Fuzzy Multi Criteria Decision Making Approach for Evaluating Sustainable Energy Technology Alternatives

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Abstract: Energy has been universally recognized as a key element for sustainable development. In developing countries, such as Turkey, energy demand increases thanks to a fast growing population and economy, posing threats of energy availability in the next decades. For this reason, Turkey has to evaluate and develop domestic, clean, and reliable energy sources from different alternative sources for sustainable development. In this process, as selecting the best energy alternatives requires both quantitative and qualitative evaluation criteria, two multi criteria decision making methods (MCDM) are employed for the analysis. More precisely, the fuzzy Analytic Hierarchy Process (AHP) is used to determine the evaluation criteria weights and fuzzy Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) is applied to select the most suitable alternative. The originality of the paper comes from its ability to propose an effective framework for both Turkey and literature and apply it to a real industrial problem to improve the sustainable energy alternative technology selection process.

Key-Words: Sustainable energy selection, Multi-criteria decision-making, Fuzzy AHP, Fuzzy TOPSIS

1 Introduction

The exhaustion of fossil fuels, the variability in energy prices and environmental concerns have made energy one of the priority issues in the industrialized world. Low cost, clean, native and secure energy supply is a common and fundamental issue for sustainable development. As the 17th largest economy in the world and 6th largest in European countries, Turkey is experiencing an increase in its energy demand, which is predicted to increase around 4 - 6 percent per annum until 2023 [1]. The Turkish economy is highly dependent on imported energy supplies, mostly dominated with fossil fuels [2]. Turkey's primary energy sources include hydropower, geothermal, lignite, hard coal, oil, natural gas, wood, animal and plant wastes, solar and wind energy [3]. Turkey has not utilized nuclear energy yet. Approximately 74% of total energy supply for Turkey's energy demand is met by imports.

The term "sustainable energy" has become popular in recent years which stands for "green" or "clean" energy that is environmentally sound and economically viable to sustain human progress [4]. In addition, sustainability is related with economic, environmental, social and technical aspects considering both qualitative and quantitative factors in the decision process [5]. Therefore, sustainable alternative energy technology selection can be viewed as a Multi Criteria Decision Making (MCDM) problem with several correlating criteria and alternatives [6,7]. Traditional single criteria decision making approaches cannot cope with the particular complexity of current systems. However, MCDM offers a flexible method to handle complicated situations and bring together a wide range of variables appraised in different ways and assist multiple Decision Makers (DMs) in mapping out the problem [8,9]. In this study an integrated MCDM model based on fuzzy approach is applied to Turkey's sustainable energy selection problem. The objective of this research is to first identify important decision criteria and sub-criteria and then utilize an effective integrated framework to evaluate and select the most appropriate sustainable energy alternatives. For this purpose the Analytic Hierarchy Process (AHP) [10] technique is utilized, which can successfully handle priorities within the context of MCDM [11]. This method provides an objective method for deciding among a set of solution strategies for solving problems. In some situations, DMs might not assign crisp evaluation values to the comparison judgments due to DMs limited knowledge or the subjectivity about the subject [11]. To overcome this challenge, fuzzy logic [12] is adapted to AHP in measuring the ambiguity of these

concepts. In addition, fuzzy TOPSIS (technique for order preference by similarity to ideal solution), one of the most known classical MCDM methods developed by Chen and Hwang [13], is integrated to the framework to rank energy alternatives.
This study is structured such that the 2nd section presents a literature review briefly, and the 3rd section provides a description of the methods used. The 4th section gives a case study by using application steps of the framework. Finally, concluding remarks and guidance for future studies are presented in 5th section.

