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Decision Support

Multi-criteria decision aid for the formulation of sustainable technological energy priorities using linguistic variables

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Abstract

Implementation of new and innovative energy technologies is a key mean towards a sustainable energy system. Currently, governments have to decide from an increasingly diverse mix of them, the ones which warrant support, including funding and other incentives for private sector efforts. However, appraising energy technologies in terms of their sustainability is a really complex task, considering the series of uncertainties and implications that have to be encountered so as to obtain realistic and transparent results. In this context, the main aim of this paper is to present a direct and flexible multi-criteria decision making approach, using linguistic variables, to assist policy makers in formulating sustainable technological energy priorities. Furthermore, its software realization will be applied to a number of technologies, in the context of the Greek Technology Foresight Programme, and the results will be presented and discussed.

Keywords: Multiple criteria analysis; Sustainable energy policy; Linguistic variables; Decision support

1. Introduction

Energy planning and policy making have attracted the attention of decision analysts for a long time, since the energy sector exhibits particular dynamics. Moreover, over the last decade, the impact of "sustainability" on the development of national and international policy has increased. It is realised that the energy sector and its contribution to the greenhouse effect should play a major role in the policy for a sustainable development (SD). In this context, efforts towards a sustainable energy system are progressively becoming an issue of universal concern and of paramount importance for most politicians and decision makers (Cornelissen et al., 2001). Efficient production, distribution and use of energy resources and provision of equitable and affordable access to energy while ensuring security of energy supply and environmental sustainability are some of the energy policy objectives towards a sustainable energy system.

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Implementation of new and innovative energy technologies is key means of satisfying these objectives. Technological advances are of critical importance for the improvement of living conditions, the production and the transportation of the energy and the efficiency of its use thus it is expected to produce major public benefits (World Energy Council, 2001).

Especially concerning environmental technologies, they can be considered to be an important bridge between the Lisbon Strategy objective of making the European Union "the most competitive and dynamic knowledge-based economy in the world" and the SD Strategy agreed at the Göteborg European Council (European Commission, 2003). These technologies which are economically and environmentally attractive can be taken up by business and households. In this context, governments have to decide from an increasingly diverse mix of new energy technologies, the ones which warrant support, including funding (e.g., R&D support) and other incentives for private sector efforts.

However, the identification of these technologies that can comply with the emerging needs and opportunities in the four SD dimensions, namely the economic, environmental, social and technological (Spangenberg et al., 2002; Krajnc and Glavič, 2005) is a very complex process. Therefore, evident is the need for methods and tools that can assist policy design, in terms of establishing technological priorities towards a sustainable energy system.

Indeed, the majority of Organization for Economic Co-operation and Development (OECD) countries has carried out national Technology Foresight (TF) Programmes, given the importance of research priorities for supporting the new and innovative energy technologies (Organisation for Economic Co-operation and Development, 1996; Gavigan and Scapolo, 1999). Moreover, the multicriteria methods can be an important supportive tool in the policy making, providing the flexibility and capacity to assess the technologies' implications to the economy, the environment and the social framework (Salo et al., 2003). Especially, this is true taking into consideration that many of the key attributes of energy technologies, which are not market-valued and concern the social and environmental dimension of SD, are often excluded from the analysis (Van den Bergh et al., 2000). In particular, the concept of Multi-Criteria Decision Making (MCDM) has been widely used for the design of energy and environmental policies (Greening and Bernow, 2004) as well as for sustainable energy planning (Pohekar and Ramachandran, 2004).

However, the assessment of innovative energy technologies through a number of criteria is a complex and time consuming task, since the analysis has to face a series of uncertainties such as fossil fuel price, environmental regulations, market structure, technological, and demand and supply uncertainty (Venetsanos et al., 2002). Furthermore, sustainability is an inherently vague and complex concept and the implications of SD as a policy objective is difficult to be defined or measured (Phillis and Andriantiatsaholiniaina, 2001). In particular, the information needed for the evaluation of technologies in terms of their sustainability may be unquantifiable due to its nature or even unavailable since the cost of its computation is too high. Taking into consideration the imprecision and subjectivity of the related information, the crisp values may lead to an oversimplification of the specific decision making problem.

In order to handle the abovementioned uncertainties in "traditional" MCDM methods, such as PROMETHEE and ELECTRE, qualitative information was traditionally transformed into numerical using an ordinal scale. Particular applications of such methods for energy planning exist in the international literature, such as for the ranking of environmental projects (Al-Rashdan et al., 1999), for promoting the diffusion of RES (Haralambopoulos and Polatidis, 2003; Beccali et al., 2003; Georgopoulou et al., 1998) and for defining national priorities for greenhouse gases emissions reduction (Georgopoulou et al., 2003). However, a wrong choice of the ordinal scale in such applications could lead to economic, social and cultural repercussions. Furthermore, in these methods, the so-called pseudo-criteria that have to be applied (indifference and preference thresholds) to deal with the inaccuracy of the data are in many cases difficult to be defined.

