Obtaining the Decision Criteria and Evaluation of Optimal Sites for Renewable Energy Facilities Through a Decision Support System

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Abstract In projects regarding renewable energy facilities, decision making is an essential activity that provides greater consistency and viability to the project. The first step that any promoter of such facilities should face is to select an optimal location. To do so, it is necessary to consider all the criteria that influence the decision. However, not all the criteria are equally important, which means that determining their weights is extremely important. The objective of this chapter is to obtain the weights of the decision criteria that influence the location problems of wind farms and solar photovoltaic and thermoelectric plants. For this, a Decision Support System (DSS) has been designed that allows to carry out the extraction of knowledge from an expert group by Fuzzy AHP methodology. Finally, DSS will sort the viable locations based on the importance of the criteria that influence the decision.

Keywords Decision support systems (DSS) · Optimal location · Renewable energy facilities · Fuzzy AHP

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K. Madani et al. (eds.), *Computational Intelligence*,
Studies in Computational Intelligence 613,
DOI 10.1007/978-3-319-23392-5_19

1 Introduction

Renewable energy is the energy obtained from virtually inexhaustible natural sources, either due to the vast amount of energy they contain, or because they are able to regenerate by natural media. One of the great problems of humanity's dependence on fossil fuels is their depletion and the environmental impact they cause [1, 2].

When implementing renewable energy facilities, the promoter must find and select the best location in order to obtain a better use of energy and reduce the risks that, in facilities of this size, can cause serious economic and environmental damage [3]. It is, however, not unusual that in choosing the right site among various sites, there is a degree of uncertainty. If the knowledge and experience of the decision group are combined with methodologies and tools to assist in decision making [4], this uncertainty could be avoided.

Decision Support Systems DSS [5] appeared in the 1970s as solutions which could be used to help with complex decision-making and problem solving in a structured manner. The DSS are particularly suitable for solving the same complex problem several times. In location problems in industrial plants and specifically in the problems of locating renewable energy facilities a set of decision criteria exist which affect the decision on the location of these facilities. These criteria will depend on the type of technology (solar, wind ...) to be installed on the facilities. Therefore it is of great interest to have a DSS to help obtain the weights of criteria when deciding on the optimal locations for renewable energy installations [6].

Thus, this chapter focuses on the design of a DSS that facilitates the decision maker to obtain the weights of the criteria in a location problem of renewable energy facilities.

The chapter will be structured as follows: Sect. 2 will focus on the hierarchical structure of decision criteria for the case of wind facilities and solar photovoltaic and thermoelectric plants. Section 3 will focus on the design of the DSS algorithms to work with and the data entry into the system and the results of the DSS output for different renewable technologies. Section 4 presents an example of how it is possible to obtain a classification of suitable locations through the DSS and finally in Sect. 5 we present the main conclusions of the work.

2 Decision Criteria for the Optimal Location of Renewable Energy Facilities

It is necessary to know which criteria influence (and to what extent), the decision-making problem proposed. Although previous studies have been conducted indicating the features that these criteria should meet [7, 8], the fact of using one or another will depend mainly on the study area. However, it is possible to establish common generic criteria that subsequently may be decomposed into specific criteria, which will depend on the characteristics and nature of the area to be analyzed.

Therefore, following the guidelines established in [9], four groups of main criteria will be established (environment, location, orography and climatology criterion).

Through the environment criterion it is not intended to assess the impact that these renewable energy plants cause in certain sites, the description of this criterion is based on the suitability of installing renewable energy plants depending on the capacity that the land presents to host them. Location criteria will be composed on the one hand by those criteria that allow to evaluate the distances that the future renewable plants would have regarding infrastructures or areas in which they cannot be implemented (cities, airports, masts, etc.) and, on the other hand by those criteria that will not only allow to reduce the installation costs but will also favour its performance (distance to main roads, power lines, etc.). Orography criteria are based on both the extension and the orographic features that the land presents to implement this type of facilities in order to minimize the installation costs and increase efficiency, for example, to implement solar facilities it will not only be appropriate that the land has sufficient area but it must also have low slopes and a correct orientation. Finally climatology criteria will allow evaluating the production capacity of the renewable energy plants. Sites should be chosen where these criteria present appropriate values because these criteria are essential not only for the correct operation of the plant but also to optimize the production.

