[\frac{\sum_{i=1}^{n} X_{ia}}{n}, \frac{\sum_{i=1}^{n} X_{ib}}{n}, \frac{\sum_{i=1}^{n} X_{ic}}{n} \right] \tag{4.2}$$

By the homogeneous aggregations indicated, the weights of the criteria will be obtained, taking into account the entire decision making group, therefore, the values obtained for the problem location of solar photovoltaic plants are those indicated in Table 4.5.

The results shown in Table 4.5 are represented graphically in Fig. 4.6.

Analyzing both Table 4.5 and Fig. 4.6 it is shown that the three best criteria for the location problem for solar plants are the distance to power lines (C_6); distance to electricity transformer substations (C_8); and distance to cities (C_7), with the latter being the highest rated. By contrast the criteria that less influence the decision, that is to say, those with the lowest values, correspond to the criterion of agrological capacity (C_1) and to the criterion of distance to main roads (C_5).

Proceeding analogously to the decision problem of solar thermoelectric plants, the values of the weights of the criteria will be obtained (Table 4.6).

The results shown in Table 4.6 are represented graphically in Fig. 4.7.

Analyzing in this case Table 4.6 and Fig. 4.7 it is shown that the three best criteria for the location problem for solar thermoelectric plants are potential solar radiation (C_9); distance to electricity transformer substations (C_8); and distance to main roads (C_5), with the latter being the highest rated. By contrast the criteria that have less influence in the decision in this case are distance to cities (C_7); and field orientation (C_3).

Table 4.4 Weights of the criteria for location of solar thermoelectric plants

	Expert 1	Expert 2	Expert 3	Expert 4
C_1	[0.029, 0.036, 0.047]	[0.036, 0.042, 0.053]	[0.233, 0.272, 0.298]	[0.056, 0.068, 0.082]
C_2	[0.066, 0.109, 0.188]	[0.080, 0.127, 0.211]	[0.029, 0.039, 0.050]	[0.049, 0.053, 0.061]
C_3	[0.066, 0.109, 0.188]	[0.040, 0.054, 0.070]	[0.029, 0.039, 0.050]	[0.049, 0.053, 0.061]
C_4	[0.044, 0.065, 0.094]	[0.053, 0.076, 0.105]	[0.233, 0.272, 0.298]	[0.049, 0.053, 0.061]
C_5	[0.033, 0.047, 0.063]	[0.036, 0.042, 0.053]	[0.058, 0.091, 0.149]	[0.444, 0.477, 0.490]
C_6	[0.044, 0.065, 0.094]	[0.080, 0.127, 0.211]	[0.058, 0.091, 0.149]	[0.049, 0.053, 0.061]
C_7	[0.044, 0.065, 0.094]	[0.036, 0.042, 0.053]	[0.029, 0.039, 0.050]	[0.056, 0.068, 0.082]
C_8	[0.044, 0.065, 0.094]	[0.320, 0.380, 0.421]	[0.058, 0.091, 0.149]	[0.049, 0.053, 0.061]
C_9	[0.264, 0.327, 0.377]	[0.040, 0.054, 0.070]	[0.029, 0.039, 0.050]	[0.049, 0.053, 0.061]
C_{10}	[0.066, 0.109, 0.188]	[0.040, 0.054, 0.070]	[0.026, 0.030, 0.037]	[0.056, 0.068, 0.082]

Table 4.5 Weight vector by homogeneous aggregation and arithmetic average for the location problem for solar installations

Criteria	Weight vector		
C_1	0.0384	0.0419	0.0493
C_2	0.0464	0.0586	0.0728
C_3	0.0421	0.0513	0.0622
C_4	0.1145	0.1271	0.1414
C_5	0.0427	0.0493	0.0599
C_6	0.1242	0.1449	0.1778
C_7	0.1725	0.1855	0.1931
C_8	0.1458	0.1680	0.1871
C_9	0.1097	0.1195	0.1293
C_{10}	0.0448	0.0538	0.0675

