



EVALUATION OF RENEWABLE ENERGY ALTERNATIVES USING MACBETH AND FUZZY AHP MULTICRITERIA METHODS: THE CASE OF TURKEY

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Abstract. Energy is a critical foundation for economic growth and social progress. It is estimated that 70% of the world energy consumption could be provided from renewable resources by the year 2050. Renewable energy is the inevitable choice for sustainable economic growth, for the harmonious coexistence of human and environment as well as for the sustainable development. The aim of this paper is to evaluate the renewable energy alternatives as a key way for resolving the Turkey's energy-related challenges because of the fact that Turkey's energy consumption has risen dramatically over the past three decades as a consequence of economic and social development. In order to realize this aim, we comparatively use MACBETH and AHP-based multicriteria methods for the evaluation of renewable energy alternatives under fuzziness. We use 4 main attributes and 15 sub-attributes in the evaluation. The potential renewable energy alternatives in Turkey are determined as Solar, Wind, Hydropower, and Geothermal.

Keywords: multi criteria decision making, MACBETH software, AHP, fuzzy, renewable energy alternatives, linguistic terms.

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Introduction

Energy is essential for economic and social development and improved quality of life in all countries. For that reason, energy constitutes one of the main inputs for economic and social development. In line with the increasing population, urbanization, industrialization, spreading of technology and rising of wealth, energy consumption is increasing. Energy consumption and consequently energy supply at minimum amount and cost is the main objective, within the approach of a sustainable development that supports economic and social development. Much of the world's energy, however, is currently produced and consumed in ways that could not be sustained if technology were to remain constant and if overall quantities were to increase substantially.

Renewable energy is the inevitable choice for sustainable economic growth, for the harmonious coexistence of human and environment as well as for the sustainable development. Renewable energy is usually regarded as energy that does not pollute environment and could be recycled in nature. Renewable energy is an important factor for the strengthening of the regional development. However, there are many challenges facing the efforts to increase renewable energy use. The most drawbacks for higher renewable energy penetration into energy systems lie in their costs and related insufficient cost effectiveness. Thus, it is necessary to introduce financial support mechanism and favorable promotion schemes, especially ones that will attract private financing into energy sector and in such manner reduce the financial burden on the state budget.

Turkish energy consumption has risen dramatically over the past 20 years due to the combined demands of industrialization and urbanization. Turkey's primary energy consumption has increased from 32 mtoe (million tons of oil equivalent) in 1980 to 74 mtoe in 1998. According to the planning studies, Turkey's final consumption of primary energy is estimated to be 171 mtoe in 2010 and 298 mtoe in 2020. In other words, in 1999, domestic energy production met 36% of the total primary energy demand and will probably meet 24% in 2020. The level of Turkey's energy consumption is still low relative to similar sized countries, such as France and Germany, with gross inland consumptions of 235 and 339 mtoe in 1995 and with estimated values of 290 and 350 mtoe in 2020, respectively (Hepbaslı, Ozalp 2003). When the case of Turkey is considered, it can be said that Turkey is heavily dependent on imported energy resources, which places a big burden on the economy. Air pollution is also becoming a great environmental concern in the country. In this situation, renewable energy resources appear to be the one of the most efficient and effective solutions for clean and sustainable energy development in Turkey. Turkey's geographical location has several advantages for extensive use of most of these renewable energy sources. As Turkey's economy has expanded in recent years, the consumption of primary energy has increased. Presently in order to increase the energy production from domestic energy resources, to decrease the use of fossil fuels as well as to reduce of greenhouse gas emissions, different renewable energy sources are used for energy production in Turkey. Among these renewable energy resources, hydropower, biomass, biogas, bio-fuels, wind power, solar energy and geothermal energy are the most favorite ones in the future. The selection of the best alternative for Turkey takes an important role for energy investment decision making.

Decision-making is the process of finding the best option from all of the feasible alternatives. Sometimes, decision-making problems considering several criteria are called multi-criteria decision-making (MCDM) problems. The MCDM problems may be divided into two kinds. One is the classical MCDM problems (Kaklauskas *et al.* 2006; Zavadskas *et al.* 2008a, b; Ginevičius *et al.* 2008), among which the ratings and the weights of criteria are measured in crisp numbers. Another is the fuzzy multiple criteria decision-making (FMCDM) problems (Liu, Wang 2007; Wei, Liu 2009; Jin *et al.* 2007), among which the ratings and the weights of criteria evaluated on imprecision, subjective and vagueness are usually expressed by linguistic terms, fuzzy numbers or intuitionistic fuzzy numbers (Liu 2009).

