Decision Support Systems to Obtain Decision Criteria by Fuzzy AHP for Location of Renewable Energy Facilities

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Abstract: Location of Renewable Energy Facilities will depend on various factors such as environmental, orography location and climatology criteria, which in turn are broken down into sub-criteria that will depend on the technology to locate. The objective of the present paper is to obtain the weights of the decision criteria which influence in the problem of location of renewable energy facilities, especially in wind farms and solar plants (photovoltaic and thermoelectric). To that end a Decision Support System (DSS) has been designed to help the decision-maker to obtain the weights of the criteria involved in this decision. Fuzzy AHP methodology is used with that DSS for the extraction of expert knowledge and to model the vague and imprecise data by triangular fuzzy numbers.

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 (Intergovernmental Panel on Climate Change IPCC, 1992; United Nations, 1997).

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 (Kahraman et al., 2009). 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 (Ramirez- Rosado et al., 2008), this uncertainty could be avoided.

Decision Support Systems DSS (Turban et al., 2006) 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. Location problems in industrial plants and specifically in the problems of locating renewable energy facilities there is a set of decision criteria which affect the decision on the location of these facilities and that 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 to decide the optimal locations for renewable energy installations.

Thus, this article 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 paper will be structured as follows: Section 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. Section 4 presents the results of the DSS output for different renewable technologies and finally in section 5 we present the main conclusions of the paper.

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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 (Janke, 2010; Al-Yahyai et al., 2012), 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 of sub-criteria, which will depend on the characteristics and nature of the area to be analyzed.

Therefore, following the guidelines established in (Aran Carrión et al., 2008), four groups of main criteria will be established:

- Environment criterion
- Location criteria
- Orography criteria
- Climatology criteria

Through environment criterion it is not intended to assess the impact that these facilities cause of renewable energy plants in certain sites, the description of this criterion is based on the suitability of installing renewable energy plants depending on the capacity that it presents a land to host them. Location criteria will be compose on the one hand by those criteria that allow to evaluate the distances that it would have the future renewable plants 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 also will favour its performance (distance to main roads, power lines, etc). Orography criteria are based on both the extension and the orographic features that it presents a land to implement this type of facilities in order to minimize the installation costs and increase efficiency, for example, to implement solar facilities 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. It should be chosen sites 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 sub-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 Figure 1 when (Sanchez-Lozano et al., 2013b):

- 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 (m²): 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 centres (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.
- 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 Figure 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 (Sanchez-Lozano et al. 2013a):

- C_4: Field Orientation (Cardinal points): Position or direction of the ground to a cardinal point.
- C_9: Potential solar radiation (kJ·m²/day): It corresponds to the amount of solar energy a ground surface receives over a period of time (day).

- C_{10}: Average temperature (ºC): Average temperatures measured on ground in the course of one year.

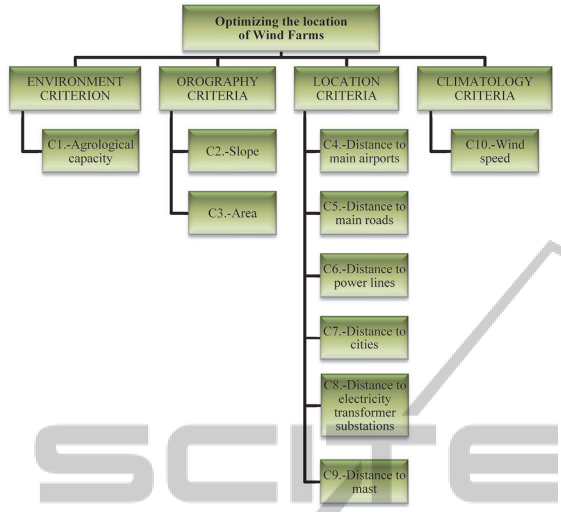

Figure 1: Criteria tree for optimizing the location of wind farms.