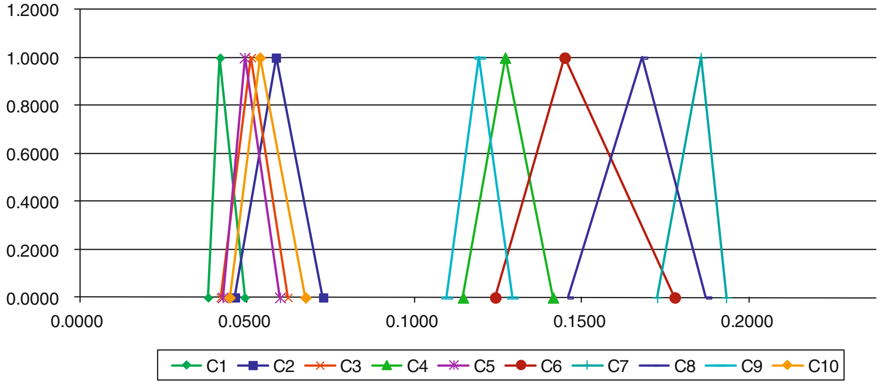

Fig. 4.6 Location criteria of solar photovoltaic plants (homogeneous aggregation)

Table 4.6 Weight vector by homogeneous aggregation and arithmetic average for the location problem of solar thermoelectric plants

Criteria	Weight vector		
C_1	0.0884	0.1046	0.1197
C_2	0.0561	0.0819	0.1275
C_3	0.0461	0.0638	0.0924
C_4	0.0949	0.1165	0.1396
C_5	0.1428	0.1642	0.1885
C_6	0.0579	0.0840	0.1287
C_7	0.0410	0.0537	0.0695
C_8	0.1179	0.1474	0.1813
C_9	0.0956	0.1184	0.1395
C_{10}	0.0468	0.0655	0.0944

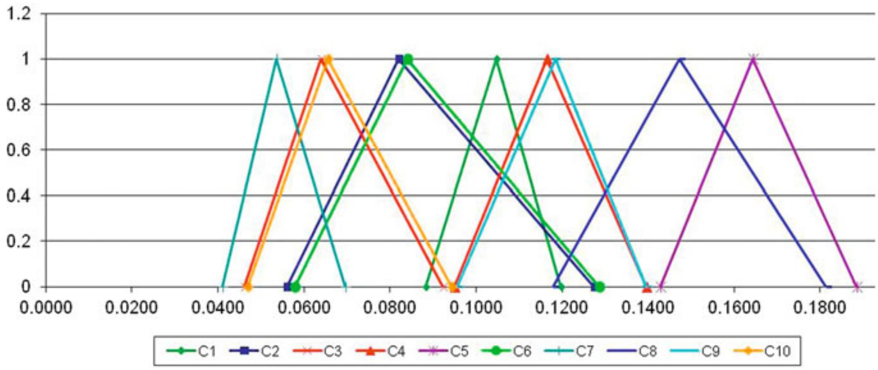

Fig. 4.7 Location criteria for solar thermoelectric plants (homogeneous aggregation)

4.6 Conclusions

Comparing the results for both RE technologies, it is noted that although, according to the experts, the decision criteria that influence the location of these installations are identical, they do not affect the decision equally.

The highest rated criterion for solar photovoltaic plants corresponds to distance to cities (C_7), while this criterion for the case of solar thermoelectric plants is the one with the worst rating.

For the case of solar thermoelectric plants the highest rated criterion corresponds to distance to main roads (C_5), while this same criterion for the case of solar photovoltaic is one of the worst rated. Among the various reasons cited for this notable difference is the emphasis placed on the physical characteristics of these types of plants. For example, the equipment systems and components required to implement a solar thermoelectric plant are such that it is essential to have infrastructure networks such as roads sufficiently close to the implantation site. In the case of photovoltaic plants this is not a great advantage because their equipment systems are smaller and more manageable.

It is also interesting to highlight that there are a number of criteria whose importance is similar for both technologies: these are potential solar radiation (C_9); distance to electricity transformer substations (C_8); and area (C_4).

The current study has shown that a number of criteria must be taken into account when selecting the best location for a solar photovoltaic or thermoelectric plant. Moreover, such criteria do not equally influence the decision making, so it is very important to know beforehand the weights of these criteria for each technology when implementing such facilities.

Extending the analysis to other technologies (wind energy, biomass, etc.), selecting a set of sites to study and supplementing it with other techniques for decision support, are all pending issues that could well be framed as future research.

Acknowledgments This work is partially supported by FEDER funds, the DGICYT and Junta de Andalucía under projects (TIN2008-06872-C04-04, TIN2011-27696-C02-01) and (P07-TIC02970, P11-TIC-8001), respectively.

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