There are various decision-making methodologies developed by researchers in the literature. Among the most used multi-criteria decision making methods for renewable energy investments are counted Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), the elimination and choice translating reality (ELECTRE), a hybrid of ELECTRE III, and PROMETHEE II, and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Since each method has its own properties to select the best alternative, different ranking orders of alternatives can be obtained. For example, AHP is based on pairwise comparisons using a 1–9 scale while TOPSIS uses negative and positive ideal solutions to select the best alternative. New methods having different properties may present new opportunities to decision makers. As another multi-criteria decision making method, MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) is an interactive approach that requires only qualitative judgments about differences to help a decision maker.

MACBETH is an approach designed to build a quantitative model of values, developed in a way that enables facilitators to avoid forcing decision makers to produce direct numerical representations of their preferences. It employs an initial, interactive, questioning procedure that compares two elements at a time, requesting only a qualitative preference judgment about their difference of attractiveness. As the answers are given, their consistency is verified, and a numerical scale that is representative of the decision maker's judgments is subsequently generated and discussed. The originality of this paper comes from MACBETH multi-criteria method's first time application to renewable energy investments area and comparison with the obtained results of a multicriteria decision making methodology based on Zeng *et al.* (2007) fuzzy AHP. This paper makes use of the MACBETH approach and software to help an individual selection among alternatives of renewable energy.

MACBETH has an increasing popularity in the literature. Cliville *et al.* (2007) dealt with the use of the MACBETH methodology as a global framework for multi-criteria industrial performance expressions. This methodology satisfies the measurement theory requirements, and thus ensures the coherence of the elementary and aggregated performance expressions. Bana e Costa and Manuel (2004) used the MACBETH approach and software to help an individual select his future career from a number of self-imposed possibilities. A comparison is made with the direct numerical technique SMART, previously used with the same intent. Roubens *et al.* (2006) presented an application of the MACBETH approach to a certain model of coalition formation. They apply the MACBETH technique to quantify the attractiveness and repulsiveness of possible governments to parties. Bana e Costa *et al.* (1999) described a real application of Multi-Criteria Decision Analysis (MCDA) in which several Decision

Support Systems (DSSs) were harmoniously integrated in the interactive learning process of tackling the complex strategic problematic situation faced by the Santa Catarina textile industry, in the south of Brazil. They reached significant conclusions from their conjoint use of Graphics COPE, MACBETH, V.I.S.A, and EQUITY in building a model of values. Bana e Costa *et al.* (2008) presented the development of a multicriteria value model enabling the prioritization of bridges and tunnels according to their structural vulnerability and strategic importance for the formulation and implementation of civil protection policies, both for retrofitting and emergency management, in face of seismic events. An interactive structuring process was developed with a group of key-players to carefully define the evaluation criteria and the MACBETH approach is extensively used (i) to facilitate the assessment from the group of the judgmental information necessary to build value functions and (ii) to establish relative weights for the criteria. Montignac *et al.* (2009) provided some results obtained from the implementation of the MACBETH multi-criteria evaluation approach for the evaluation and comparison of the technical performance of three hydrogen storage technologies.

