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Multi-criteria decision methods applied to the assessment of photovoltaic technologies

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Abstract.

The aim of this paper is the study and analysis of the decision criteria to be used when searching for the best technology for manufacturing photovoltaic modules, considering both technical and non-technical criteria such as social and environmental factors. Multi-criteria decision making (MCDM) methods will be used for the modelling of the selection problem of the best technology for manufacturing photovoltaic cells. Combining these techniques with the use of fuzzy sets will mean that linguistic labels can be used to value the criteria used.

Keywords

Photovoltaic modules, manufacturing technology, Multi-criteria decision making (MCDM), fuzzy sets, linguistic labels

1. Introduction

Photovoltaic energy has presented a major evolution and it is forecasted as an important contributor to power generation and an alternative to other non-renewable energy sources. It has been encouraged in part by present energy policies, that are promoting the deployment of photovoltaics (PV); an ambitious scenario considered from EPIA is to generate 12% of electricity from PV systems by 2020 [1], when the cost of PV electricity could approach to residential tariff, finally achieving the so-called grid parity [2].

From the first solar modules used in spatial applications, the advances in semiconductor technologies have had a large impact on the photovoltaic industry [3]. Applications may vary attending to different PV technologies, in stand-alone systems, or major power supply in the case of grid-connected systems.

The high cost of solar electricity is today the main reason why electricity from photovoltaic systems is not introduced in a more widespread way. For this energy to present lower costs it is necessary to achieve continued and sustained growth of its market and at the same time, to keep a large effort in technological research aimed to progress towards much lower manufacturing costs through the learning curve of the technology.

Solar photovoltaic technology, like any other technology has travelled a long way, based mainly on experience; and in this paper, we seek to assess the leading photovoltaic technologies presently available, using MCDM methods to do so.

The rest of the paper is organized as follows: "The statement of decision problem" is related with the problem in question. In the following sections, we describe the suggested methods in detail. The linguistic variable and the fuzzy sets are described, as well as the AHP and TOPSIS methods which will be used later. In "a problem of decision in technologies of manufacture" we present the application of the methods. Finally, "Conclusions" details the most important conclusions and future works.

2. The statement of decision problem

Any multi-criteria decision problem (*MCDP*) may be expressed by means of the following five elements, $\{C, D, r, I, \prec\}$;

Where:

1. $C = \{C_1, C_2, ..., C_m\}$ It is the set of criteria that represent the tools which enable alternatives to be compared from a specific point of view.
2. $D = \{D_1, D_2, ..., D_n\}$ It is the set of feasible alternatives for the decision-maker, and from which the decision-maker must choose one. In this case, the sets C and D are finite sets. This allows us to avoid convergence, integrability and measurability problems.
3. $r: D \times C \rightarrow$ R is a function to every decision d_i and to every criterion C_j .

$$(D_i, C_j) \rightarrow r(D_i, C_j) = r_{ij}$$

Once that set of criteria and alternatives have been selected, then we need a measure of the effect produced by each alternative with respect to each criterion.

By means of linguistic terms, the decision-maker represents the goodness of an alternative with respect to a criterion; the different values of r can be represented by means of a matrix called the *Matrix of decision making*.

4. A relation of preferences $\prec$ by the decision maker. We shall suppose a coherent decision-maker, therefore he should try to maximize his profits or at least minimize his losses. In this case the decision-maker needs to obtain the best alternative according to the considered criteria.
5. Certain information about the criteria, which in this case is also linguistic. The decision-maker gives us linguistic information about the importance for each criterion.

3. Linguistic variable and fuzzy sets

3.1. Linguistic variable

Most of the times, the decision-maker is not able to define the importance of the criteria or the goodness of the alternatives with respect to each criterion in a strict way. In many situations, we use measures or quantities which are not exact but approximate.
Since Zadeh [4] introduced the concept of fuzzy set and subsequently went on to extend the notion via the concept of linguistic variables, the popularity and the use of fuzzy sets have been extraordinary. We are particularly interested in the role of linguistic variables, and their associated terms, in this case fuzzy numbers, which will be used in the multi-criteria decision making.
By a *linguistic variable* [5,6] we mean a variable whose values are words or sentences in a natural or artificial language. For example *Age* is a linguistic variable if its values are linguistic rather than numerical, i.e., *young, not young, very young, quite young, old, not very old and not very young*, etc., rather than numbers as 20, 21,22, 23,...