Fuzzy uncertainty, in contrast, relates to events that have no well defined, unambiguous meaning (Dubois and Prade, 1980) and therefore fuzzy set theory offers a formal mathematical framework to assess SD. In this context, a realistic approach is the use of linguistic variables in the processes of the different MCDM methods, which are composed of a finite set of linguistic terms and their meaning is a fuzzy subset in a universe of discourse.

This linguistic approach has been widely used in variant fields, for example information retrieval (Bordogna and Passi, 1993), clinical diagnosis

(Degani and Bortolan, 1998), marketing (Yager et al., 1994), risk in software development (Lee, 1996a,b), technology transfer strategy selection (Chang and Chen, 1994), education (Law, 1996) and decision making (Bordogna et al., 1997; Delgado et al., 1992; Delgado et al., 1994; Herrera et al., 1995). Especially concerning the last field, MCDM methods using linguistic variables have been used for energy planning (Beccali et al., 1998), for environmental assessment of iron and steel making industry (Geldermann et al., 2000), for ranking of alternative energy exploitation projects (Goumas and Lygerou, 2000) and for assessing renewables-to-electricity systems (Kaminaris et al., 2006). In all of these cases the membership functions of the fuzzy numbers has to be defined which may be a difficult task.

To reduce these inconsistencies and to obtain more realistic results, it is necessary to reduce the amount of information needed (Cornelissen et al., 2001). With respect to the above, direct computation on linguistic variables, with independence of their semantic representation can be considered as a direct and adequate framework, which can reduce fuzziness to a manageable level.

To the best of our knowledge, multi-criteria approaches with direct computation on linguistic variables for the evaluation of energy technologies in terms of their sustainability are not present in the literature. In this context, the main aim of this paper is to present a direct and transparent MCDM approach, using linguistic variables, to assist policy makers in formulating technological energy priorities towards a sustainable energy system. In addition to this, its software realization will be applied to a number of technologies in the context of the Greek Technology Foresight Programme and the results of its pilot operation will be presented and discussed.

The paper is structured along four parts, as follows:

- The first part is the introduction of the paper.
- The second part briefly describes the decision analysis using linguistic variables, giving emphasis on two approaches, namely the "Symbolic" and the "2-tuple Representation".
- The third part is devoted to the presentation of the adopted multi-criteria approach and its software realization as well as to the results from its pilot application to a number of energy technologies, in the context of the Greek Foresight Programme.
- Finally, the main points drawn up from the paper are summarised in the last part.

2. Decision analysis using linguistic variables

2.1. Theoretical framework

The linguistic approach is an approximate technique which represents qualitative aspects as linguistic values by means of linguistic variables. In the linguistic decision analysis of a multi-criteria problem, the solution scheme must be formed by the following three steps (Herrera and Herrera-Viedma, 2000):

1. The choice of the linguistic term set with its semantic. It consists of establishing the linguistic expression domain used to provide the linguistic performance values about alternatives according to the different criteria. To do so, the granularity of the linguistic term set, its labels and its semantic have to be chosen.
2. The choice of the aggregation operator of linguistic information. It consists of establishing an appropriate aggregation operator of linguistic information in order to aggregate and combine the linguistic performance values provided.
3. The choice of the best alternatives. It consists of choosing the best alternatives according to the linguistic performance values provided.

Therefore, the first priority is to establish the kind of label set to be used. Then, let $S = \{s_i\}$, $i \in H = \{0, \ldots, T\}$, be a finite and totally ordered term set in $[0, 1]$ in the usual sense. Any label s_i represents a possible value for a linguistic real variable, that is, a vague property or constraint in $[0, 1]$. Considering a term set with odd cardinal, the middle label represents an uncertainty of "approximately 0.5" and the remaining terms are placed symmetrically around it. For example, a set of seven terms S could be given as follows:

$$\begin{aligned}S =\{&s_0 = \text{none},\ s_1 = \text{very low},\ s_2 = \text{low},\\ &s_3 = \text{medium},\ s_4 = \text{high},\ s_5 = \text{very high},\\ &s_6 = \text{perfect}\}.\end{aligned}$$

Moreover, the term set must have the following characteristics (Herrera and Herrera-Viedma, 2000):

- The set presents a total order: $s_i \geqslant s_j$ if $i \geqslant j$.
- There is the negation operator: $\mathrm{Neg}(s_i) = s_j$ such that $j = T - i$.

- Maximization operator: $\mathrm{MAX}(s_i, s_j) = s_i$ if $s_i \geqslant s_j$.
- Minimization operator: $\mathrm{MIN}(s_i, s_j) = s_i$ if $s_i \leqslant s_j$.

Concerning the choice of the aggregation operator of the linguistic information, the "Symbolic" and the "2-tuple Representation" approaches will be discussed, which implement a direct computation on the linguistic values (labels), taking into account only the meaning and properties of such linguistic assessments (Herrera and Martínez, 2000).