These criteria are common to the main renewable energy facilities, and especially to those which this paper is focused on: wind farms, solar photovoltaic plants and thermoelectric plants.

The difference between the different technologies exists in the definition of the criteria to be considered in the location, based on the type of technology used. So for wind farms the hierarchy of criteria is that shown in Fig. 1 [10]:

- C_1: Agrological capacity (Classes): Suitability of land for agricultural development, if the land presents excellent agrological capacity it will not be suitable to implement the renewable facility and vice versa.
- C_2: Slope (%): Inclination of the land, the higher the percentage of surface inclination, the worse fitness it will have to implement a wind farm.
- C_3: Area (m^2): Surface contained within a perimeter of land that can accommodate a renewable energy facility.
- C_4: Distance to main airports (m): Space of interval between the nearest airport and the different possible sites.
- C_5: Distance to main roads (m): Space of interval between the nearest main road and the different possible sites.
- C_6: Distance to power lines (m): Space of interval between the nearest power line and the different possible sites.
- C_7: Distance to cities (m): Space of interval between the population centers (cities and towns) and the different possible sites.
- C_8: Distance to electricity transformer substations (m): Space of interval between the nearest electricity transformer substation and the different possible sites.

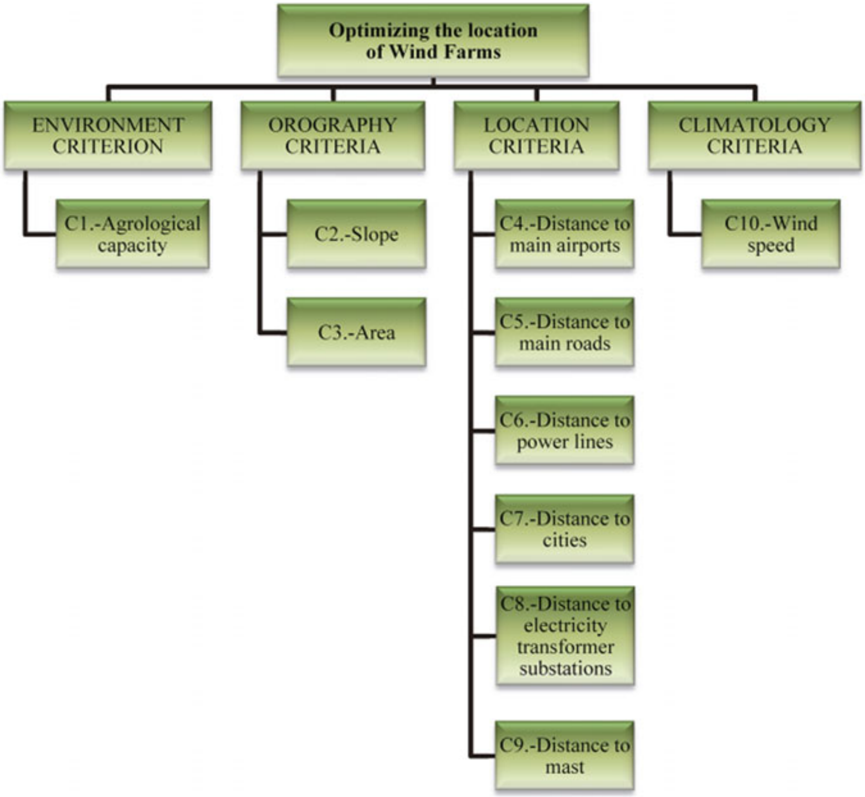


Fig. 1 Criteria tree for optimizing the location of wind farms

- C_9: Distance to mast (m): Space of interval between the nearest mast and the different possible sites.
- C_{10}: Wind speed (m/s): It corresponds to the wind speed at an elevation of 80 meters in the different possible sites.

In the case of solar photovoltaic and thermoelectric plants the criteria tree is as in Fig. 2 where we have some similar criteria (C_1, C_2, C_3, C_5, C_6, C_7, and C_8) but others which are different, due to the technology used [11]:

- C_4: Field Orientation (Cardinal points): Position or direction of the ground to a cardinal point.
- C_9: Potential solar radiation (kJ m^2/day): It 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 ground in the course of one year.