Definition 1.- *A linguistic variable* is characterized by a quintuple *{X; T(X);U;G;M}* in which:
1. *X* is the name of the variable,
2. *T(X)* is the term set of *X*, that is, the collection of its linguistic values
3. *U* is a universe of discourse,
4. *G* is a syntactic rule for generating the elements of *T(X)* and
5. *M* is a semantic rule for associating meaning with the linguistic values of *X*.

In general for the decision-maker it is easier when he/she evaluates their judgments by means of linguistic terms [7]. In those cases, the concept of fuzzy number is more adequate than that of real number.

3.2. Fuzzy sets

In our case, we identify the linguistic variable with a fuzzy set [8,9,10]. The fuzzy set theory, introduced by Zadeh [4] to deal with vague, imprecise and uncertain problems has been used as a modelling tool for complex systems that can be controlled by humans but are hard to define precisely. A collection of objects (universe of discourse) X has a fuzzy set A described by a membership function f_A with values in the interval $[0,1]$.

$$f_A : X \to [0,1]$$

Thus A can be represented as $A = \{f_A(x) \mid x \in X\}$. The degree that u belongs to A is the membership function $f_A(x)$.

The basic theory of the triangular fuzzy number is described in [11].

In this paper, we only make reference to the operations on fuzzy sets that we will use in the application, as well as the defuzzification process used.

Definition 2.- If A_1 and A_2 are two TFN defined by the triplets (a_1, b_1, c_1) and (a_2, b_2, c_2), respectively. For this case, the necessary arithmetic operations with positive fuzzy numbers are:

a) Addition:

$$A_1 \oplus A_2 = [a_1 + a_2, b_1 + b_2, c_1 + c_2] \quad (1)$$

b) Subtraction:

$A_1 \Theta A_2 = A_1 + (-A_2)$ when the opposite $-A_2 = (-c_2, -b_2, -a_2)$ then

$$A_1 \Theta A_2 = [a_1 - c_2, b_1 - b_2, c_1 - a_2] \quad (2)$$

c) Multiplication:

$$A_1 \otimes A_2 = [a_1 \times a_2, b_1 \times b_2, c_1 \times c_2] \quad (3)$$

d) Division:

$$A_1 \varnothing A_2 = [[a_1, b_1, c_1] \cdot [1/c_2, 1/b_2, 1/a_2]], \quad (4)$$
$$0 \neq [a_2, b_2, c_2]$$

e) Scalar Multiplication:

$$k \circ T_1 = (k \circ a_1, k \circ b_1, k \circ c_1) \quad (5)$$

f) Root:

$$T_1^{1/2} = [a_1^{1/2}, b_1^{1/2}, c_1^{1/2}] \quad (6)$$

3.3. Defuzzification

Definition 3: Let A=(a,b,c) be a fuzzy number, with membership function f_A ,we define the area related to the left side as $S_L(A_i) = b - \int_a^b f_A^L(x)dx = \int_0^1 g_A^L(y)dy$, the area related to the right side as $S_R(A_i) = b + \int_b^d f_A^R(x)dx = \int_0^1 g_A^R(y)dy$, and the area related with the mode as $S_M(A_i) = b$. The meaning of $S_L(A_i)$, $S_M(A_i)$ and $S_R(A_i)$ are expressed in Fig 1.

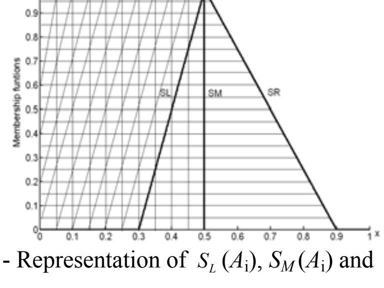

Fig. 1- Representation of $S_L(A_i)$, $S_M(A_i)$ and $S_R(A_i)$

In this way, we define an index that is a function of the three integrals previously defined.

Definition 4. The index associated with the ranking is a bi-convex combination:

$$I_{\beta,\lambda}(A_i) = \beta S_M(A_i) + (1-\beta)[\lambda S_R(A_i) + (1-\lambda)S_L(A_i)]$$
$$= \beta S_M(A_i) + (1-\beta)\lambda S_R(A_i) + (1-\beta)(1-\lambda)S_L(A_i) \quad (7)$$

β ∈ [0,1], is the index of modality that represents the importance of the central value against the extreme values and λ ∈ [0,1] is the degree of optimism of the decision maker. For more details, see [12].