2.2. Symbolic approach

The symbolic approach is computationally simple, quick and may be easily applied in user-driven interactive systems. Two aggregation operators, which are built on the symbolic approach, are the linguistic ordered weighted averaging (LOWA) operator and the linguistic weighted averaging (LWA) operator, which can combine non-weighted and weighted linguistic information respectively.

2.2.1. LOWA operator

The LOWA operator aggregates linguistic information provided for different criteria which are equally important.

Let $A = \{a_1, \dots, a_m\}$ be a set of labels to be aggregated. Then the LOWA operator Φ, is defined as (Herrera and Herrera-Viedma, 2000)

$$\begin{aligned}\Phi(a_1, \dots, a_m) &= W \cdot B^{\mathrm{T}} = C^m\{w_k, b_k, k = 1, \dots, m\} \\ &= w_1 \odot b_1 \oplus (1 - w_1) \odot C^{m-1}\{\beta_h, b_h, h \\ &= 2, \dots, m\},\end{aligned}$$

where $W = [w_1, \dots, w_m]$, is a weighting vector, such that,

- $w_i \in [0, 1]$ and,
- $\sum_i w_i = 1$,
- $B = \{b_1, \dots, b_m\}$ is a vector associated to A, such that, $B = \sigma(A) = \{a_{\sigma(1)}, \dots, a_{\sigma(n)}\}$ in which, $a_{\sigma(j)} \leqslant a_{\sigma(i)} \forall i \leqslant j$ with σ being a permutation over $\{1, \dots, m\}$.
- $\beta_h = w_h / \sum_2^m w_k$, $h = 2, \dots, m$, and
- C^m is the convex combination operator of m labels.

If $m = 2$, then C^2 is defined as $C^2\{w_i, b_i, i = 1, 2\} = w_1 \odot s_j \oplus (1 - w_1) \odot s_i = s_k$, with s_j, $s_i \in S$ $(j \geqslant i)$ such that,

$$k = \min\{T, i + \mathrm{round}(w_1 \cdot (j - i))\},$$

where 'round' is the usual round operation, and $b_1 = s_j$, $b_2 = s_i$. If $w_j = 1$ and $w_i = 0$ with $i \neq j \forall i$, then the convex combination is defined as

$$C^m\{w_i, b_i,\ i = 1, \dots, m\} = b_j.$$

For the weighting vector of LOWA operator, W, the weights represent the concept of fuzzy majority in the aggregation of LOWA operator using fuzzy linguistic quantifier. Yager proposed an interesting way to compute the weights by means of a fuzzy linguistic quantifier, Q, which, in the case of a non-decreasing proportional fuzzy linguistic quantifier is given by this expression (Yager, 1988): $w_i = Q\ (i/n) - Q((i - 1)/n)$, $i = 1, \dots, n$, being the membership function of Q, as follows:

$$Q_{(y)} = \begin{cases} 0 & \text{if } y < a, \\ (y - a)/(b - a) & \text{if } a \leqslant y \leqslant b, \\ 1 & \text{if } y > b. \end{cases}$$

with $a, b, y \in [0, 1]$, and $Q(y)$ indicating the degree to which the proportion y is compatible with the meaning of the quantifier it represents. In this context, the quantifiers can vary, based on the parameters (a, b). Some representative examples of relative quantifiers, where the parameters (a, b) are defined as (0.3, 0.8) for "Most", (0, 0.5) for "At least half" and (0.5, 1) for "As many as possible", are illustrated in Fig. 1 (Herrera and Herrera-Viedma, 2000).

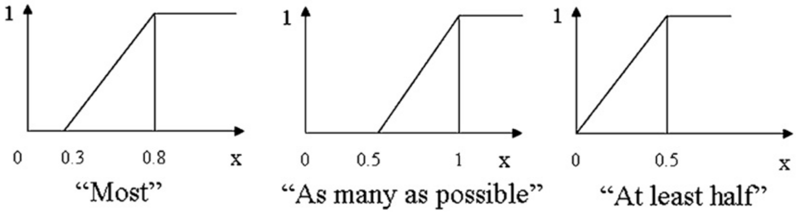

Fig. 1. Proportional fuzzy linguistic quantifier.

2.2.2. LWA operators

These operators aggregate linguistic information provided for different criteria, which are not equally important (Herrera and Herrera-Viedma, 2000). In order to design an aggregation operator of linguistic weighted information, two aggregations have to be defined, namely, the aggregation of importance degrees of information, and the aggregation of weighted information, which combines information with its importance degrees (Yager, 1988). The first aggregation consists of obtaining a collective importance degree from individual importance degrees which characterizes the final result of the aggregation operator. In order to achieve the aggregation of weighted information, a transformation of the weighted information under the importance degrees and the final aggregation of the transformed information, has to be conducted.