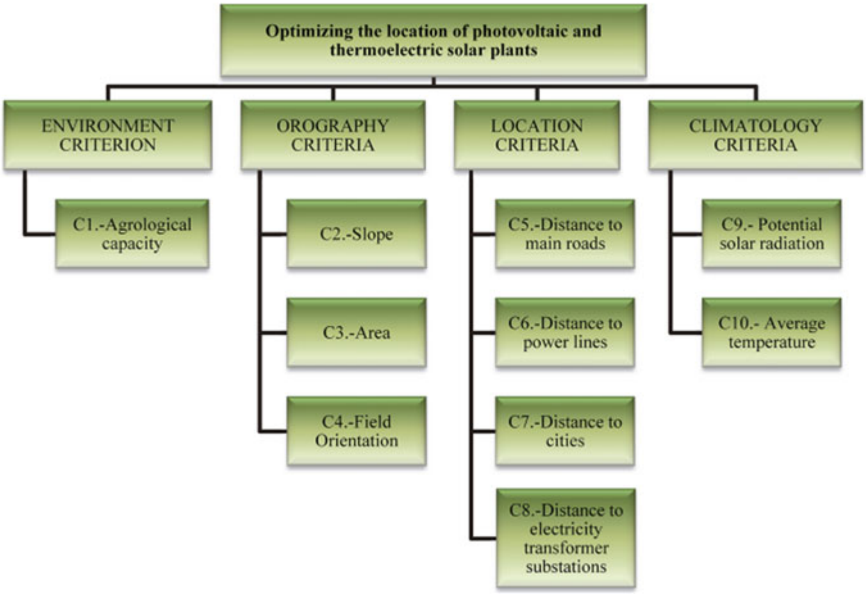


Fig. 2 Criteria tree for optimizing the location of solar photovoltaic and thermoelectric plants

3 Decision Support System for the Location of Renewable Energy Facilities

We have developed a Decision Support System DSS for the location of renewable energy facilities with the structure shown in Fig. 5 and called Optimal Location v1.0. Optimal Location v1.0 is formed by three sub-systems [5]:

- Data handling sub-system: Contains information about the problem. In this case, the Data Base is obtained by means of a Geographical Information System (GIS).
- Models' handling sub-system: Mathematical models that are used to solve the problem. Optimal Location v1.0 uses AHP and the TOPSIS method with or without fuzzy logic. By means of AHP we obtain the weights of the criteria.
- AHP estimates the impact of each one of the alternatives on the overall objective of the hierarchy. In this method the quantified judgments provided by experts in the field on pairs of criteria (C_i, C_j) are represented in an $n \times n$ matrix expressed by the following expression (1).

$$C = \begin{array}{c} \\ C_1 \\ C_2 \\ . \\ . \\ C_n \end{array} \begin{array}{c} \begin{array}{cccc} c_1 & c_2 & \ldots & c_n \end{array} \\ \begin{bmatrix} c_{11} & c_{12} & \ldots & c_{1n} \\ c_{21} & c_{22} & \ldots & c_{2n} \\ . & . & \ldots & . \\ . & . & \ldots & . \\ c_{n1} & c_{n2} & \ldots & c_{n3} \end{bmatrix} \end{array} \quad (1)$$

The c_{12} value is supposed to be an approximation of the relative importance of C_1 to C_2, i.e., $c_{12} \approx (w_1/w_2)$. The statements below can be concluded:

- $c_{ij} \approx (w_i/w_j)$ i, j = 1, 2, …, n
- $c_{ii} = 1$, i = 1, 2, …, n
- If $c_{ij} = \alpha, \alpha \neq 0$, then $c_{ji} = 1/\alpha$, i=1,2,…, n
- If C_i is more important than C_j then $c_{ij} \cong (w_i/w_j) > 1$

Matrix C should be a positive and reciprocal matrix with 1's in the main diagonal; so the expert needs only to provide value judgments in the upper triangle of the matrix. The TOPSIS method is applied to obtain the ranking of the alternatives. Nevertheless, this chapter has been focused on the aim of obtaining the weight of the criteria.

