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Computing with words to assess the sustainability of renewable energy options

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ABSTRACT

Appraising the Renewable Energy Sources (RES) options' contribution to Sustainable Development (SD) is a complex task, considering the different aspects of SD the imprecision and uncertainty of the related information as well as the qualitative aspects embodied, that cannot be represented by numerical values. The objective of the paper is to show how energy policy objectives towards SD and RES options are related and assessed using linguistic variables. The presented method extends the numerical multicriteria method TOPSIS for processing linguistic information, eliminating in parallel the loss of information caused by the approximation procedures and the ambiguity of the fuzzy ranking method's selection. Moreover, the application of the method's computerized software to the RES interventions proposed in the Hellenic National Action Plan for Greenhouse Gases is presented and discussed.

1. Introduction

In the pursuit of appropriate approaches to energy market restructure from unsustainable to sustainable forms of development, governments have at their disposal an increasingly diverse mix of Renewable Energy Sources (RES) options corresponding to consumers, businesses and governments themselves, as also pointed out by Palmer and Burtraw (2005) and Rivers and Jaccard (2006). Appraising RES options in terms of their contribution to the energy policy objectives towards Sustainable Development (SD) needs to be in accordance with the main principles of the Commission of the European Communities (2007, 2008a, 2008b). Each of these RES options contributes differently to the energy SD objectives to be accomplished. Therefore, selecting appropriate RES options is inevitably a very complex process, taking into consideration the incomplete and uncertain information as well as inconsistent and/or conflicting objectives and evaluation criteria, as analyzed by Komor and Bazilian (2005). In this context, coherent and transparent decision support methods could assist decision makers in formulating policy priorities towards a sustainable energy system through RES development.

The Multiple Criteria Decision Making (MCDM) methods can be an important supportive tool in the policy making, providing the flexibility and capacity to assess the technologies' implications to the economical, environment and social framework, as pointed out by Doukas, Patlitzianas, and Psarras (2006). Based on Pohekar and Ramachandran (2004), some of the most common methods used for assisting energy policy and planning towards sustainability are the Multi-Attribute Utility, the ELECTRE and the PROMETHEE methods, the Analytical Hierarchy Process and the TOPSIS, which was proposed by Hwang and Yoon (1981). However, the information needed for the evaluation of RES options in terms of their contribution to SD is often unquantifiable, imprecise and uncertain, since Phillis and Andriantiatsaholiniaina (2001) explicitly analyzed that sustainability is an inherently vague concept with parameters that are difficult to be measured. In this context, Doukas, Botsikas, and Psarras (2007) pointed out that a realistic approach is to use linguistic variables for expressing alternatives' ratings to criteria and the weights' importance within the process of a MCDM method. The linguistic variables take values from a set of linguistic terms and their semantics is represented by the corresponding fuzzy sets.

Many fuzzy MCDM methods have been developed by Ölçer and Odabaşi (2005), Wang and Lin (2003), Xu and Chen (2007) and many applications have benefited from these methods such as the ones by Chen and Tzeng (2004), Chen, Tzeng, and Ding (2008), Chiou, Tzeng, and Cheng (2005), Ding and Liang (2005), Yang, Chiu, Tzeng, and Yeh (2008) among others. The use of the ideal solutions to obtain a multicriteria compromise solution was first suggested by Zeleny (1974). Hwang and Yoon (1981) introduced the multicriteria method TOPSIS, which considers that the chosen alternative should have the shortest distance from the ideal solution and the longest distance from the non-ideal solution. Several extensions of TOPSIS have been made to incorporate fuzzy numbers in the process. Chen (2000) measured the distance between two triangular fuzzy numbers by a vertex method resulting in a crisp distance value and used the ideal and non-ideal solutions to define a crisp overall score for each alternative. Kuo, Tzeng, and Huang (2007) proposed a fuzzy multicriteria method combining

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the efficient fuzzy model (Li, 1999) and the principles of TOPSIS. This method results in fuzzy distance values which are compared by a fuzzy ranking method. Further, Kuo, Liang, and Huang (2006) combined grey relations and pairwise comparison, to obtain fuzzy preference relations and ranking orders of the alternatives. Jahanshahloo, Hosseinzadeh Lotfi, and Izadikhah (2006) extended fuzzy TOPSIS by using α-cuts to calculate the normalised fuzzy ratings. Wang and Elhag (2006) constructed a fuzzy TOPSIS method based on α-cuts and a nonlinear programming solution procedure.

Some fuzzy multicriteria methods, which use the ideal and the non-ideal solutions use crisp distances for fuzzy numbers thus, resulting in crisp distance values. Other methods use fuzzy distances or use fuzzy arithmetic and result in fuzzy overall scores. The first cases lead to loss of information and the second cases, apart from the computational complexity, imply the use of a fuzzy ranking method to order the fuzzy final scores of the alternatives. The use of a fuzzy ranking method involves considerable computation and produces inconsistency among different ranking methods.

In view of the abovementioned difficulties when using fuzzy numbers, a new fuzzy linguistic representation model has been proposed by Herrera and Martínez (2000), namely the 2-tuple linguistic representation model, to tackle them. The objective of the paper is to extend the numerical multicriteria method TOPSIS for processing linguistic data in the form of 2-tuples, so as to show how energy policy objectives towards SD and RES options are related and assessed using linguistic variables. Moreover, the application of the proposed method to the RES interventions proposed in the Hellenic National Action Plan for Greenhouse Gases is presented and discussed.