2 Literature Review

2.1 Identification of criteria for sustainable energy technology selection

Based on a detailed literature survey and the contribution of industrial experts, this study attempts to develop a model for selecting sustainable energy alternatives for Turkey. The criteria are briefly explained in the following [2,14,15]. Under the main criterion Technical aspects (C1); Efficiency (C11): Efficiency measures how much useful energy can be obtained from an energy source [2,9,14]. Exergy efficiency (C12): Exergy efficiency computes the efficiency of a process taking the second law of thermodynamics into consideration [2,16]. Reliability (C13): Reliability is defined as the ability to operate a system under intended or designed conditions [2,14,15].
Under the main criterion Economic aspects (C2);
Investment cost (C21): It represents the total expenditures occurred for establishing the energy technology alternative including labor, purchase of mechanic equipment, technological installation or other related services [9,14]. Operation and maintenance costs (C22): Operation cost includes employees' wages and the funds spent for the energy. Maintenance cost aims to prolong energy system's life and avoid failures that may lead to its operational suspension [2,14,15]. Return on investment (C23): This criteria judges the proposed energy alternative economically and considers the project's worth on its investment [2].
Under the main criterion Social aspects (C3); Social acceptability (C31): Social acceptability expresses the overview of opinions related to the renewable energy sources by the local population [2,15-17]. Job creation (C32): This criteria generates direct and indirect employment opportunities and introduces possible new profession areas [2,15-17]. Social benefits (C33): It encompasses all benefits from energy resources and represents social progress in local community [2,15-17]. Under the main criterion Environmental aspects (C4); NOx emission (C41): NOx comprises a group of molecules that can contribute to air pollution, acid deposition and climate change [2, 14]. CO_2 emission (C42): It contributes to air pollution, acid deposition and climate change [2, 14]. Land use (C43): It indicates renewable energy systems' needed space in order to generate energy [2, 14-17].

2.2 Sustainable energy technology selection for Turkey with fuzzy MCDM

Determining the appropriate energy alternatives is a very complex and crucial problem for sustainable development of Turkey. Each alternative has its own advantages and disadvantages towards Turkey's energy sector. Hence, it is important to seek and recognize the best sustainable energy technology with the maximum utility. In this view, as the complexity of decisions increases, it becomes more difficult to identify an alternative that maximizes all decision criteria at once [2]. Here, Multi-criteria analysis is quite useful in undertaking difficult assessment procedures [14].
In literature there are several studies where MCDM techniques (such as Analytic hierarchy process (AHP), TOPSIS, ELECTRE, PROMETHEE, VIKOR) are used both in online journals and theses in energy planning and technology selection for Turkey. As an example, Köne and Büke [18] attempted to determine the best fuel mixture for the electricity production which is necessary for Turkey's sustainable development. Önüt, Tuzkaya and Saadet [19] dealt with the existing energy sources of the Turkish manufacturing industry by using the multi-criteria evaluation method of ANP. Kahraman [20] used a fuzzy AHP method to choose the best alternative among Turkey's renewable energy sources. Kaya and Kahraman [21] focused on the energy technology selection problem for Turkey considering AHP and TOPSIS with fuzzy approach. At the same year Erol and Kılkış [22] utilized AHP to select energy policy for Turkey. Stein [23] developed a model for energy technology evaluation by using AHP. More recently, Abdullah [16] utilized Intuitionistic fuzzy AHP to determine the best energy technology for Malaysia. Streimikiene, Sliogeriene and Turskis [24] focus on electricity generation technologies of Lithuania using AHP. According to these contributions, there is large number of MCDM literature in Turkey on

sustainable energy technology and related issues in the last ten years.

3 Methodology

In this paper, a hybrid fuzzy MCDM methodology that consists of AHP and TOPSIS under fuzzy sets is used to evaluate the sustainable energy alternatives for Turkey. Fuzzy AHP is used to obtain weights of criteria and fuzzy TOPSIS is used to evaluate the alternatives.

3.1 Fuzzy AHP

The fuzzy AHP methodology extends Saaty's AHP [10] by combining it with the fuzzy set theory pioneered by Zadeh [12]. Fuzzy set theory is designed to model the vagueness or imprecision of human cognitive processes [25]. In AHP linguistic terms are used to represent the experts' assessments, and then triangular fuzzy numbers, $\tilde{1}\ to\ \tilde{9}$, are used for evaluations which can be see seen in Saaty's [10] study. In the first step the performance score of elements are compared in the same hierarchy. Then the fuzzy comparison matrix is constructed. By using triangular fuzzy numbers, the fuzzy judgment matrix $\tilde{A}$ is constructed via pair-wise comparison, as given below:

$$\tilde{A} = \begin{bmatrix} \tilde{\alpha}_{11} & \tilde{\alpha}_{12} & \dots & \tilde{\alpha}_{1n} \\ \tilde{\alpha}_{21} & \tilde{\alpha}_{21} & \dots & \tilde{\alpha}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{\alpha}_{n1} & \tilde{\alpha}_{n1} & \dots & \tilde{\alpha}_{nn} \end{bmatrix} \quad (1)$$

where $\tilde{a}_{ij}^{\alpha}$= 1, if i=j and $\tilde{a}_{ij}^{\alpha}=\tilde{1},\tilde{3},\tilde{5},\tilde{7},\tilde{9}$, or $\tilde{1}^{-1},\tilde{3}^{-1},\tilde{5}^{-1},\ \tilde{7}^{-1},\ \tilde{9}^{-1}$ if i is not equal to j. Next, solve the fuzzy eigenvalue. A fuzzy eigenvalue, $\tilde{\lambda}$ is a fuzzy number solution to:

$$\tilde{A}\,\tilde{x}=\tilde{\lambda}\,\tilde{x} \quad (2)$$

where $\tilde{\lambda}_{\max}$ is the largest eigenvalue of $\tilde{A}$ and $\tilde{x}$ is a non-zero nx1, fuzzy vector containing fuzzy number $\tilde{x}_i$. To perform fuzzy multiplications and additions by using the interval arithmetic and α -cut, the equation $\tilde{A}\,\tilde{x}=\tilde{\lambda}\,\tilde{x}$ is equivalent to:

$$[\tilde{a}_{i1l}^{\alpha}\,\tilde{x}_{1l}^{\alpha},\tilde{a}_{i1u}^{\alpha}\tilde{x}_{1u}^{\alpha}]\oplus\dots\oplus[\tilde{a}_{inl}^{\alpha}\,\tilde{x}_{nl}^{\alpha},\tilde{a}_{inu}^{\alpha}\tilde{x}_{nu}^{\alpha}] = \left[\lambda x_{il,}^{\alpha},\lambda x_{iu}^{\alpha}\right] \text{ ve, } \tilde{A} = \left[\tilde{a}_{ij}^{\alpha}\right],\tilde{x}^{t} = (\tilde{x}_{1,\dots}\tilde{x}_{n}),$$
$$\tilde{a}_{ij}^{\alpha} = \left[\alpha_{ijl}^{\alpha},\alpha_{iju}^{\alpha}\right],\tilde{x}_{1j}^{\alpha} = \left[x_{il,}^{\alpha},x_{j1u}^{\alpha}\right],\tilde{\lambda}^{\alpha}=[\lambda_{l},\lambda_{u}] \quad (3)$$

for $0 < \alpha \leq 1$ and all i, j, where i = 1,2,...,n, j = 1,2..., n. The α -cut is known to incorporate the experts or DMs confidence over his/her preferences. The degree of satisfaction for the judgment matrix e A is estimated by the index of optimism $\tilde{A}$. A larger value of the index μ indicates a higher degree of optimism. The index of optimism is a linear convex combination defined as:

$$\tilde{a}_{ij}^{\alpha} = \mu a_{ijl,}^{\alpha} + (1-\mu)a_{ijl,}^{\alpha} \forall\, a\epsilon\,[0,1] \quad (4)$$

When α is fixed, the following matrix can be obtained after setting the index of optimism, μ, in order to estimate the degree of satisfaction:

$$\tilde{A} = \begin{bmatrix} \tilde{a}_{11}^{\alpha} & \tilde{a}_{12}^{\alpha} & \dots & \tilde{a}_{1n}^{\alpha} \\ \tilde{a}_{21}^{\alpha} & \tilde{a}_{22}^{\alpha} & \dots & \tilde{a}_{2n}^{\alpha} \\ \dots & \dots & \dots & \dots \\ \tilde{a}_{n1}^{\alpha} & \tilde{a}_{n2}^{\alpha} & \dots & \tilde{a}_{nn}^{\alpha} \end{bmatrix} \quad (5)$$

The eigenvector is calculated by fixing the μ value and identifying the maximal eigenvalue. In order to control the result of the method, the consistency ratio for each of the matrices and the overall inconsistency for the hierarchy are calculated. The consistency ratio (CR) is used to directly estimate the consistency of the pair-wise comparisons and should be less than 0.10. Then it can be said the comparisons are acceptable, otherwise they are not acceptable and should be revised. Finally, the priority weight of each criterion can be obtained.