In recent years, some studies have concentrated on fuzzy energy planning and fuzzy energy policy making. Kahraman and Kaya (2010a) suggested a fuzzy multicriteria decision-making methodology based on Zeng *et al.* (2007) analytic hierarchy process (AHP) under fuzziness and allowed the evaluation scores from experts to be linguistic expressions, crisp or fuzzy numbers for the selection among energy policies for Turkey. Aydın *et al.* (2010) developed a decision support tool for site selection of wind energy turbines in the Geographic Information System environment using fuzzy decision making approach. This decision support tool enabled aggregation of individual satisfaction degrees of each alternative location for various fuzzy environmental objectives. Kahraman *et al.* (2010b) suggested axiomatic design methodology for the selection among renewable energy alternatives under fuzzy environment. Kaya and Kahraman (2010) proposed a methodology based on fuzzy VIKOR and fuzzy AHP to determine the best renewable energy alternative for Istanbul. They also used the proposed methodology for selection among alternative energy production sites in Istanbul. Kucukali and Baris (2010) employed a fuzzy logic method to forecast the gross electricity demand of Turkey. Kahraman *et al.* (2009) suggested two fuzzy multicriteria decision making methodologies for the selection among renewable energy alternatives. The first methodology was based on Zeng *et al.* (2007) fuzzy AHP which allows the evaluation scores from experts to be linguistic expressions, crisp, or fuzzy numbers, while the second is based on AD principles under fuzziness which evaluates the alternatives under objective or subjective criteria with respect to the functional requirements obtained from experts. In the application of the proposed methodology the most appropriate renewable energy alternative was determined for Turkey.

Çam (2007) compared a conventional proportional integral controller and a fuzzy gain scheduled proportional integral controller for applying to a single area and a two area hydroelectric power plant, considering Turkey's several hydro power sources. Jebaraj and Iniyani (2007) developed a fuzzy-based linear programming optimal energy model that minimized the cost and determined the optimum allocation of different energy sources for the centralized and decentralized power generation in India. Cavallaro and Ciraolo (2005) proposed a multicriteria method in order to support the selection and evaluation of one or more of the solutions to make a preliminary assessment regarding the feasibility of installing

some wind energy turbines in a site on the island of Salina in Italy. They compared the four wind turbine configurations. They used a multicriteria methodology to rank the solutions from the best to the worst. Beccali *et al.* (2003) made an application of the multicriteria decision-making methodology to assess an action plan for the diffusion of renewable energy technologies at regional scale. They also carried out a case study for the island of Sardinia. They used ELECTRE-III method under fuzzy environment. Borges and Antunes (2003) presented an interactive approach to deal with fuzzy multiple objective linear programming problems based on the analysis of the decomposition of the parametric (weight) diagram into indifference regions corresponding to basic efficient solutions. The approach was illustrated to tackle uncertainty and imprecision associated with the coefficients of an input–output energy-economy planning model, aimed at providing decision support to decision makers in the analysis of the interactions between the energy system and the economy on a national level. Goumas and Lygerou (2000) extended a multicriteria method of ranking alternative projects, PROMETHEE, to deal with fuzzy input data. The proposed method was applied for the evaluation and ranking of alternative energy exploitation schemes of a low temperature geothermal energy.

The rest of this paper is organized as follows: Renewable energy alternatives and evaluation criteria are presented in Section 1. An application based on MACBETH and Fuzzy AHP, whose theoretical background is given in Appendices A and B, is presented in Section 2. Finally, conclusions are presented in the last Section.

1. Renewable energy alternatives and the evaluation criteria system

Renewable energy is energy generated from natural resources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (naturally replenished). In 2006, about 18% of global final energy consumption came from renewable resources, with 13% coming from traditional biomass, such as wood-burning and 3% from hydroelectricity. New renewable (small hydro, modern biomass, wind, solar, geothermal, and biofuels) accounted for another 2.4% and are growing very rapidly. The share of renewable in electricity generation is around 18%, with 15% of global electricity coming from hydroelectricity and 3.4% from new renewable (REN21 2008)

While most renewable energy projects and production is large-scale, renewable energy technologies are also suited to small off-grid applications, sometimes in rural and remote areas, where energy is often crucial in human development. Some renewable energy technologies are criticized for being intermittent or unsightly, yet the renewable energy market continues to grow. Climate change concerns, coupled with high oil prices, peak oil, and increasing government support, are driving increasing renewable energy legislation, incentives and commercialization.