Remark: If we consider a *TFN* defined by the triplet (*a,b,c*). it is possible to consider different values β and λ in $I_{\beta,\lambda}(A_i)$. Thus, for example:

If λ =1/2 and β =1/3 $\Rightarrow I_{1/3,1/2}(A_i) = \frac{1}{3}\left(\frac{a+4b+c}{2}\right)$ (8)

4. Analytic Hierarchy Process (AHP)

The AHP methodology was proposed by Saaty in 1980 [13], has been accepted by the international scientific community as a robust and flexible multi-criteria decision making tool for dealing with complex decision problems. Basically, AHP has three underlying concepts: structuring the complex decision as a hierarchy of goal, criteria and alternatives, pair-wise comparison of elements al each level of the hierarchy with respect to each criterion on the preceding level, and finally vertically synthesizing the judgements over the different levels of the hierarchy. AHP attempts to estimate the impact of each one of the alternatives on the overall objective of the hierarchy. In this case, we only apply the method in order to obtain the criteria´s weights.

We assume that the quantified judgements provided by the decision-maker on pairs of criteria (C_i, C_j) are represented in an n x n matrix as in the following:

$$C = \begin{array}{c} \\ C_1 \\ C_2 \\ . \\ . \\ C_n \end{array} \begin{bmatrix} c_1 & c_2 & \cdots & c_n \\ c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ c_{n1} & c_{n2} & \cdots & c_{n3} \end{bmatrix} \quad (9)$$

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

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

This implies that matrix A should be a positive and reciprocal matrix with 1´s in the main diagonal and hence the decision maker needs only to provide value judgments in the upper triangle of the matrix. The values assigned to c_{ij} according to Saaty scale are usually in the in the interval of 1-9 or their reciprocals. In our case, Table I presents the linguistic decision-maker's preferences in the pair-wise comparison process.

Table I. Scale of valuation in the pair-wise comparison process

Verbal judgements of preferences between alternative i and alternative j	Fuzzy numbers
A_i and A_j is equally important to	[1, 1, 1]
A_i is slightly more/less important than A_j	[2, 3, 4]
A_i is strongly more/less important than A_j	[4, 5, 6]
A_i is very strongly more/less important than A_j	[6, 7, 8]
A_i is extremely more/less important than A_j	[8, 9, 9]

It can be shown that the number of judgements (L) needed in the upper triangle of the matrix are:

$$L = n(n-1)/2 \quad (10)$$

where *n* is the size of the matrix C.

In AHP problems, where the values are fuzzy, not crisp; instead of using lambda as an estimator to the weight, we will use the geometric normalized average, expressed by the following expression:

$$w_i = \frac{\left(\prod_{j=1}^{n}(a_{ij},b_{ij},c_{ij})\right)^{1/n}}{\sum_{i=1}^{m}\left(\prod_{j=1}^{n}(a_{ij},b_{ij},c_{ij})\right)^{1/n}} \quad (11)$$

where, (a_{ij},b_{ij},c_{ij}) is a fuzzy number.

5. TOPSIS method

Technique for order performance by similarity to ideal solution (TOPSIS) is one of the known classical MCDM methods, that was developed by Hwang and Yoon [14]. It is based upon the concept that the chosen alternative should have the shortest distance from the positive ideal solution, and the farthest from the negative ideal solution.

This approach is employed for four reasons [15]:

a) TOPSIS logic is rational and understandable;

b) The computation processes are straightforward;

c) The concept permits the pursuit of best alternatives for each criterion depicted in a simple mathematical form, and

d) The importance weights are incorporated into the comparison procedures

In this study, the TOPSIS method, which is very simple and easy to implement, was used to select the preference order of the alternatives. The MCDM that includes both numeric and linguistic labels can be expressed in a matrix.

The fuzzy TOPSIS methods are derived from the generic TOPSIS method with minor differences, with the pertinent adaptation of the operations associated to the linguistic labels [16].

5.1. The algorithm:

Step 1: Identify the evaluation criteria and the appropriate linguistic variables for the importance weight of the criteria and determine the set of feasible alternatives with the linguistic score for alternatives in terms of each criterion. Once the decision matrix is formed, the normalized decision matrix (n_{ij} ; *i=1,2,..,m* (number of alternatives); *j=1,2,..,n* (number of criteria)) is constructed using equation (11):

$$\overline{n}_{ij}^{1} = z_{ij} \Big/ \sqrt{\sum_{j=1}^{m} \left(z_{ij} \right)^2}, \ j = 1, \ldots, n, \ i = 1, \ldots, m. \qquad (12)$$

where z_{ij} is the performance score of alternative i against criteria j.