3.2 Fuzzy TOPSIS

TOPSIS, one of the most known classical MCDM methods, was developed by Hwang and Yoon [26]. TOPSIS incorporates a simple computation process, systematic procedure, and a sound logic that considers the rationale of human choice. It provides a wide range of criteria and performance attributes and enables trade-offs between attributes.The steps of the methodology are as follows.

$$\tilde{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \end{bmatrix} \end{array} \text{ and } i = 1,2,\dots,m;\ j\ 1,2,\dots n \quad (6)$$

Firstly establish fuzzy decision matrix for evaluation of the alternatives. $\tilde{D}$ represents the fuzzy decision matrix with alternatives A and criteria C. Then, normalize the decision matrix. Normalized fuzzy decision matrix e $\tilde{D}$ is calculated as:

$\tilde{R}=[\tilde{r}_{ij}]_{mxn}\ i = 1,2,\dots,m;\ j = 1,2,\dots n$ and,

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^+}, \frac{b_{ij}}{c_j^+}, \frac{c_{ij}}{c_j^+}\right) \text{ and } C_j^+ = max_i c_{ij} \quad (7)$$

where $C_j^+ = max_i c_{ij}$. To avoid the complicated normalization formula used in the classical TOPSIS, the linear scale transformation is used to transform the various criteria scales into a comparable scale. Here, the normalized decision matrix remains the same because max $C_{ij} = 1$. In the next step, compute the weighted decision matrix. Weighted normalized fuzzy decision matrix is computed by using Eq. (8), where w_j is the weight for the criterion j obtained from AHP matrices.

$$\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \tilde{w}_j \text{ and } \tilde{V} = [\tilde{v}_{ij}]_{mxn} \quad i = 1,2,\dots,m;\ j = 1,2,\dots n \quad (8)$$

In the next step, calculate the distances from positive and negative ideal points (FPIRP, FNIRP) which are shown in Eq. (9-10).

$$A^+ = (\tilde{v}_1^+, \tilde{v}_2^+, \dots, \tilde{v}_n^+) \text{ and } \tilde{v}_j^+ = max_i\{v_{ij3}\},\ i = 1,2,\dots,m;\ j = 1,2,\dots,n \quad (9)$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_n^-) \text{ and } \tilde{v}_j^- = min_i\{v_{ij1}\},\ i = 1,2,\dots,m;\ j = 1,2,\dots,n \quad (10)$$

The next step is to calculate the distance of alternatives from FPIRP and FNIRP

$$d_i^+ = \sum_{j=1}^n d_v(\tilde{v}_{ij}, \tilde{v}_j^+),\ i = 1,2,\dots,m;\ j = 1,2,\dots,n \quad (11)$$

$$d_i^- = \sum_{j=1}^n d_v(\tilde{v}_{ij}, \tilde{v}_j^-),\ i = 1,2,\dots,m;\ j = 1,2,\dots,n \quad (12)$$

$$d(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{3}[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2]} \quad (13)$$

Next, compute the closeness coefficient (CC_i) of each alternative. The closeness coefficient CC_i represents the distances to the fuzzy positive ideal solution and the fuzzy negative ideal solution simultaneously. The closeness coefficient of each alternative is calculated as:

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+},\ i = 1,2,\dots,m \quad (14)$$

Finally rank the alternatives. Different alternatives are ranked according to the closeness coefficient (CC_i) in decreasing order.