In particular, the aggregation of the set of weighted individual information, $\{(c_1, a_1), \ldots, (c_m, a_m)\}$, where c_i is the importance degree of information and a_i is the information, according to the LWA operator is obtained as

$$a_E = f[g(c_1, a_1), \ldots, (c_m, a_m)],$$

where

- f is a linguistic aggregation operator of transformed information, and
- g is the importance transformation function.

With respect to the above, aggregation techniques for weighted information based on only ordinal scale are the ordered weighted maximum (OWMAX) and ordered weighted minimum operators (OWMIN). More specifically (Marichal, 1999),

- OWMAX associated with the weights $w \in [0,1]^n$, $1 = w_1 \geqslant \cdots \geqslant w_{\mathrm{n}}$ is defined by

$$\mathrm{OWMAX}_w(x) = \max_{i=1\ldots n}\{\min(w_i, x_i)\}; \quad x \in [0,1]^n;$$

- OWMIN associated with the weights $w' \in [0,1]^{\mathrm{n}}$, $w'_1 \geqslant \cdots \geqslant w'_n = 0$ is defined by

$$\mathrm{OWMIN}_{w'}(x) = \min_{i=1\ldots n}\{\max(w'_i, x_i)\}, \quad x \in [0,1]^n.$$

In this context, these operators can be used for linguistic weighted aggregations, where, in order to assign the x and w, the linguistic term set has to be defined.

2.3. Two-Tuple representation

An important limitation of the symbolic linguist approach is the "loss of information" that implies a lack of precision in the final results (Herrera and Herrera-Viedma, 2000). In the computational techniques, such as the LOWA and the LWA, the linguistic approximation process needed to express the result in the original expression domain increases the vagueness of the results. To tackle this limitation, a new fuzzy linguistic representation model has been proposed, namely the 2-tuple representation model (Herrera and Herrera-Viedma, 2000). In particular,

- let $S = \{s_0, \ldots s_g\}$ be a linguistic term set, if a symbolic method aggregating linguistic information obtains a value $\beta \in [0, g]$ and $\beta \notin \{0, \ldots, g\}$, then an approximation function ($\mathrm{app}_2(\cdot)$) is used to express the index of the result in S;
- let β be the result of an aggregation of the indexes of a set of labels assessed in a linguistic term set S, i.e., the result of a symbolic aggregation operation. $\beta \in [0, g]$, being $g + 1$ the cardinality of S. Let $i = \mathrm{round}(\beta)$ and $\alpha = \beta - i$ be two values such that $i \in [0, g]$ and $a \in [-0.5, 0.5)$ then "α" is called a symbolic translation.

Therefore, the symbolic translation of a linguistic term, s_i, is a numerical value assessed in $[-0.5, 0.5)$ that supports the "difference of information" between a counting of information $\beta \in [0, g]$ obtained after a symbolic aggregation operation and the closest value in $\{0, \ldots, g\}$ that indicates the index of the closest linguistic term in S ($i = \mathrm{round}(\beta)$).

From this concept, a linguistic representation model was developed, which represents the linguistic information by means of 2-tuples (s_i, α_i), $s_i \in S$ and $a_i \in [-0.5, 0.5)$:

- s_i represents the linguistic label center of the information;
- α_i is a numerical value expressing the value of the translation from the original result β to the closest index label, i, in the linguistic term set (s_i).

This model defines a set of transformation functions between linguistic terms and 2-tuples and between numeric values and 2-tuples.

- Let $S = \{s_0, \ldots, s_g\}$ be a linguistic term set and $\beta \in [0, g]$, a value representing the result of a

symbolic aggregation operation, then the 2-tuple that expresses the equivalent information to β is obtained with the following function:
✓ $\Delta : [0,g] \to S \times [-0.5, 0.5)$
✓ $\Delta(\beta) = (s_i, a)$, with $\begin{cases} s_i, i = \text{round}(\boldsymbol{\beta}) \\ a = \beta - i, \alpha \in [-0.5, 0.5), \end{cases}$
where round(·) is the usual round operation, s_i has the closest index label to "β" and "α" is the value of the symbolic translation.

- Let $S = \{s_0, \ldots, s_g\}$ be a linguistic term set and (s_i, a_i) be a 2-tuple. There is always a Δ^{-1} function such that from a 2-tuple it returns its equivalent numerical value $\beta \in [0, g] \subset \Re$. In this context, we consider the following function:
✓ $\Delta^{-1}: S \times [-.5, .5) \to [0, g]$;
✓ $\Delta^{-1}(s_i, a) = i + a = \beta$.

Let (s_k, a_1) and (s_l, a_2) be two 2-tuples, with each one representing a counting of information, then it has to be noted that:

- If $k < l$ then (s_k, a_1) is smaller than (s_l, a_2);
- If $k = l$ then:
  ✓ If $a_1 = a_2$ then (s_k, a_1), (s_l, a_2) represents the same information;
  ✓ If $a_1 < a_2$ then (s_k, a_1) is smaller than (s_l, a_2);
  ✓ If $a_1 > a_2$ then (s_k, a_1) is bigger than (s_l, a_2).