The criteria that will be used to evaluate renewable energy alternatives are briefly explained in the following (Kahraman *et al.* 2009; Kahraman, Kaya 2010a): Under the main criterion C1: Technological:

C11. Feasibility: This criterion measures the secure of the possibility for implementation of the renewable energy. The number of times tested successfully can be taken into account as a decision parameter. C12. Risk: The risk criterion evaluates the secure of the possibility for

implementation of a renewable energy by measuring the number of problems for failures in a tested case. C13. Reliability: This criterion evaluates the technology of the renewable energy. Technology may have been only tested in laboratory or only performed in pilot plants, or it could be still improved, or it is a consolidated technology. C14. The duration of preparation phase: The criterion measures the availability of the renewable energy alternative to decrease financial assets and reach the minimum cost. The preparation phase is judged by taking into accounts years or months. C15. The duration of implementation phase: The criterion measures the applicability of the renewable energy alternative to reach the minimum cost. The cost of implementation phase is judgment by taking into accounts years or months of implementation. C16. Continuity and predictability of performance: This criterion evaluates the operation and performance of the technology for renewable energy alternative. It is important to know if the technology operates continuously and confidently. C17. Local technical knowhow: This criterion includes an evaluation which is based on a qualitative comparison between the complexity of the considered technology, and the capacity of local actors to ensure an appropriate operating support for maintenance and installation of technology for renewable energy alternative. Under the main criterion C2: Environmental: C21. Pollutant emission: The criterion measures the equivalent emission of CO₂, air emissions which are the results of combustion process, liquid wastes which are related to secondary products by fumes treatment or with process water, and solid wastes. The evaluation of the criterion includes type and quantity of emissions, and costs associated with wastes treatments. Also the electro-magnetic interferences, bad smells, and microclimatic changes for energy investment are taken into account in the evaluation of this criterion. C22. Land requirements: Land requirement is one of the most critical factors for the energy investment. A strong demand for land can also determine the economic losses. C23. Need of waste disposal: The criterion evaluates the renewable energy's damage on the quality of the environment. The renewable energy alternative can be evaluated to reduce damage on the quality of life and to increase sustainability by taking into account this criterion. Under the main criterion C3: Socio-Political: C31. Compatibility with the national energy policy objectives: The criterion analyzes the integration of the national energy policy and the suggested renewable energy alternative. It measures the degree of objectives' convergence between the government policy and the suggested policy. The criterion also takes into account the government's support, the tendency of institutional actors, and the policy of public information. C32. Political acceptance: The criterion makes whether or not a consensus among leaders' opinions for proposed renewable energy alternative exists. Also it takes into account avoiding the reactions of the politicians and satisfying political leaders. C33. Social acceptance: The criterion enhances consensus among social partners. Also it takes into account avoiding the reactions from special interest social groups for renewable energy alternatives. C34. Labor impact: Renewable energy alternatives are evaluated by taking into account labor impact which is related to direct and indirect employment and the possible indirect creation of new professional figures are also assessed. Under the main criterion C4: Economical: C41. Implementation cost: This criterion analyzes the total cost of the energy investment in order to be fully operational. C42. Availability of funds: This criterion evaluates the national and international sources of funds, and economic support of government. C43. Economic value (PW, IRR, B/C): This criterion judges the proposed renewable energy alternative as economic by using one of the engineering economics techniques which are

present worth (PW), internal rate of return (IRR), benefit/cost analysis (B/C), and payback period (PP). The renewable energy alternatives which will be considered in this paper are hydropower, wind, solar, biomass, and geothermal.

The selection of the suitable renewable energy alternative is very important to plan future's energy consumption. Since the most forms of renewable energy alternatives are dependent on multicriteria decision making, this paper is concerned with using MACBETH and fuzzy AHP multicriteria methods that are detailed into Appendix A and B, respectively to evaluate renewable energy resources for Turkey.

2. An application

The Republic of Turkey, located in Southeastern Europe and Southwestern Asia, has an area of about 780,580 km² and a population of over 70 million. With its young population, growing energy demand per person, fast growing urbanization and economic development, Turkey has been one of the fast growing power markets of the world for the last two decades. Turkey is an energy importing country; more than half of the energy requirement has been supplied by imports. Turkey's primary energy sources include hydropower, geothermal, lignite, hard coal, oil, natural gas, wood, animal and plant wastes, solar and wind energy. In 2004, primary energy production and consumption has reached 24.1 million tones (Mt) of oil equivalent (Mtoe) and 81.9 Mtoe, respectively. Fossil fuels provided about 86.9% of the total energy consumption of the year 2004, with oil (31.5%) in first place, followed by coal (27.3%) and natural gas (22.8%). Turkey has not utilized nuclear energy yet. The Turkish coal sector, which includes hard coal as well as lignite, accounts for nearly one half of the country's total primary energy production (43.7%). The renewable collectively provided 13.2% of the primary energy, mostly in the form of combustible renewables and wastes (6.8%), hydropower (about 4.8%) and other renewable energy resources (approximately 1.6%) (Erdogdu 2010; IEA 2007).