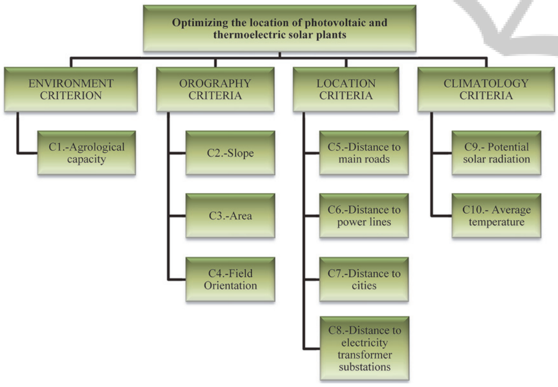

Figure 2: Criteria tree for optimizing the location of photovoltaic and thermoelectric plants.

3 DECISION SUPPORT SYSTEM FOR 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 Figure 3 and called Optimal Location v1.0.

Optimal Location v1.0 is formed by three sub-systems (Turban et al., 2006):

- *Data handling sub-system*: Contains information about the problem. In this case, the Data Base is obtained by means of a Geographical Information Systems (GIS)

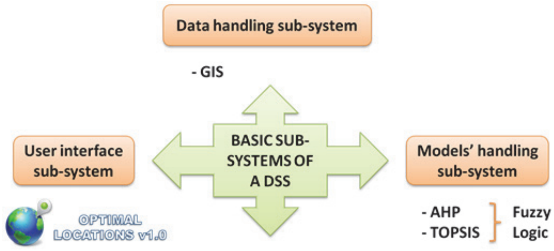

Figure 3: Structure of DSS.

- *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 judgements provided by experts in the field on pairs of criteria (Ci, Cj) are represented in an nxn matrix expressed by the following expression (1).

$$C = \begin{array}{c c} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{array}{c} C_1 \\ C_2 \\ \vdots \\ C_n \end{array} & \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \ddots & \cdots & \vdots \\ c_{n1} & c_{n2} & \ddots & c_{nn} \end{bmatrix} \end{array} \tag{1}$$

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:

$c_{ij} \approx (w_i/w_j)$ $i, j = 1, 2, \ldots, n$
$c_{ii} = 1$, $i=1, 2, \ldots, n$
If $c_{ij}=\alpha$, $\alpha \neq 0$, then $c_{ji}=1/\alpha$, $i=1,2,\ldots, n$
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.

TOPSIS method is applied to obtain the ranking of the alternatives. Nevertheless, this paper has been carried out with the aim of obtaining the weight of the criteria.

- *User interface sub-system*: It is the environment in which the user controls the DSS. By means of this interface, on the one hand we are able to introduce the input data in order to apply the AHP method (see Figures 4, 5) and on the other, we are able to show the results (output of the DSS), these results are shown in figs 8-13.

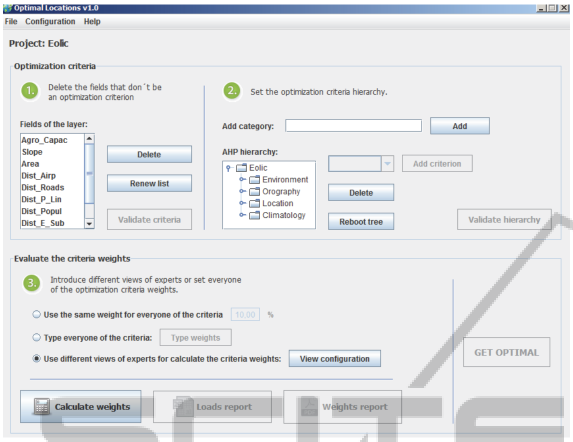

Figure 4: Insertion the criteria and categories in Optimal Location v1.0.

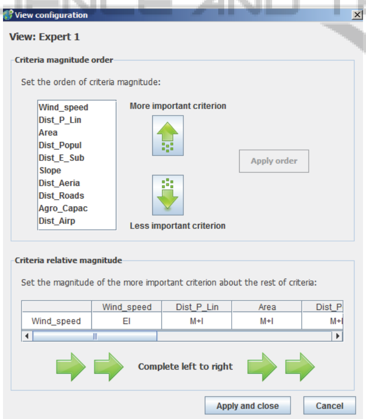

Figure 5: Insertion the order of importance for each criterion in Optimal Location v1.0.