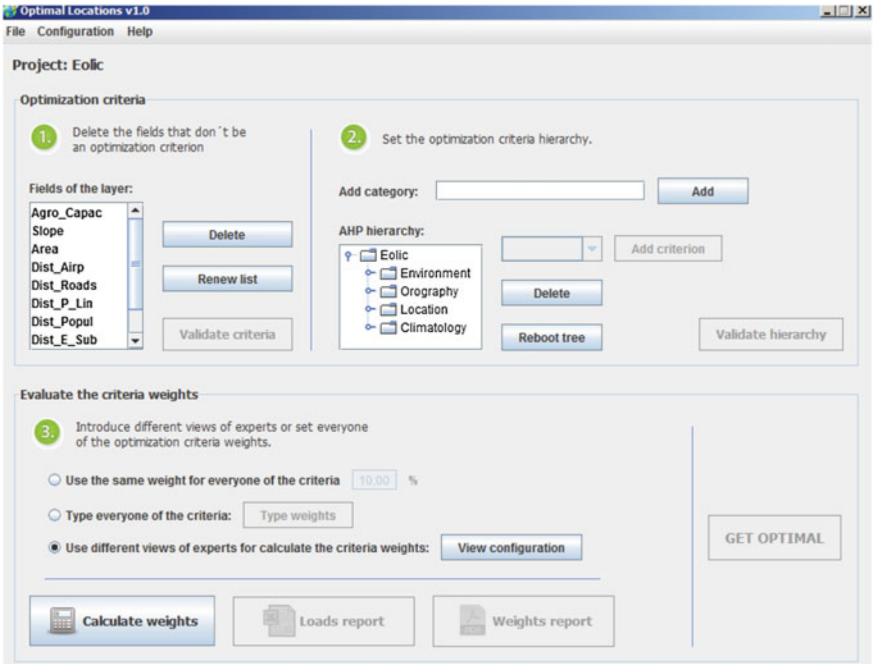


Fig. 3 Insertion of the criteria and categories in Optimal Location v1.0

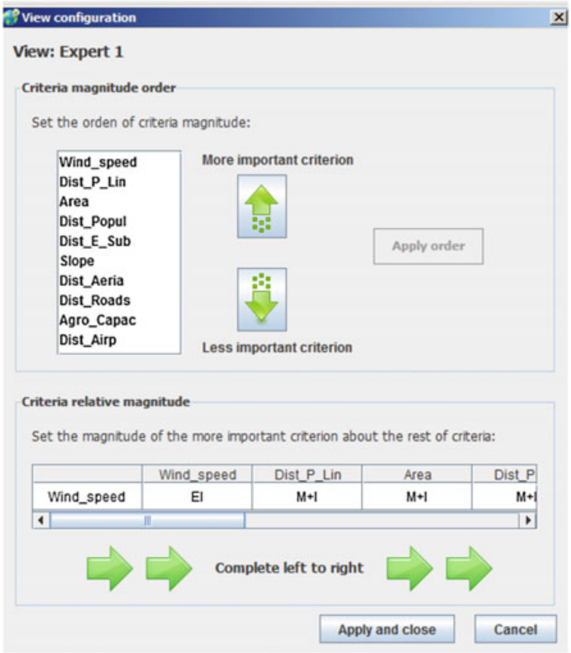


Fig. 4 Insertion of the order of importance for each criterion in Optimal Location v1.0

Fig. 5 Group decision making with Optimal Location v1.0

- *User Interface Sub-system*: It is the environment in which the user controls the DSS. By means of this interface, the input data can be introduced in order to apply the AHP method (see Figs. 3 and 4) and additionally the results (output of the DSS) can be shown, these results are shown in Figs. 7, 8 and 9.

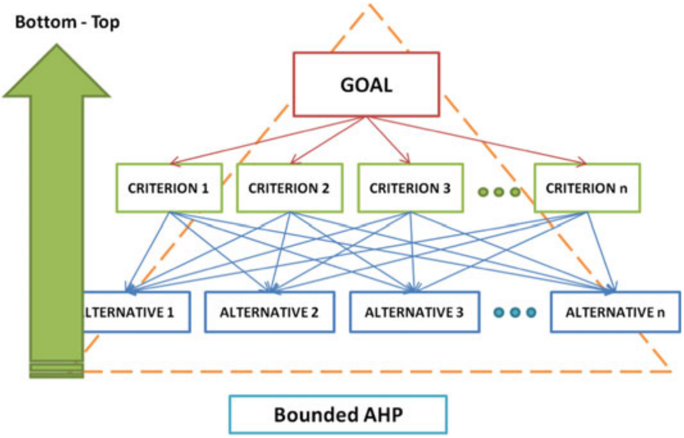
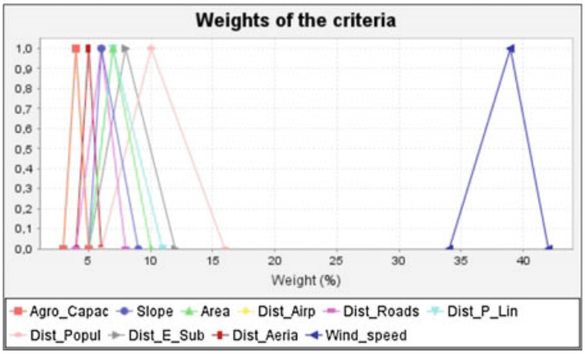