Because of the increasing population and life standards in Turkey, fossil fuel consumption is increasing. As a result, fossil fuels are being depleted rapidly. Another important problem associated with fossil fuels is that their consumption has major negative impacts on the environment. Therefore, Turkey has to include renewable energy alternatives in their future energy plans so that they can produce reliable and environmentally friendly energy. For this aim, two multicriteria decision making methodologies called MACBETH and fuzzy AHP are used to determine the most appropriate renewable energy alternative for Turkey in this paper.

2.1. MACBETH evaluation

The theoretical background of MACBETH is given in Appendix-A. The hierarchy of the decision problem for the selection among renewable energy alternatives is given by Fig. 1. The goal of the problem is to provide a sustainable development considering the environmental, socio-political, economical, and technological attributes. The hierarchy is composed of four levels, four main attributes, 15 subattributes, and five alternatives.

We use M-Macbeth software for the pairwise comparisons of alternatives with respect to main attributes and subattributes. Figure 2 gives the pairwise comparisons for renewable

energy alternatives with respect to the main attribute *technological*. The other pairwise comparison matrices are not given for the sake of page constraints. As it is seen in the Figure Hydropower is evaluated as *weak* with respect to Wind while it is evaluated by the interval *moderate-very strong* with respect to Biomass. After all comparison matrices are filled in, the next is to obtain the value tree.

Figure 3 shows the hierarchy of the main and sub attributes together with the alternatives' scores over a 100 points scale with respect to some subattributes. From the value tree in Figure 3 each alternative's normalized score is obtained with respect to each subattribute. As it is seen in Figure 4, Wind alternative gets the best score with respect to the subattri-

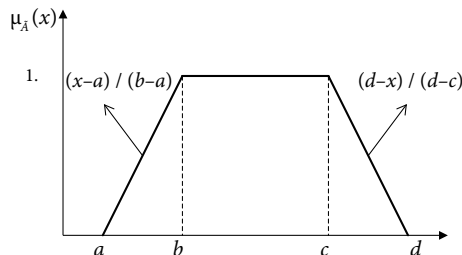


Fig. 1. Membership function of STFN \tilde{A}

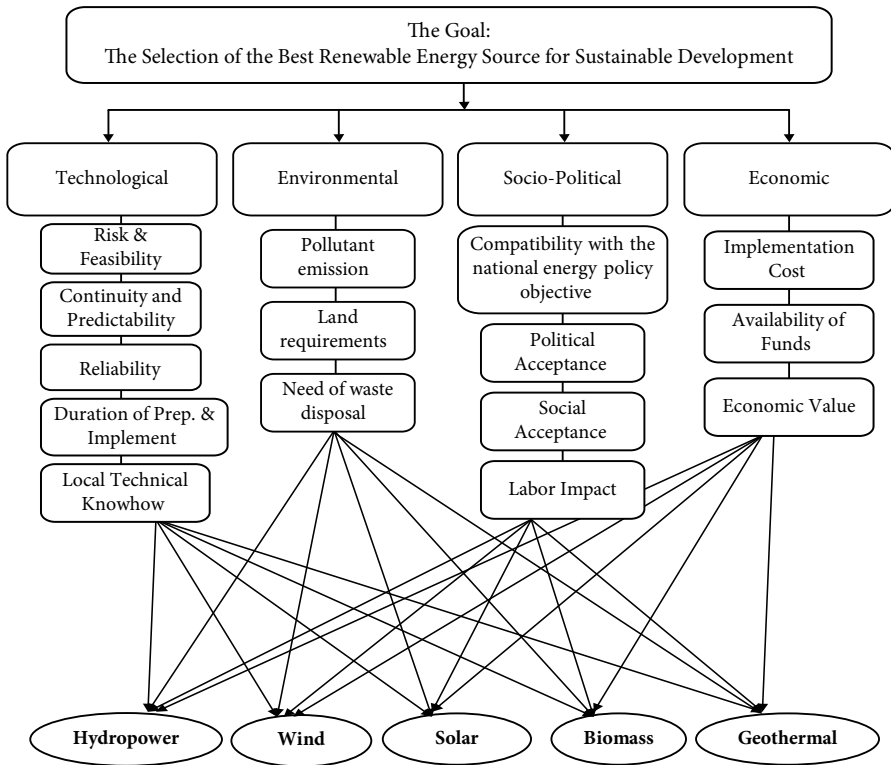


Fig. 2. Hierarchy of the problem

butes *social acceptance* and *compatibility with the national energy policy objective* of the main attribute *socio-political* and the subattribute *economic value* of the main attribute *economic*.