4 Case Study

This section presents the results of a real case study of sustainable energy alternative application in Turkey. The most frequently used technical, economic, social and environmental criteria and the contribution of industrial experts are added to the selection problem. The sustainable energy alternatives considered are: Wind energy (A1), Solar energy (A2), Biomass energy (A3), Conventional energy (Coal, oil etc.) (A4), Combine heat and power (A5), Nuclear energy (A6) and Hydraulic (A7).

4.1 Fuzzy AHP & Fuzzy TOPSIS Evaluation

In the decision process, DMs make pair-wise comparisons with the help of Saaty's [10] nine point scale. As an example Table 1 and 2 give the results of pair-wise comparisons of main criteria evaluations.

Table 1. Fuzzy evaluation matrix of main criteria

	C1	C2	C3	C4
C1	1	0.375	1	3
C2	1	1	3	3
C3	1	0.375	1	1
C4	0.375	0.375	1	1

Table 2. Fuzzy evaluation matrix results

	C1	C2	C3	C4	Average
C1	0.296	0.176	0.167	0.375	0.254
C2	0.296	0.471	0.500	0.375	0.410
C3	0.296	0.176	0.167	0.125	0.191
C4	0.111	0.176	0.167	0.125	0.145

$\tilde{\lambda}_{max}$ is 4.019 and by using the equations CI=0.006 and CR=0.007 which means appropriate. The other matrices are computed and the evaluations are summarized in Table 3.

Then after obtaining the weights of criteria and fuzzy ratings of alternatives with respect to each criterion, TOPSIS steps are considered. Table 4 presents the evaluation scores and Table 5 gives the final results of the selection problem.

Table 3. Summary of criteria weights

Criteria	Local weights	Sub- Criteria	Local weights	Global weights
Technical A. (C1)	0.254	Efficiency (C11)	0.436	0.110
		Exergy Efficiency (C12)	0.236	0.060
		Reliability(C13)	0.329	0.083
Economical A.(C2)	0.410	Investment Cost (C21)	0.424	0.174
		Operation & M. Cost (C22)	0.153	0.063
		Return on Investment (C23)	0.424	0.174
Social A. (C3)	0.191	Social acceptability (C31)	0.205	0.039
		Job creation (C32)	0.590	0.113
		Social benefits (C33)	0.205	0.039
Environmental A. (C4)	0.145	Nox emission (C41)	0.230	0.033
		Co2 emission (C42)	0.318	0.046
		Land use (C43)	0.451	0.065

Table 4. Evaluation scores of the sustainable energy alternatives.

Criteria	C11	C12	C13	C21	C22	C23	C31	C32	C33	C41	C42	C43
A1	8	9	8	5	7	8	6	8	7	6	9	8
A2	8	6	6	6	8	9	5	5	6	9	6	9
A3	6	5	6	5	6	7	7	7	8	8	8	7
A4	5	5	5	5	5	8	5	5	6	5	7	8
A5	6	7	5	5	5	6	5	6	6	5	5	4
A6	8	8	8	8	9	8	9	9	8	8	9	8
A7	6	8	7	7	6	5	6	7	6	7	7	7

Table 5.Final ranking of sustainable energy alternatives

Alternatives	A+	A-	CC_i
A1	19.513	1.282	0.062
A2	19.573	1.223	0.059
A3	19.651	1.145	0.055
A4	19.733	1.065	0.051
A5	19.811	0.987	0.047
A6	19.359	1.435	**0.069**
A7	19.610	1.186	0.057

5 Conclusion

The main purpose of this study is to evaluate sustainable energy resources and to select the most suitable energy alternative for Turkey. Evaluation of sustainable energy technology alternatives involves subjective and qualitative judgments and requires different complex factors. For this reason, energy resources evaluation problem needs MCDM methods to select the most appropriate energy alternative correctly. In this study fuzzy AHP – fuzzy TOPSIS are used and the proposed model is implemented to a Turkish sustainable energy decision case. According to Table 5, alternative A6, which is nuclear energy, has the highest score among all alternatives and A6 should be preferred over the others. While it is believed that the presented model gives value, there are also further points that can be improved. As an example, future work can involve sensitivity analysis in order to examine the robustness of the obtained results. Moreover, considering the dependencies between criteria with fuzzy ANP can be utilized and the results can be compared to each other.

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