Fig. 6 *Bottom* to *Top* AHP method

Fig. 7 Weights of the criteria for wind farms

Table of weights of the criteria		
Environment		
	Agro_Capac	[03,78, 04,36, 05,35] %
Orography		
	Slope	[05,08, 06,97, 09,36] %
	Area	[05,12, 07,17, 10,61] %
Location		
	Dist_Airp	[03,78, 04,36, 05,35] %
	Dist_Roads	[04,73, 06,35, 08,33] %
	Dist_P_Lin	[05,32, 07,66, 11,28] %
	Dist_Popul	[06,73, 10,15, 16,05] %
	Dist_E_Sub	[05,79, 08,40, 12,47] %
	Dist_Aeria	[04,26, 05,32, 06,91] %
Climatology		
	Wind_speed	[34,06, 39,26, 42,83] %



3.1 Data Input to the DSS

The DSS starts with a file format ESRI Shape file (.Shp.) to perform its functions. This file must have been previously published and analyzed on professional GIS

Fig. 8 Weights of the criteria for photovoltaic plants

Table of weights of the criteria		
Environment		
	Agro_Capac	[03,84, 04,19, 04,93] %
Orography		
	Slope	[04,64, 05,86, 07,28] %
	Orientatio	[04,21, 05,13, 06,22] %
	Area	[11,45, 12,71, 14,14] %
Location		
	Dist_Roads	[04,27, 04,93, 05,99] %
	Dist_P_Lin	[12,42, 14,49, 17,78] %
	Dist_Popul	[17,25, 18,55, 19,31] %
	Dist_E_Sub	[14,58, 16,80, 18,71] %
Climatology		
	Solar_Rad	[10,97, 11,95, 12,93] %
	Av_Temp	[04,48, 05,38, 06,75] %

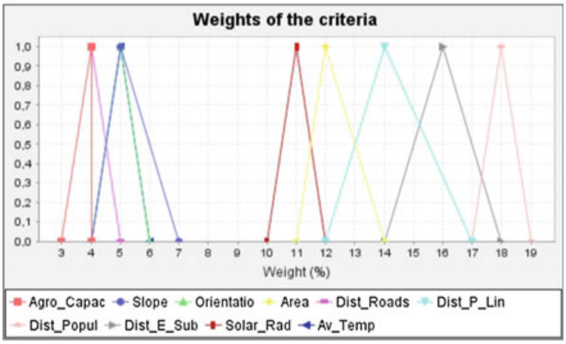
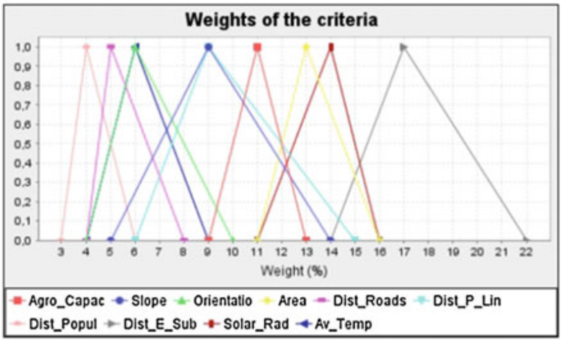


Fig. 9 Weights of the criteria for thermoelectric plants

Table of weights of the criteria		
Environment		
	Agro_Capac	[09,93, 11,67, 13,24] %
Orography		
	Slope	[05,84, 09,16, 14,95] %
	Orientatio	[04,50, 06,74, 10,27] %
	Area	[11,01, 13,77, 16,57] %
Location		
	Dist_Roads	[04,23, 05,99, 08,81] %
	Dist_P_Lin	[06,07, 09,43, 15,12] %
	Dist_Popul	[03,62, 04,89, 06,55] %
	Dist_E_Sub	[14,07, 17,88, 22,14] %
Climatology		
	Solar_Rad	[11,10, 14,02, 16,56] %
	Av_Temp	[04,39, 06,46, 09,86] %



software. In this particular case, the gvSIG tool has been used because it is free software.