In this context, the 2-tuple LOWA operator, that makes the appropriate linguistic aggregation processes over 2-tupple, is built as follows (Herrera and Martinez, 1999):

Let $A = \{(r_1, a_1), \ldots, \{(r_m, a_m)\}$ be a set of 2-tuples to be aggregated, such that, $(r_i, a_i) \in Sx$ $[-0.5, 0.5)$. The Extended Convex Combination to combine 2-tuples, EC^m, is defined as

$$\mathrm{EC}^m\{w_i, (r_{\sigma(j)}, a_{\sigma(j)}), j = 1, \ldots m\} = \Delta w_1 \cdot \Delta^{-1}(r_{\sigma(1)}, a_{\sigma(1)}) + (1 - w_1)\Delta^{-1} (\mathrm{EC}^{m-1}\{\eta_h, (r_{\sigma(h)}, a_{\sigma(h)}), h = 2, \ldots, m\}).$$

Since $\eta_h = w_h / \sum_2^m w_k$, $h = 2, \ldots, m$, $W = [w_1, \ldots, w_m]$ is a weighted vector associated to A, such that

- $w_i \in [0, 1]$;
- $\sum_i w_i = 1$;
- $B = \{(r_{\sigma(1)}, a_{\sigma(1)}),\ (r_{\sigma(m)}, a_{\sigma(m)})\}$, is an ordered set associated to A, such that, $(r_{\sigma(j)}, a_{\sigma(j)}) \leqslant (r_{\sigma(i)}, a_{\sigma(i)})$, $\forall i \leqslant j$.

In the above expression the calculation obtained is the following:

$$\mathrm{EC}^m\{w_i, (r_{\sigma(j)}, a_{\sigma(j)}), j = 1, \ldots m\} = \Delta\left(\sum_{i=1}^m w_i \Delta^{-1}(r_{\sigma(i)}, a_{\sigma(i)})\right) = \Delta\left(\sum_{i=1}^m w_i \beta_{\sigma(i)}\right), \quad \text{where } \beta_{\sigma(i)} = \Delta^{-1}(r_{\sigma(i)}, a_{\sigma(i)}).$$

If $m = 2$, then it is defined as

$$\mathrm{EC}^2\{w_i, (r_{\sigma(i)}, a_{\sigma(i)}), i = 1, 2\} = \Delta(w_1 \cdot \Delta^{-1}(r_{\sigma(i)}, a_{\sigma(i)}) + (1 - w_1)\Delta^{-1}(r_{\sigma(j)}, a_{\sigma(j)})) = (r_f, a_f), \quad \text{such that } (r_f, a_f) = \Delta(\beta_{\sigma(j)} + w_1(\beta_{\sigma(i)} - \beta_{\sigma(j)})).$$

If $w_j = 1$ and $w_i = 0$ with $i \neq j \forall i$, then the extended convex combination is defined as

$$\mathrm{EC}^m\{w_i, (r_{\sigma(i)}, a_{\sigma(i)}), i = 1, \ldots m\} = (r_{\sigma(j)}, a_{\sigma(j)}).$$

With this definition, the approximation computations are eliminated. In this context, the 2-tuple LOWA operator is defined as follows:

Let $A = \{(r_1, a_1), \ldots, (r_m, a_m)\}$ be a set of 2-tuples to be aggregated, then the extended LOWA operator, Φ^{e}, is defined as

$$\Phi^{\mathrm{e}}[(r_1, a_1), \ldots, (r_m, a_m)] = W \cdot B^{\mathrm{T}} = \mathrm{EC}^m\{w_i, (r_{\sigma(i)}, a_{\sigma(i)}),\ i = 1, \ldots m\}.$$

3. Methodological approach

3.1. Background

The analysis of the presented methodological approach is mainly based on the context of a project funded by the Greek government entitled "Technology Foresight in Greece" and managed by the Hellenic General Secretariat for Research and Technology (GSRT) of the Ministry of Development, which was held from 2003 to 2005. The project aimed to examine technologies' future role towards a sustainable energy system, with the year 2021 being the time horizon. Most of the information and data presented in this section have been derived from the activities carried out within this project and the final deliverable produced (Koukios, 2004).

3.2. Problems specifications

In the context of the Technology Foresight Programme, a methodological approach was developed, to assist the decision making process of the Greek State Government and especially the GSRT for the identification of these technologies that should be supported, towards a sustainable energy system. The methodological approach was based on a transparent MCDM supportive framework with direct computation on the linguistic variables, so as to be relatively straightforward to incorporate experts' preferences as well as trying to deal with the incompleteness and inconsistency of the information concerning technologies' impacts to the SD dimensions.