3.1 Data Input to the DSS

The DSS starts with a file format ESRI Shape file (.Shp.) (Zeiler, 2010) to perform its functions. This file must have been previously published and analysed on professional GIS software. In this particular case, the gvSIG tool has been used because it is free software.

For optimisation calculations it is necessary to establish the relative importance of each decision criterion. To do that, the DSS uses the AHP method (Saaty, 1980, 1989).

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, we aim 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 Figure 6.

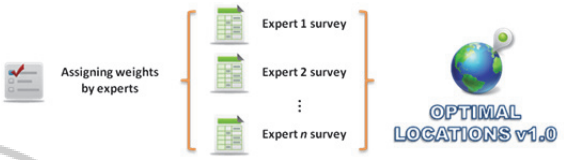

Figure 6: Group Decision Making with Optimal Location v1.0.

The information provided by the experts is qualitative in character or is very vague since is has been obtained through linguistic terms; because of this the data obtained should be set modelled 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 case studied, the data provided shall be represented by triangular fuzzy numbers (Zadeh 1965, Klir and Yuan, 1995; Dubois and Prade, 1980).

3.2 Treatment of the Data

For that purpose, a questionnaire similar to that made by (Garcia-Cascales et al., 2012) 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, we will use the geometric normalized average, expressed by the following expression (2):

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

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 type bottom to top (see Figure 7), this

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)

is to calculate all the weights of the sub-criteria at the second level by comparing all the sub- criteria with each other. Subsequently, the sub-criteria are aggregates to their main criterion.

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 (Figures 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 sub-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.

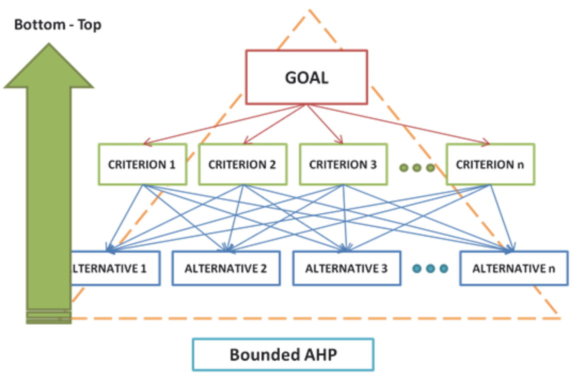

Figure 7: AHP method Bottom to Top.

In the particular case of wind farms, the answers for each of the sub-criteria indicated in fig. 2 were the followings.

Answer Q1: NO

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

Table 2: Order of importance of the sub-criteria for each of the experts for the case of location of wind farms.

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

Answer Q3: The pair comparisons among sub-criteria by the experts are shown in Table 3.

Table 3: Pair comparison among sub-criteria for the case of location of wind farms by linguistic labels.

	Expert 1	**Expert 2**	**Expert 3**
$1^o \rightarrow 2^o$	*S+I*	*VS+I*	*S+I*
$1^o \rightarrow 8^o$	*VS+I*	*Ex+I*	*Ex+I*
$1^o \rightarrow 5^o$	*S+I*	*VS+I*	*+I*
$1^o \rightarrow 3^o$	*S+I*	*VS+I*	*+I*
$1^o \rightarrow 9^o$	*Ex+I*	*Ex+I*	*Ex+I*
$1^o \rightarrow 7^o$	*+I*	*Ex+I*	*VS+I*
$1^o \rightarrow 4^o$	*S+I*	*VS+I*	*+I*
$1^o \rightarrow 6^o$	*+I*	*VS+I*	*VS+I*
$1^o \rightarrow 10^o$	*Ex+I*	*Ex+I*	*Ex+I*

So, the weights of the criteria will be determined by pair-wise 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, 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 figures 1 and 2, both for the sub-criteria as well as for the principal criteria.