Step 2: The weighted decision matrix $\overline{v}_{ij}$ is calculated using equation (12). The weight of the criteria j is represented by w_j :

$$\overline{v}_{ij} = w_j \otimes \overline{n}_{ij}, \ j = 1, \ldots, n, \ i = 1, \ldots, m, \qquad (13)$$

where, w_j such that $1 = \sum_{j=1}^{n} w_j$ is the weight of the jth attribute or criterion. It is well known that the weights of criteria in decision-making problems do not have the same mean and not all of them have the same importance.

Step 3: The ideal solution, $\overline{A}^{+}$ ($\overline{A}_i^{+}$; *i = 1,2,...,m*), is made of all the best performance scores

$$\overline{A}^{+} = \left\{ \overline{v}_1^{+}, \ldots, \overline{v}_n^{+} \right\} = \left\{ \left(\max_i \overline{v}_{ij}, j \in J \right) \left(\min_i \overline{v}_{ij}, j \in J' \right) \right\} \qquad (14)$$

i = 1,2,...,m

and the negative ideal solution, $\overline{A}^{-}$ ($\overline{A}_i^{-}$; *j= 1,2,...,n*), is made of all the worst performance scores at the measures in the weighted normalized decision matrix.

$$\overline{A}^{-} = \left\{ \overline{v}_1^{-}, \ldots, \overline{v}_n^{-} \right\} = \left\{ \left(\min_i \overline{v}_{ij}, j \in J \right) \left(\max_i \overline{v}_{ij}, j \in J' \right) \right\} \qquad (15)$$

i=1,2,...,m

They are calculated using equations (13) and (14) and where J is associated with benefit criteria, and J' is associated with cost criteria.

Step 4: The distance of an alternative to the ideal solution $\overline{d}_i^{+}$,

$$\overline{d}_i^{+} = \left\{ \sum_{j=1}^{n} \left(\overline{v}_{ij} - \overline{v}_j^{+} \right)^2 \right\}^{\frac{1}{2}}, \ \mathrm{i} = 1, \ldots, m \qquad (16)$$

and from the negative ideal solution $\overline{d}_i^{-}$,

$$\overline{d}_i^{-} = \left\{ \sum_{j=1}^{n} \left(\overline{v}_{ij} - \overline{v}_j^{-} \right)^2 \right\}^{\frac{1}{2}}, \ \mathrm{i} = 1, \ldots, m \qquad (17)$$

in this case we use the m-multidimensional Euclidean distance

Step 5: The ranking score $\overline{R}_i$ is calculated using equation (18). The obtained ranking scores represent the alternatives' performance achievement within their status. A higher score corresponds to a better performance.

$$\overline{R}_i = \frac{\overline{d}_i^{-}}{\overline{d}_i^{+} + \overline{d}_i^{-}}, \ \mathrm{i} = 1, \ldots, m \qquad (18)$$

If $\overline{R}_i = 1 \rightarrow A_i = \overline{A}^{+}$

If $\overline{R}_i = 0 \rightarrow A_i = \overline{A}^{-}$

where the $\overline{R}_i$ value lies between 0 and 1. The closer the $\overline{R}_i = 1$ value implies a higher priority of the i^{th} alternative.

Step 6: Rank the preference order

6. A problem of decision in manufacturing technologies.

6.1. Structuring the problem

The different kinds of technologies for manufacturing the existing photovoltaic cells today will be the alternatives that constitute the decision problem to solve.