The paper is structured along six sections. Section 2 gives some fundamental aspects of the linguistic variables, regarding their representation models and computational techniques. Section 3 presents the proposed linguistic multicriteria method. Section 4 is dedicated to the application of this method to the Greek energy market. A sensitivity analysis of the model's results is carried out in Section 5. Lastly, Section 6 contains the conclusions, which summarizes the main points drawn up in the paper.

2. Linguistic variables: computational techniques and representation models

In many daily problems related information and data are imprecise and uncertain, since they embody qualitative aspects and cannot be represented by numerical values. The linguistic variables are assessed by linguistic terms which are represented by fuzzy numbers. The linguistic descriptors of the term set and their semantics have to be determined by the decision-maker(s). One possibility of generating the linguistic term set consists of directly supplying it by considering all terms distributed on a scale on which a total order is defined.

This results in the definition of an ordered scale $S = \{s_0, s_1, \ldots, s_g\}$, which is a set of $g + 1$ ordered terms. The fundamental property of the scale terms is the order: $s_a \leqslant s_b$ if and only if $a \leqslant b$, $a, b \in \{1, 2, \ldots, g\}$. Additionally, a unique negation operator n for the terms of S can be defined as $n(s_i) = s_{g-i}$, for each $s_i \in S$. The negation has the following properties:

1. $n(s_0) = s_g$,
2. $n(s_g) = s_0$,
3. $n(n(s_i)) = s_i, \forall i = 1, 2, \ldots, g$.
4. $s_i \geqslant s_j \iff n(s_i) \leq n(s_j), \forall i, j \in \{1, 2, \ldots, g\}$.

Another important characteristic of the scale terms is their semantics, meaning the shape of the membership function and the domain of the fuzzy set under each linguistic term of the ordinal scale. The fuzzy set that represents the semantics of each linguistic term is defined on the interval [0, 1]. An example can be given if one considers an ordinal scale with seven linguistic terms:

$$S = \{s_0 = \textit{None}, s_1 = \textit{Very Low}, s_2 = \textit{Low}, .s_3 = \textit{Medium}, s_4 = \textit{High}, s_5 = \textit{Very High}, s_6 = \textit{Perfect}\}. \quad (1)$$

The use of linguistic computational techniques to process linguistic information is called Computing with Words (CW). One model for CW is the approximate computational model which uses fuzzy arithmetic based on the Extension Principle. The approximate computational model processes the membership functions of the fuzzy terms and results in an aggregated fuzzy number. These aggregated fuzzy numbers do not necessarily belong to the initial set of linguistic terms. The ordering of the aggregated fuzzy values can be achieved by using a fuzzy ranking method to compare them. However, this comparison process can be quite complex and produce unreliable results, as it may: (i) involve considerable computations, (ii) produce inconsistency via respective fuzzy ranking methods, and (iii) generate counter-intuitive ranking outcomes for similar fuzzy numbers.

Another approach to order the aggregated fuzzy number is to use an approximation process. The approximation process obtains the linguistic term which is closest to the aggregated fuzzy number in the initial term set by applying an approximation function. In this second approach the loss of information due to the approximation procedure cannot be hampered.

Another approach used to operate on linguistic data is the symbolic one that makes computations on the indices of the linguistic terms. Usually, it uses the ordered structure of the linguistic term set, $S = \{s_0, s_1, \ldots, s_g\}$ to perform the operations. The symbolic method uses an aggregation operator, for instance the LOWA, as proposed by Herrera, Herrera-Viedma, and Verdegay (1996) and Delgado, Verdegay, and Vila (1993), which is based on the convex combination of the linguistic terms. LOWA combines the indices of the linguistic terms to be aggregated with numerical weight coefficients. The result of the aggregation is a numerical value $a \in [0, g]$ which must be approximated by means of an approximation function $H : [0, g] \rightarrow \{0, 1, \ldots, g\}$. The approximation function obtains a numerical value which belongs to $\{0, 1, \ldots, g\}$ and it indicates the index of the associated linguistic term $s_{H(a)} \in S$.

Formally, it can be expressed as $S^n \xrightarrow{M} [0, g] \xrightarrow{H} \{0, 1, \ldots, g\} \rightarrow S$, where M is the symbolic aggregation operator that aggregates the indices of the linguistic terms used as arguments. The need to express the results of the process in the initial term set S causes a loss of information, which originates from two main sources: the approximation function and the use of the round operation embodied in the aggregation operator. As an example of the use of the round operation is the LOWA operator.

It is evident that there is a need to develop a representation of the linguistic information and a computational technique that diminishes or even totally eliminates the loss of information caused by the approximation procedures and the ambiguity of the fuzzy ranking method's selection. This aim is attained by defining the 2-tuple linguistic computational model. This model uses two concepts: the symbolic translation and the 2-tuple fuzzy linguistic representation. These concepts are based on the work of Herrera and Martínez (2000), who base their linguistic model on the symbolic computational approach and define a new representation method of linguistic information. Let $S = \{s_0, s_1, \ldots, s_g\}$ be a linguistic term set. Assume that a symbolic method aggregating linguistic information obtains a value $\beta \in [0, g]$ and $\beta \notin \{0, 1, \ldots, g\}$.

Definition 1. Let $\beta \in [0, g]$ be the result of an aggregation of the indices of labels assessed in a linguistic term set S, i.e., the result of