Figure 4 shows the same hierarchy together with the pairwise comparison matrix and the rank of alternatives with respect to the subattribute *pollutant emission* of the main attribute *environmental*. In Figure 4, the rank order of the alternatives Geothermal and Hydropower is changed. The alternative Geothermal takes the fifth place with respect to *pollutant emission* while it does the fourth order with respect to all the main attributes.

According to M-Macbeth results, Wind energy is the best for Turkey. The rank order of the alternatives is obtained as Wind > Biomass > Solar > Geothermal > Hydropower.

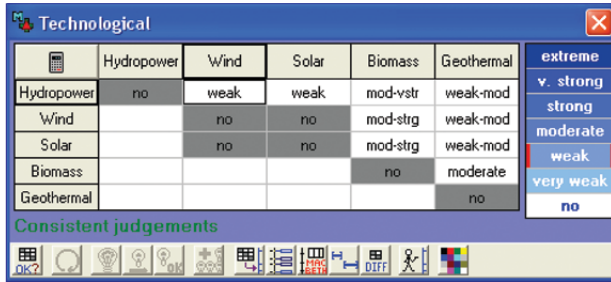


Fig. 3. Pairwise comparisons for renewable energy alternatives in MACBETH

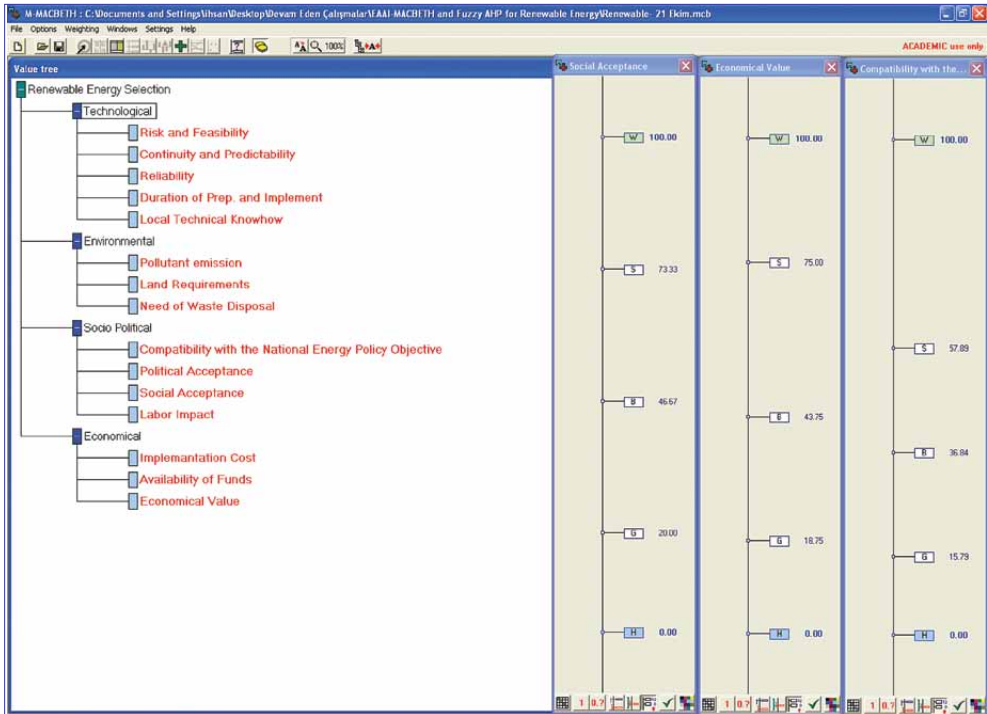


Fig. 4. The results for selected sub-criteria

2.2. Fuzzy AHP evaluations

In this subsection a modified fuzzy AHP is used to determine the most appropriate renewable energy alternative for Turkey. For this aim, three energy experts evaluate the considered criteria to determine the most appropriate renewable energy alternative with respect to the hierarchy given in Figure 1. As it is seen from Figure 1, the hierarchy composed of 4 main criteria and 15 sub-criteria