For optimization calculations it is necessary to establish the relative importance of each decision criterion. To do so, the DSS uses the AHP method [12, 13].

This seeks to establish the pairwise comparisons required by this method by conducting surveys to different experts in the field. It is a pseudo-Delphi technique, in which different independent experts without mutual interaction value judgments made for pairwise comparison. In this way, the aim is to obtain a vector of weights of the criteria from each expert and then to produce a single weight vector by performing an arithmetic mean between them, see Fig. 6.

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

Among the various options for representing information and because the data is grouped perfectly, and that handling it is simple and effective, fuzzy numbers will be chosen to represent information [14, 15].

In the case studied, the data provided shall be represented by triangular fuzzy numbers [16–18].

3.2 Treatment of the Data

For that purpose, a questionnaire similar to that made by [19] was developed, which was given to experts with the aim of reducing uncertainty and imprecision of the proposed problem. The linguistic labels used in the Fuzzy AHP model are shown in Table 1.

In AHP problems, where the values are fuzzy, the geometric normalized average will be used, expressed by the following expression (2):

Table 1 Linguistic labels used in fuzzy AHP

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

$$W_i = \frac{\prod_{j=1}^{n} \left(a_{ij}, b_{ij}, c_{ij}\right)}{\sum_{i=1}^{m} \prod_{j=1}^{n} \left(a_{ij}, b_{ij}, c_{ij}\right)} \tag{2}$$

where $\left(a_{ij}, b_{ij}, c_{ij}\right)$ is a fuzzy number

The group of experts involved in the decision process answer a survey based in the Fuzzy AHP model. In this case the way to obtain the weighted criteria is bottom to top type (see Fig. 6), this is to calculate all the weights of the criteria at the second level by comparing all the criteria with each other.

The survey is divided into two parts:

1. The decision problem is explained indicating what the goal to achieve is (optimal location of sites for renewable energy facilities), 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 trees (Figs. 1 and 2).
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 three questions:
   - Q_1: Do you believe that all the criteria have the same weight?
     - If the answer is yes, 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:
   - Q_2: List the criteria in descending importance.
   - Q_3: Compare the approach to be considered first with respect to that considered secondly and successively, using the linguistic labels in Table 1.

In the particular case of wind farms, the answers for each of the criteria indicated in Fig. 2 were the following.

Answer Q1: NO

Answer Q2: The orders of importance for each of the experts are shown in Table 2.

Answer Q3: The pairwise comparisons among criteria by the experts are shown in Table 3

So, the weights of the criteria will be determined by pairwise comparison among criteria. As a result of the data collection used, a total of (n − 1) comparisons will be required against the complete AHP method n(n − 1)/2 comparisons.

3.3 Weights of the Criteria in Wind, Solar Photovoltaic and Thermoelectric Plants

The results of the DSS output are discussed for the three types of technologies and with the hierarchical structure criteria according to Figs. 1 and 2 for the criteria.

DSS provides the results for the criteria as seen in Fig. 7, in the case of the decision criteria for the location of wind farms; Fig. 8 for the case of the decision criteria for the location of solar photovoltaic plants; and Fig. 9 in the case of decision criteria for locating thermoelectric plants.

In the case of wind farms the criterion (Fig. 7) which clearly stands out above the other criteria is the wind speed (C_{10}) with almost 40 % of the total weight. This result is logical since to implement a wind farm the wind speed plays a crucial role, and if this is not enough in a given area, that area is removed by any promoter of these facilities. The remainder of these criteria are further apart and grouped around weights between 5 and 10 % of the total.

In the case of solar technologies the situation is different since there is no single criterion whose weight or importance coefficient is so high that it allows to discard the rest. Analyzing Fig. 8, the criteria for photovoltaic plants, 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).