Nowadays, several ways of classifying the technologies for manufacturing photovoltaic cells exist, depending on the characteristics to highlight (thickness, efficiency, cost… etc). A typical classification will be made on the basis of the semiconductor element/s and of their thickness [17,18,19]. For that reason, the technologies are divided as follows:

- *A_1: Manufacturing technology with crystalline silicon (mono-crystalline and poly-crystalline)*: the material of origin of the silicon cells is the silicate that, through reduction process, refining, fractional distillation, melting, crystallization and laminating permits to obtain mono-crystalline and poly-crystalline silicon wafers .
- *A_2: Manufacturing technology with inorganic thin layer (amorphous silicon)*: using thin films (about 1-3μm) of amorphous silicon and the addition of intercalated hydrogen in order to avoid the losses associated to the Stabler-Wronski effect.
- *A_3: Manufacturing technology with inorganic thin layer (CdTe and CIGS)*: it also shows small thickness (~μm). The cadmium telluride cells are compound by a cadmium telluride layer (type p) joined by a CdS thin layer (type n) and, finally by a transparent conducting oxide layer (generally SiO_2). The $Cu(InGa)Se_2$ cells (CIGS) are compound by a CdS thin layer (or ZnS), double aluminium layer and a transparent conducting oxide layer.
- *A_4: Manufacturing technology with advanced III-V thin layer with tracking systems for solar concentration*: based in alloys of III-V elements (the most common alloys are made by using the following elements: Al, As, Ga, In y P) these cells are very expensive, but since they are the most efficient, specially when using tandem technology and solar concentration and tracking systems, they can be cost competitive with the above mentioned technologies
- *A_5: Manufacturing technology with advanced, low cost, thin layers (Organic and hybrid cells)*: two classes, hybrid technology based in inorganic TiO_2 network sensityzed with organic dyes and embedded in an electrolite; or the full organic solar cells based in polymeric layers offer the possibility of large cost reduction in the manufacturing process.

After analysing the technologies that will be identified as alternatives to study, the criteria with highest impact in their manufacturing processes will be defined.

The criteria considered for the assessment of the decision problem are the following:

- *C1: Manufacturing cost:* it will constitute a criterion to minimize, it will be characterized in a quantitative way in the following terms: euros for watt peak that each cell produces (€/Wp)
- *C2: Efficiency in energy conversion:* it will constitute a criterion to maximize; it will be characterized in a qualitative way in terms of per cent (%)
- *C3: Market share:* it will constitute a criterion to maximize; it will be characterized in a qualitative way through linguistic assessment labels.
- *C4: Emissions of greenhouse gases (that are generated in the manufacturing):* it will constitute a criterion to minimize; it will be equally characterized in a qualitative way through linguistic assessment labels.
- *C5: Energy pay-back time:* Time that the system takes to generate the consumed energy in manufacturing. It will constitute a criterion to minimize; it will be equally characterized in a qualitative way through linguistic assessment labels.

It will be use a hierarchic structure with two levels as representation of this problem (Fig 2.).

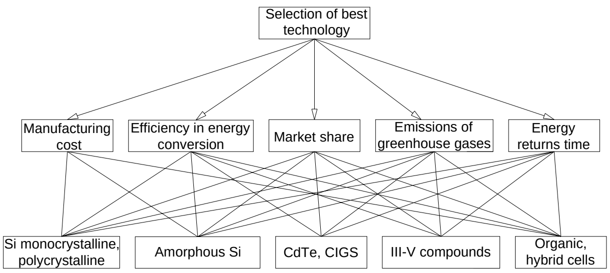

Fig. 2 – Hierarchy structure of the problem

In this case the AHP method was used for obtaining the importance that the decision-maker gives to each criterion. In this case the decision-maker is a physicist expert in manufacturing photovoltaic cells.

Using the scale of valuation indicated in Table 1 in the pair-wise comparison process, and the application of AHP method, together with the normalized geometric average, we obtain Table II.

Table II.–Importance weight of criteria

	Normalized
C1	[0.0930, 0.1209, 0.1593]
C2	[0.5581, 0.6046, 0.6372]
C3	[0.0620, 0.0672, 0.0796]
C4	[0.0930, 0.1209, 0.1593]
C5	[0.0698, 0.0864, 0.1062]

Once that set of criteria have been selected, and the weight of criteria obtained, then we need a measure of the effect produced by each alternative with respect to each criterion.

The TOPSIS method was used to select the preference order of the alternatives. By means of linguistic labels and numerical values, the decision-maker represents the goodness of the alternatives with respect to criteria C_1, C_2, C_3, C_4 and C_5. The different values of *r* can be represented means of matrix called the "Matrix of decision making". In order to deal with the information using the fuzzy TOPSIS for the ratings of the alternatives using the linguistic variables explained in Table III.