and 5 alternatives. Each criterion of the hierarchy is evaluated by the experts using a linguistic scoring system, which is shown in Figure 5. Each expert provides a decision about his/her judgment only as a linguistic term. Then these evaluations are converted into STFNs as defined in Eq. (2) in Appendix B and aggregated with respect to experts' weights.

The linguistic evaluations of the criteria for Solar Energy are shown in Table 1.

The aggregations of the obtained scores are calculated by Eq. (3) in Appendix B. For example, the aggregation of the scores for “Land requirements” under “Environmental” criterion is calculated as follows:

$$\tilde{S}_{LR} = [(7.5, 10.0, 10.0, 10.0) \otimes 0.4] \oplus [(7.5, 10.0, 10.0, 10.0) \otimes 0.3] \oplus [(7.5, 10.0, 10.0, 10.0) \otimes 0.3];$$

$$\tilde{S}_{LR} = (7.5, 10.0, 10.0, 10.0).$$

The other values of evaluation criteria for solar energy and their aggregation are shown in Table 1. The pair-wise comparisons of “Socio-Political Criteria” and the corresponding STFNs are shown in Table 2. The aggregation of STFN scales are calculated by Eq. (4) in Appendix B.

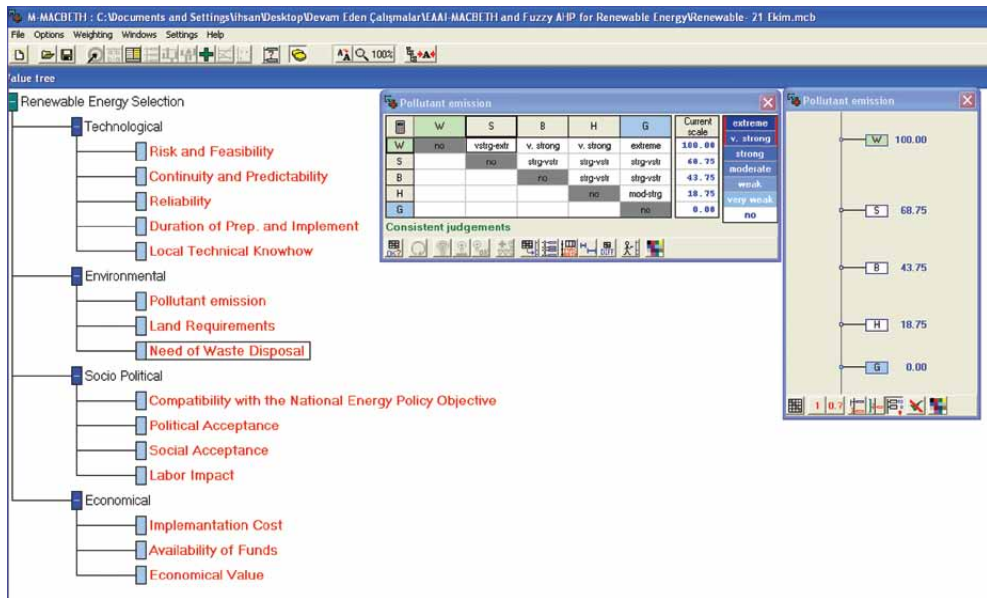


Fig. 5. The ranking result with respect to “Pollutant Emission”