First of all, a working group was formulated, having twenty five participants from all the relevant energy "actors" in Greece (Public Power Corporation – utility, independent power producers, financing organizations, relevant researchers and academics, governmental managers, the regulatory authority, the transmission system operator, the Center for Renewable Energy Sources). The workgroup looked systematically into the longer-term future, trying to examine technologies, which have not been used in the energy sector or have been introduced at a very small percentage, but are likely to support the four dimensions of SD. In this context, the following technologies, which match with the country's energy system specific requirements, were pre-selected:

- The natural fossil fuels technologies:
  - ✓ T1: Pressurized Fluidized Bed Combustion;
  - ✓ T2: Pressurized pulverized coal combustion;
  - ✓ T3: Natural Gas Combined Cycle;
- The hydrogen technologies:
  - ✓ T4: Molten Carbonate Fuel Cell;
  - ✓ T5: Fuel Cell/Turbine Hybrids;
- Renewable energy technologies:
  - ✓ T6: Biomass Co-firing;
  - ✓ T7: Biomass Gasification;
  - ✓ T8: Off-shore Wind farms;
  - ✓ T9: Large scale Wind farms;
  - ✓ T10: Building Integrated Photovoltaics.

For the assessment of these technologies impact on the environmental, social, economical and technological dimension of SD, the working group selected a number of criteria, which are presented in Table 1 according to the dimensions in which they are referred to.

Moreover, the following 7-grade label set was used for the technologies' evaluation to the criteria: $S = \{l_0 = \mathrm{I}, l_1 = \mathrm{VL}, l_2 = \mathrm{L}, l_3 = \mathrm{M}, l_4 = \mathrm{H}, l_5 = \mathrm{VH}, l_6 = \mathrm{P}\}$, where I = Insignificant, VL = Very Low, L = Low, M = Medium, H = High, VH = Very High and P = Perfect.

In this context, numerous meetings were organized among the working group (October–December 2003, Athens) and based on the aforementioned scale, the technologies' performances to each one of the criteria as well as the criteria weights based on the country's specific energy policy priorities were defined, as depicted in Table 2.

Table 1
Selected criteria

SD dimension	Criterion	
Economic	C1: Investment cost	Economic magnitude expressing the cost for introducing a technology. It comprises the required costs for all the project implementation phases
	C2: Economic viability using payback period	Reflects the required time period for full depreciation of the investment's capitals
Environmental	C3: Contribution to confrontation of the climate change phenomenon	Represents the technology's share in reducing the potential effects on the climate change during its operation. It is used as a measure of the GHGs emitted in the atmosphere
	C4: Effects on natural environment	Reflects the technology's intervention rate on the natural environment (forest abalienation, noise, aesthetics' alteration, desolation)
Technological	C5: Efficiency rate	Expresses the technology's ability to convert the primary energy source to electricity
	C6: Knowledge of the innovative technology	Represents the technology's maturity rate as well as its penetration percentage in the international market
Social	C7: Contribution to employment opportunities' creation	Reflects the increase in direct and indirect numbers of employment opportunities
	C8: Contribution to regional development	Expresses the progress induced in the less developed regions of the country by introducing a new technology

Table 2
Technologies performance per criterion

Criteria	Weights	Technologies									
		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
C1	M	VH	H	VH	VL	I	H	M	H	H	VL
C2	H	H	H	H	H	M	P	H	M	H	I
C3	VH	VH	H	VH	H	H	VL	L	L	L	H
C4	M	VH	P	VH	VH	VH	H	H	L	L	VH
C5	M	H	L	VH	H	M	H	VH	M	M	VH
C6	P	H	M	P	M	VL	H	H	H	VH	VH
C7	VH	H	H	VH	H	L	VH	P	VH	VH	M
C8	H	H	H	H	M	L	H	VH	VH	P	L

3.3. Technologies prioritization

For the technologies assessment a two-staged methodology was developed, so as to tackle the occasional fogginess of the symbolic operators' aggregation results. In advance, the sustainable energy technologies were identified, by assessing the pre-selected energy technologies contribution to all SD dimensions in a balanced way. In this context, the LOWA operators was used, where no discrimination is made among the SD dimensions, since it aggregates linguistic information provided for criteria which are equally important.

In the second stage, from the sustainable technologies identified, the most promising one is selected, in terms of its contribution to the country's main development priorities and objectives. In this context, the OWMAX is used, which aggregates linguistic information provided for criteria which are not equally important, but their weights are directly assigned by the decision maker (DM). Thus, the OWMAX usage as a second step of the methodology is very important for this decision problem, since it provides the DMs with the opportunity to distinguish the technology that complies with the country's specific priorities and objectives.

Moreover, the 2-tuple LOWA was used for solving this problem and the final outputs were compared with the two-staged previously mentioned methodology, so as to assess the consistency and validity of the results.

3.4. Software realization

For the application of the presented methodological approach, a linguistic decision support system (L-DSS) was realized on the Microsoft .NET platform. The system incorporates the three previously presented computational techniques, namely the LOWA, the 2-tuple LOWA and the OWMAX.