The results are consistent since in the implementation of a photovoltaic solar plant, the fact of having a pour point to the nearest grid greatly reduces the initial investment costs, thus reducing the payback period of the facility. However, it should also be highlighted that the most important criterion presented corresponds to the distance to centers of population, the justification for this high weight can be found in both the potential environmental impact that this type of facility can generate and

Table 2 Order of importance of the criteria for each of the experts for the case of location of wind farms

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

Table 3 Pairwise comparisons among criteria for the case of location of wind farms by linguistic labels

	Expert 1	Expert 2	Expert 3
1° → 2°	*S + I*	*VS+I*	*S + I*
1° → 8°	*VS+I*	*Ex+I*	*Ex+I*
1° → 5°	*S + I*	*VS+I*	*+I*
1° → 3°	*S + I*	*VS+I*	*+I*
1° → 9°	*Ex+I*	*Ex+I*	*Ex+I*
1° → 7°	*+I*	*Ex+I*	*VS+I*
1° → 4°	*S + I*	*VS+I*	*+I*
1° → 6°	*+I*	*VS+I*	*VS+I*
1° → 10°	*Ex+I*	*Ex+I*	*Ex+I*

in growth and expansion of cities because, given the useful life of photovoltaic solar plants, implementing these facilities in close proximity to centers of population can condition their expansion.

Analyzing Fig. 9, the criteria for thermoelectric plants, 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 area (C_3), 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 distance to roads (C_5).

The results are consistent as solar thermoelectric plants are facilities that not only require a territory covering a large area, but also, the installed capacity of them is usually very high (with the aim of reducing the payback period) therefore there is a need to have nearby transformer substations that allow to directly pour the electricity generated because, if not, the promoter himself should meet the additional

Fig. 10 Position and suitable locations in the municipality of Águilas

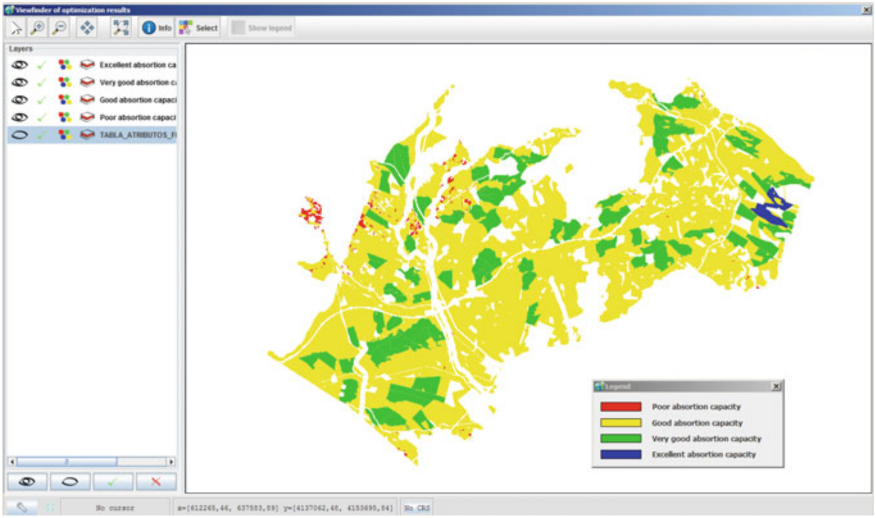


Fig. 11 Map of the capacity to accommodate solar photovoltaic farms in the municipality of Águilas

cost of building a transformer substation to discharge the energy generated in the thermoelectric plant.

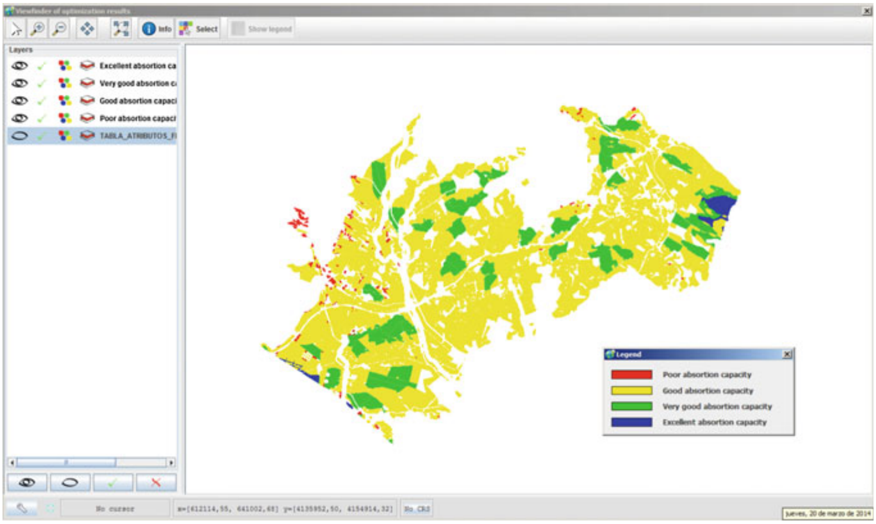


Fig. 12 Map of the capacity to accommodate solar thermoelectric farms in the municipality of Águilas