3.3.1 Data Results for the Sub-criteria

DSS provides the results for the sub-criteria as seen in Figure 8, in the case of the decision sub-criteria for the location of wind farms, Figure 9 for the case of the decision sub-criteria for the location of solar photovoltaic plants, and Figure 10 in the case of decision sub-criteria for locating thermoelectric plants.

In the case of wind farms the sub-criteria (Figure 8) which clearly stands out above the other sub-criteria is the wind speed (C_{10}) with almost 40% of total weights. 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 sub-criteria are further apart and grouped around a weight between 5 and 10% of the total.

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] %

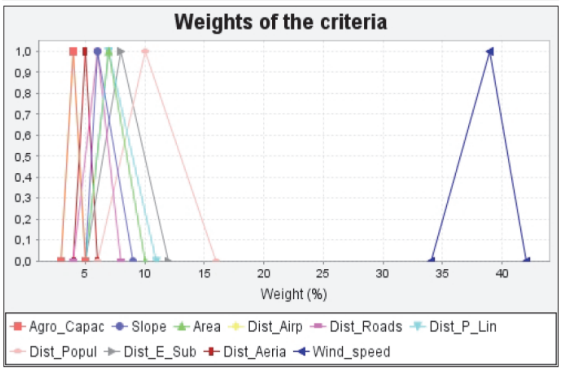

Figure 8: Weights of the sub-criteria criteria for wind farms.

This does not happen in the case of solar technologies where there is not a single criterion whose weight or importance coefficient is so high that it allows to discard the rest. Analysing Figure 9 sub-criteria for photovoltaic plants it is shown that the three best sub-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 sub-criterion of agrological capacity (C_1) and to the sub-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 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.

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] %

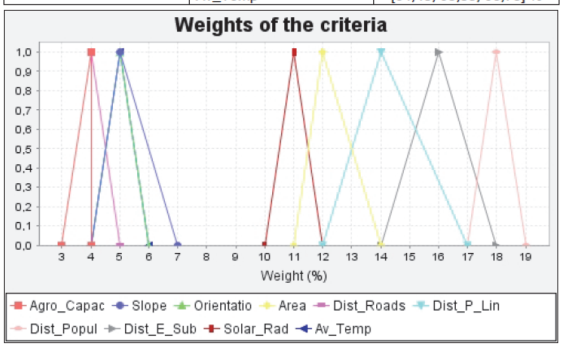

Figure 9: Weights of the sub-criteria for photovoltaic plants.

Analysing Figure 10, the sub-criteria forthermoelectric plants it is shown that the three best sub-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 sub-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 period of payback) 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 cost of building a transformer substation to discharge the energy generated in the thermoelectric plant.

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] %

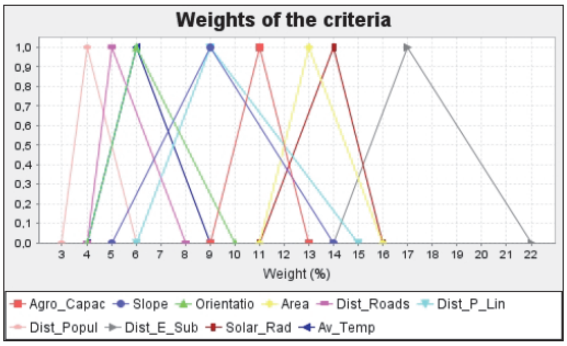

Figure 10: Weights of the sub-criteria for thermoelectric plants.

3.3.2 Data Results for the Main Criteria

The output results for the three technologies considered and the inclusion of data from at least three experts for each technology provides the following DSS data: weights of the main criteria for the location of wind farms (Figure 11); weights of the main criteria for the location of photovoltaic plants (Figure 12); and finally the weights of the main criteria for the location of thermoelectric plants (Figure 13). The results for the main criteria are obtained from the aggregation bottom to top (Figure 7) of different sub-criteria grouped into each main criterion, as can be seen in figures 1 and 2.