Table III.- Linguistic labels for the ratings of the alternatives

Linguistic label type	
Description	Fuzzy number
Very Low/Very Brief	[0, 0, 1]
Low/Brief	[0, 1, 3]
Medium low/medium brief	[1, 3, 5]
Medium/Medium	[3, 5, 7]
Medium high/Medium long	[5, 7, 9]
High/Long	[7, 9, 10]
Very High/Very Long	[9, 10, 10]

$$\begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \end{array} \begin{array}{ccccc} C_1(€/W_p) & C_2(\%) & C_3 & C_4 & C_5 \\ \end{array}$$

$$\begin{array}{c|ccccc} & C_1(€/W_p) & C_2(\%) & C_3 & C_4 & C_5 \\ \hline A_1 & 0.68 \div 2.20 & 18 \div 24 & \textit{Very high} & \textit{Medium} & \textit{Medium} \\ A_2 & 0.40 \div 0.95 & 8 \div 15 & \textit{Low} & \textit{Medium} & \textit{Medium short} \\ A_3 & 0.60 \div 1.20 & 8 \div 15 & \textit{Low} & \textit{Medium} & \textit{Medium short} \\ A_4 & 0.20 \div 0.70 & 25 \div 40 & \textit{Low} & \textit{High} & \textit{Short} \\ A_5 & 0.40 \div 0.80 & 6 \div 12 & \textit{Low} & \textit{Low} & \textit{Short} \end{array}$$

6.2. Results and discussion

We can see in Table IV the data of d^+, d^- and the ranking scores for the different alternatives

Table IV- Computation distance to ideal solution d_i^+ and from the negative ideal solution d_i^- and the ranking score, by means of fuzzy numbers

d+	A_1	(0.0903, 0.1845, 0.3534)
	A_2	(0.2096, 0.3055, 0.4427)
	A_3	(0.2100, 0.3064, 0.4458)
	A_4	(0.0735, 0.0973, 0.1195)
	A_5	(0.2312, 0.3364, 0.4854)
d-	A_1	(0.1546, 0.1832, 0.2185)
	A_2	(0.0412, 0.0747, 0.1758)
	A_3	(0.0399, 0.0670, 0.1502)
	A_4	(0.2265, 0.3404, 0.5271)
	A_5	(0.0553, 0.1061, 0.2286)
R	A_1	(0.2702, 0.4982, 0.8924)
	A_2	(0.0667, 0.1966, 0.7010)
	A_3	(0.0669, 0.1794, 0.6011)
	A_4	(0.3503, 0.7776, 1.7570)
	A_5	(0.0775, 0.2398, 0.7979)

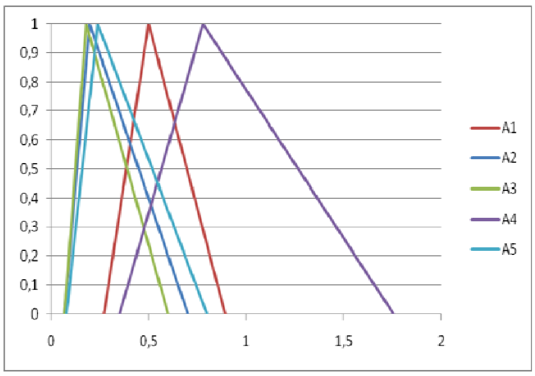

Fig. 3- Ranking score

Through the positive ideal distance d+ we consider those alternatives that are closer to the positive ideal. The smallest distance is the best alternative, so that the best alternative is A_4:

Min {0.093, 0.209, 0.210, 0.073, 0.231} =0.073 $\rightarrow A_4$
Min {0.184, 0.305, 0.306, 0.097, 0.336} =0.097 $\rightarrow A_4$
Min {0.353, 0.442, 0.445, 0.119, 0.485} =0.119 $\rightarrow A_4$

While on the negative ideal distance d- we need to be in the same conditions as before, that is this distance is maximized. Also in this case, the best alternative is A_4 because

Max {0.154, 0.041, 0.039, 0.226, 0.055} =0.226 $\rightarrow A_4$
Max {0.183, 0.074, 0.067, 0.340, 0.106} =0.340 $\rightarrow A_4$
Max {0.218, 0.175, 0.150, 0.527, 0.228} =0.527 $\rightarrow A_4$

To obtain the order of preference of the rest of alternatives, we need a defuzzyfication process, according to which:

Table V.- Results

	A_1	1.578
	A_2	0.777
$I_{1/3,1/2}$	A_3	0.693
	A_4	2.609
	A_5	0.917

7. Conclusions

The most common drawback of existing multi-criteria methods, at least for some classes of problems, is the need to translate the decision maker knowledge about a decision problem into numbers and functions. There are decision problems in which qualitative judgement prevails over more or less exact quantitative evaluation. For such problem, a natural choice is to use models that incorporate qualitative (descriptive, linguistic, ordinal) variables.