In advance the users provide the decision problem inputs, namely the grade of the label set, the criteria to be used, the technologies to be assessed, their corresponding performances as well

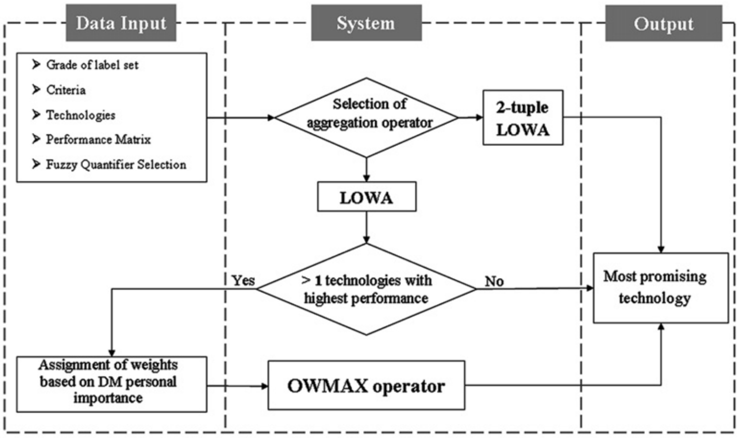

Fig. 2. L-DSS architecture.

as the selected fuzzy quantifier. Following, via the selection of the aggregation operators, the technologies' prioritization in terms of their sustainability is elaborated. In case the 2-tuple LOWA is selected, then the most promising technology is the one with the highest ranking. Regarding the LOWA operator, in case more than one technology obtains the highest performance, then the OWMAX operator is also used, with the assignment of weights provided by the DMs (Fig. 2).

The system was designed to be user-friendly, combining intuitive menus and navigation throughout the steps of the system, helping the users to execute the software. Moreover, the input data provided by the user and the results of the methodology are stored in binary and "excel" files for further processing and comparing. Finally, the system was developed in an open architecture standard, which provides unlimited horizontal and vertical expandability.

4. Results–discussion

The pre-selected technologies were assessed using the L-DSS, so as to identify these that have a significant contribution to the SD. In particular, the LOWA operator was executed. The weighting vector for the three fuzzy quantifiers is as follows:

- "Most": $W = \{0, 0, 0.15, 0.25, 0.25, 0.25, 0.1, 0\}$;
- "At least half": $W = \{0.25, 0.25, 0.25, 0.25, 0, 0, 0, 0\}$;
- "As many as possible": $W = \{0, 0, 0, 0, 0.25, 0.25, 0.25, 0.25\}$.

The final results of the LOWA are presented in Table 3.

Based on the LOWA results, the Natural Gas Combined Cycle (T3) is placed in the highest places in all LOWA's quantifiers, since it has a satisfactory performance in the majority of the criteria, due to its significant exploitable potential in the electricity sector. Moreover, the Pressurized Fluidized Bed (T1) can be regarded as a promising option, due to its satisfactory performance in the economic and technological criteria. Furthermore, the Large Scale Wind Farms (T9) and the Biomass Co-firing (T6) and Gasification (T7) perform satisfactorily based on their benign environmental impact and their social contribution, since they are closely related to the decentralised production of energy and the improved energy services of Greece's remote regions (e.g., islands). Finally, the examined hydrogen technologies are not yet fully competitive, mainly in terms of their financial performance compared to the other technologies.

Table 3
Results of LOWA

Technologies	"most"	"at least half"	"as many as possible"
T1: Pressurized Fluidized Bed Combustion	H	H	H
T2 Pressurized pulverized coal combustion	M	H	M
T3: Natural gas combined cycle	H	VH	H
T4: Molten Carbonate Fuel Cell	M	H	M
T5: Fuel Cell/Turbine Hybrids	L	H	VL
T6: Biomass co-firing	M	VH	M
T7: Biomass gasification	M	VH	M
T8: Off-shore wind farms	M	H	L
T9: Large scale wind farms	M	VH	M
T10: Building integrated PVs	M	H	L

In particular, the following observations can be made for each one of the fuzzy quantifiers:

- "Most": The two technologies identified as the most sustainable, having a "High" overall performance are the Natural Gas Combined Cycle (T3) and the Pressurized Fluidized Bed Combustion (T1).
- "At least half": With this fuzzy linguistic quantifier it is very difficult for one technology to be distinguished. The Natural Gas Combined Cycle (T3), Biomass Co-firing (T6), Biomass Gasification (T7) and Large Scale Wind Farms (T9) technologies achieve a "Very High" overall performance and can be considered as the sustainable options.
- "As many as possible": Technologies which are distinguished and can be considered as sustainable energy technologies are the Natural Gas Combined Cycle (T3) and the Pressurized Fluidized Bed Combustion (T1).

In addition to this, the final performances of the OWMAX operator, based on the weights presented in Table 2, are depicted in Table 4.