It seems clear that in general for all the primary technologies the criterion which has more weight in the decision is that of the location rather than environmental criteria which have less weight in the decision in all the technologies, wind, photovoltaic and thermoelectric, see Figures 11, 12 and 13.

Table of weights of the categories	
Environment	[03,78, 04,36, 05,35] %
Orography	[10,21, 14,14, 19,98] %
Location	[30,61, 42,24, 60,39] %
Climatology	[34,06, 39,26, 42,83] %

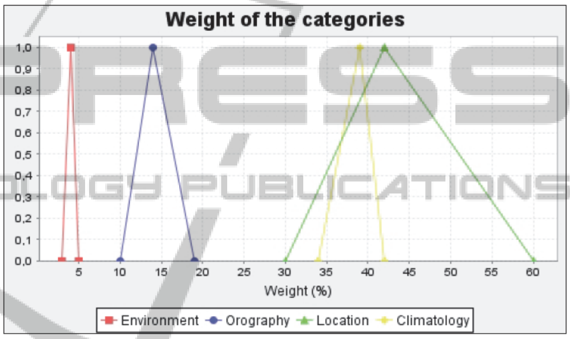

Figure 11: Weights of the main criteria for the location of wind farms.

However, the second criterion by weight is not the same for all the technologies: in the case of the location of wind farms the climatology criteria, Figure 11. This is to a certain extent a logical result since it is the only criterion in which humankind cannot intervene to improve it, that is to say that although a site may offer excellent conditions to implant a wind farm, if there is hardly any wind or the wind is very slight, then it cannot be an optimal site for such an installation. While in the case of solar, both photovoltaic, Figure 12, and thermoelectric, Figure 13, it is the orography criteria. The fact that this criterion is in second position is principally due to the fact that the proximity to or distance from population nuclei or infrastructures which influence the decision are of great importance when including if a zone is optimal to implant this type of facilities.

Table of weights of the categories	
Environment	[03,84, 04,19, 04,93] %
Orography	[20,30, 23,70, 27,64] %
Location	[48,52, 54,77, 61,79] %
Climatology	[15,45, 17,33, 19,68] %

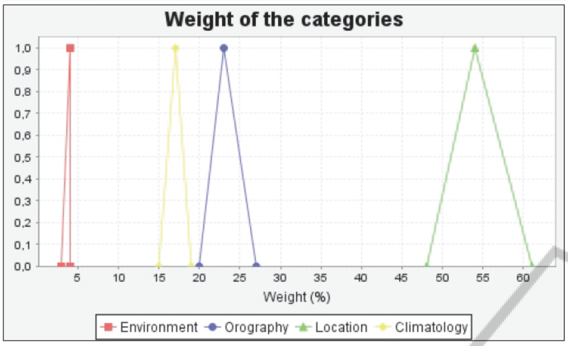

Figure 12: Weights of the main criteria for the location of photovoltaic plants.

Table of weights of the categories	
Environment	[09,93, 11,67, 13,24] %
Orography	[21,35, 29,67, 41,80] %
Location	[27,99, 38,18, 52,61] %
Climatology	[15,49, 20,48, 26,42] %

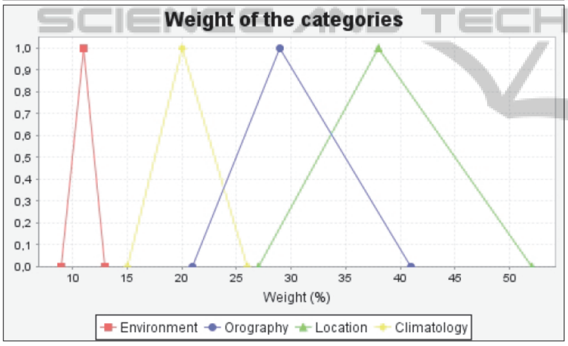

Figure 13: Weights of the main criteria for the location of thermoelectric plants.

5 CONCLUSIONS

The 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.

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

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 of sub-criteria involved in the decision making of the optimal location for renewable energy facilities.

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