In this paper, we have studied the decision criteria when searching for the best technology for manufacturing photovoltaic modules. So that, by means a decision-maker's knowledge, we have developed the study by means of quantitative data and linguistic variables, which we have modelled by fuzzy numbers.

It is possible to see how the fourth alternative, "manufacturing technology with advanced thin layer with tracking systems for solar concentration (III-V compounds)" A_4, is the best alternative with this method.

Having presented the results to the decision-maker, he considers that his satisfaction is more in accordance with the results of the solution. As is shown in Table V, according to the questionnaire submitted by the "expert", the result of the MCDM calculation has been to prioritise A_4, the "III-V" technology, where the higher costs are compensated with the reliability of high power conversion. A_1, conventional crystalline silicon PV remains in second position. It is worth to mention that option A_5 is the third best option, illustrating the flexibility of the method because the approach in this case is the opposite, where lower efficiency is compensated with lower costs.

As future work, we propose to obtain information of other experts in the topic. In this case, it is possible that the information facilitated by the different experts may not be expressed in the same terms, having to find an alternative method to integrate the information.

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References

[1] SET For 2020 Report. European Photovoltaic Industry Association (EPIA). 2009

[2] Strategic Research Agenda (SRA) for Photovoltaic Solar Energy Technology. European Photovoltaic Technology Platform. 2007

[3] Green, M.A., Third generation photovoltaics: solar cells for 2020 and beyond. Physica E: Low-dimensional Systems and Nanostructures. 14(1-2): p. 65-70. 2002

[4] Zadeh L. A. Fuzzy sets. Information and Control, 8:338-353, 1965.

[5] Zadeh L.A, Kacprzyt J. Computing with Words in Information / Intelligent Systems. Part 1. Foundations, Heidelberg and New York; Physica-Verlag (Springer-Verlag); 1999

[6] Zadeh L.A, Kacprzyt J. Computing with Words in Information/ Intelligent Systems. Part 2. Foundations, Heidelberg and New York; Physica-Verlag (Springer-Verlag); 1999

[7] M.S. Garcia-Cascales, M.T. Lamata. Solving a decision problem with linguistic information. Pattern Recognition Letters vol 28, n.16 2284-2294. 2007

[8] Bellman R, Zadeh L.A. Decision making in a fuzzy environment. Management Science; 17: 141-164. 1970

[9] Kacprzyt J, Yager R.R. Linguistic summaries of data using fuzzy logic. International Journal of General Systems. 30 (2): 133-154. 2001.

[10] Kerre E.E. The use of fuzzy set theory in electrocardiological diagnostics, in: M.M. Gupta and E. Sanchez, Eds., Approximate Reasoning in Decision Analysis Amsterdam; North-Holland 1982; 277-282

[11] Klir G.J.; Yuan B., Fuzzy sets and Fuzzy Logic, Prentice Hall PTR, New Jersey ed. 1995

[12] Garcia-Cascales, M.S., Lamata, M.T.: A modification to the index of Liou and Wang for ranking fuzzy number, International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, 411-424, 2007.

[13] Saaty T.L. The Analytic Hierarchy Process. McGraw Hill; 1980

[14] Hwang, C.L., Yoon, K.,. Multiple Attribute Decision Methods and Applications. Springer, Berlin. (1981)

[15] Wang T.C, Chang T.H. Application of TOPSIS in evaluating initial training aircraft under a fuzzy environment. Expert Systems with Applications. 33; (4), 870-880, 2007

[16] García-Cascales, M.S y Lamata, M.T. Multi-criteria analysis for a maintenance management problem in an engine factory: rational Choice. In press Journal of Intelligent Manufacturing. 2009.

[17] Green, M.A. Polycrystalline silicon on glass for thin-film solar cells, Applied Physics A Materials Science & Processing, 96:153-159, 2009.

[18] Hegedus, E y Luque, A. Ed. Handbook of photovoltaic science and engineering, Wiley, 2003.

[19] Messenger, R.A y Ventre, J. Photovoltaic Systems Engineering, Second Edition, CRC Press, 2004.