From the results, the Natural Gas Combined Cycle (T3) has the most significant contribution to the country's policy priorities, as expressed by the assignment of weights. Taking into consideration

Table 4
Results of OWMAX

Technologies	OWMAX
T1: Pressurized Fluidized Bed Combustion	VH
T2 Pressurized pulverized coal combustion	H
T3: Natural gas combined cycle	P
T4: Molten Carbonate Fuel Cell	H
T5: Fuel Cell/Turbine Hybrids	H
T6: Biomass co-firing	VH
T7: Biomass gasification	VH
T8: Off-shore wind farms	VH
T9: Large scale wind farms	VH
T10: Building integrated photovoltaics	VH

Table 5
Results of 2-tuple LOWA

Technologies	"most"	"at least half"	"as many as possible"
T1: Pressurized Fluidized Bed Combustion	(H,0,15)	(VH,−0,25)	(H,0)
T2 Pressurized pulverized coal combustion	(H,−0,1)	(H,0,5)	(M,0,25)
T3: Natural gas combined cycle	(VH,−0,1)	(VH,0,25)	(H,0,5)
T4: Molten Carbonate Fuel Cell	(H,−0,35)	(H,0,25)	(M,−0,25)
T5: Fuel Cell/Turbine Hybrids	(L,0,3)	(H,−0,25)	(VL,0,25)
T6: Biomass co-firing	(H,0)	(VH,−0,25)	(M,0,25)
T7: Biomass gasification	(H,0,05)	(VH,0)	(M,0,25)
T8: Off-shore wind farms	(M,0,3)	(H,0,5)	(L,0,5)
T9: Large scale wind farms	(H,−0,3)	(VH,0)	(M,−0,25)
T10: Building integrated PVs	(M,0,1)	(VH,−0,25)	(L,−0,5)

that this technology was a sustainable option in all fuzzy quantifiers of the LOWA operator, it can be considered to be the most promising technology.

Moreover, in order to check the validity of the results, the problem was also solved by means of the 2-tuple linguistic representation. In this context, the results of the 2-tuple LOWA operator are presented in Table 5.

Based on the results, it is obvious that with the 2-tuple LOWA operator, the accuracy of the results obtained is much higher compared to the LOWA operator. In all quantifiers the Natural Gas Combined Cycle (T3) is distinguished, as the one achieving the higher overall performance compared to the other technologies, which is in consistency with the final results of the two-staged methodology.

From the abovementioned analysis it cannot be considered that technologies ranked at lower places like fuel cells or photovoltaics should be abandoned. However, the message addressed from the results is that, based on the criteria selected, the Natural Gas Combined Cycle (T3) seems to be the technology deserving a special handling by the government including funding and other incentives for private sector efforts.

5. Conclusions

Over the last decade, the impact of "sustainability" on the development of national and international policy has increased and efforts towards a sustainable energy system become an issue of paramount importance for most politicians and decision makers. Moreover, implementation of new energy technologies is a key mean towards a sustainable energy system and currently government have to decide from an increasingly diverse mix of new energy technologies, the ones that can comply with the needs and opportunities of all SD dimensions. In this context, the policy problem to be solved is the identification of these technologies which have not been used in the energy sector or have been introduced at a very small percentage, but are likely to support the four dimensions of SD and should be thus supported.

This is a really complex procedure, taking into consideration that sustainability is an inherently vague concept and its implications as a policy objective are difficult to be defined or measured. As a result, flexible and transparent decision support approaches are needed to assist policy makers, which can handle the imprecision and subjectivity of the information associated with this kind of problems. In this context, the concept of MCDM with direct computation on linguistic variables provides the DMs with the flexibility and capacity to assess the technologies' impact in all SD dimensions in a straightforward and transparent way.

In particular, based on the presented two-staged methodological approach, the sustainable energy technologies are firstly identified and the most promising is chosen based on the country's specific priorities and objectives. Furthermore, this decision analysis technique using the LOWA combined with OWMAX operator tackles adequately the inherent limitation of the lack of precision in the final results of the symbolic approach operators. The validity of the results was also assured through the comparison of the presented approach results with the 2-tuple representation model.

The results of the presented methodological approach to the Greek energy system were also appraised as realistic and transparent by the relevant stakeholders, which participated in a final meeting, organized by GSRT in the context of the Technology Foresight Programme (September 2005). In addition to this, its software realization can be considered to be a decision support system assisting policy makers to represent the information in a direct and adequate way.

It has to be noted that the criteria and the performances are dependent on the specific problem's formulations and particularly on the country's specific energy characteristics, its development needs and perspectives and the energy actors', engaged in the decision making process, interests. Although the approach adopted assisted this specific decision making problem, the analysis provides a basis on which other policy options' evaluations, such as scenarios, operational plans, can be built. Further issues for future research are the inclusion of additional options and modules in the system as well as the investigation of other fuzzy quantifiers influence in the final results.

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