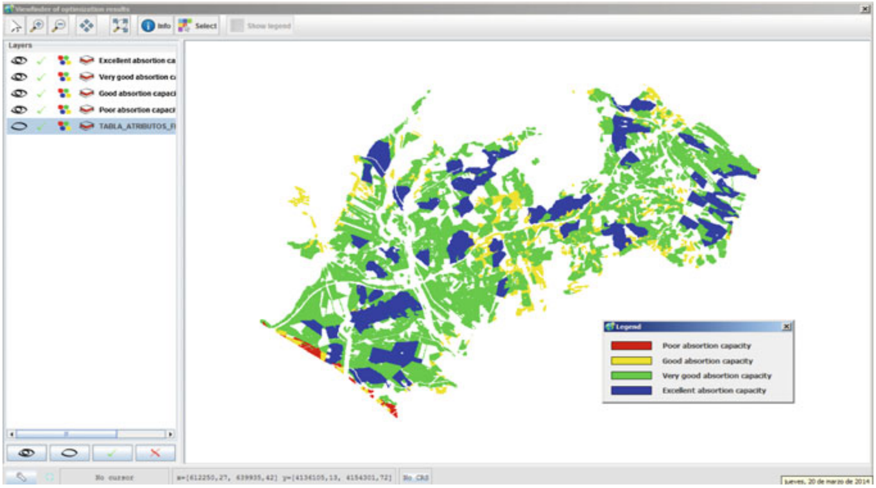


Fig. 13 Map of the capacity to accommodate wind farms in the municipality of Águilas

4 Obtaining Optimal Locations. Case Study: Municipality in Southeast of Spain

Once the weights of the criteria that influence in the decision have been obtained, the available locations to implement renewable energy facilities will be evaluated with DSS. To do so, the thematic layer obtained in [20] will be used, which will provide the suitable locations to implement wind farms, solar photovoltaic and thermoelectric plants in 13 municipalities in the Region of Murcia, in south-eastern Spain. As an example the thematic layers of one of the municipalities that compose the coast of this Region, specifically the town of Águilas, will be used (Fig. 10).

Introducing these thematic layers in the DSS, the software will be able to evaluate the plots of the municipality of Águilas according to the weights of the criteria. Once that evaluation has been made, the DSS will provide a map showing the ability of each plot to host renewable energy facilities, these capacities will be linked to a colour code (excellent: blue; very good: yellow; and regular: red). The evaluations obtained are shown in Figs. 11, 12 and 13.

Analyzing Figs. 11 and 12 it is observed that there is some similarity in the best rated locations for solar photovoltaic and thermoelectric facilities, since the categories of the available locations are very similar. Regarding wind farms it is observed that most of the locations have very good or excellent capacity for this type of facilities.

5 Conclusions

This study has shown that we must take into account a number of criteria to select which is the best location for renewable energy facilities (wind farms, solar photovoltaic plants and solar thermoelectric plants). Moreover, such criteria do not equally influence in decision making so it is very important to know beforehand the weights of these criteria for each technology when implementing such facilities.

Moreover, it is interesting to show that there are important differences among Wind and Solar technologies, while between the two solar technologies there is a greater similarity.

Carrying out the assessment of the facilities available in a case study, it is observed that the DSS is able to provide a classification of the locations according to their ability to host such facilities: it is observed that the optimal locations to host solar photovoltaic and thermoelectric farms coincide. It should also be noted that in the case of wind farms, the number of locations that have very good capacity for this type of facility increases.

It is of great interest for the promoters of renewable energy facilities to have a tool such as this, a DSS to model the importance of the decision criteria when locating renewable energy installations that aggregates all the information by different experts to be involved in decision making.

This DSS is simple and intuitive to manage for any expert in the field of renewable energy without any knowledge of soft computing, when experts only have to answer three simple questions to obtain the weights of the criteria involved in the decision making of the optimal location for renewable energy facilities.

Acknowledgments This work is partially supported by FEDER funds, the DGICYT and Junta de Andalucía under projects TIN2014-55024-P and P11-TIC-8001, respectively.

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