Table 1. Scores and their respective STFNs for solar energy

Evaluation Criteria	E1		E2		E3		Aggregated STFN
	Score	Converted STFN	Score	Converted STFN	Score	Converted STFN	
Risk & Feasibility	G	(5.0, 7.5, 7.5, 10.0)	H	(5.0, 7.5, 7.5, 10.0)	H	(5.0, 7.5, 7.5, 10.0)	(5.00, 7.50, 7.50, 10.00)
Reliability	H	(5.0, 7.5, 7.5, 10.0)	VH	(7.5, 10.0, 10.0, 10.0)	VH	(7.5, 10.0, 10.0, 10.0)	(6.50, 9.00, 9.00, 10.00)
The duration of preparation & implementation	H	(5.0, 7.5, 7.5, 10.0)	H	(5.0, 7.5, 7.5, 10.0)	VH	(0.0, 0.0, 0.0, 2.5)	(3.50, 5.25, 5.25, 7.75)
Continuity and predictability	VG	(7.5, 10.0, 10.0, 10.0)	G	(5.0, 7.5, 7.5, 10.0)	VG	(7.5, 10.0, 10.0, 10.0)	(6.75, 9.25, 9.25, 10.00)
Local technical know how	F	(2.5, 5.0, 5.0, 7.5)	F	(2.5, 5.0, 5.0, 7.5)	M	(2.5, 5.0, 5.0, 7.5)	(2.50, 5.00, 5.00, 7.50)
Pollutant emission	VL	(7.5, 10.0, 10.0, 10.0)	L	(5.0, 7.5, 7.5, 10.0)	G	(5.0, 7.5, 7.5, 10.0)	(6.00, 8.50, 8.50, 10.00)
Land requirements	VL	(7.5, 10.0, 10.0, 10.0)	VL	(7.5, 10.0, 10.0, 10.0)	VL	(7.5, 10.0, 10.0, 10.0)	(7.50, 10.00, 10.00, 10.00)
Need of waste disposal	VL	(7.5, 10.0, 10.0, 10.0)	L	(5.0, 7.5, 7.5, 10.0)	G	(5.0, 7.5, 7.5, 10.0)	(6.00, 8.50, 8.50, 10.00)
Implementation cost	VH	(0.0, 0.0, 0.0, 2.5)	VH	(0.0, 0.0, 0.0, 2.5)	VH	(0.0, 0.0, 0.0, 2.5)	(0.00, 0.00, 0.00, 2.50)
Availability of funds	L	(5.0, 7.5, 7.5, 10.0)	F	(2.5, 5.0, 5.0, 7.5)	G	(5.0, 7.5, 7.5, 10.0)	(2.25, 4.75, 4.75, 7.25)
Economic value (PW, IRR, B/C)	VG	(7.5, 10.0, 10.0, 10.0)	VG	(7.5, 10.0, 10.0, 10.0)	VH	(7.5, 10.0, 10.0, 10.0)	(7.50, 10.00, 10.00, 10.00)
Compatibility with the national energy policy objectives	VH	(7.5, 10.0, 10.0, 10.0)	VH	(7.5, 10.0, 10.0, 10.0)	VH	(7.5, 10.0, 10.0, 10.0)	(7.50, 10.00, 10.00, 10.00)
Political acceptance	H	(5.0, 7.5, 7.5, 10.0)	H	(5.0, 7.5, 7.5, 10.0)	VH	(7.5, 10.0, 10.0, 10.0)	(5.75, 8.25, 8.25, 10.00)
Social acceptance	H	(5.0, 7.5, 7.5, 10.0)	VH	(7.5, 10.0, 10.0, 10.0)	VH	(7.5, 10.0, 10.0, 10.0)	(6.50, 9.00, 9.00, 10.00)
Labour impact	G	(5.0, 7.5, 7.5, 10.0)	M	(2.5, 5.0, 5.0, 7.5)	G	(5.0, 7.5, 7.5, 10.0)	(4.25, 6.75, 6.75, 9.25)

Table 2. The pair-wise comparisons of “Socio-Political”

	Compatibility with the national energy policy objectives		Political acceptance		Social acceptance		Labour impact	
	Scale	STFN	Scale	STFN	Scale	STFN	Scale	STFN
Compatibility with the national energy policy objectives	E1	(1, 2)	(1, 1, 2, 2)	(0.75, 1)	(0.75, 0.75, 1, 1)	(2, 3)	(2, 2, 3, 3)	
	E2	1	(1, 1, 1, 1)	(2, 3)	(2, 2, 3, 3)	(3, 4)	(3, 3, 4, 4)	
	E3	(2, 3)	(2, 2, 3, 3)	(2, 3)	(2, 2, 3, 3)	(2, 3)	(2, 2, 3, 3)	
	Aggregation	1.00	(1.30, 1.30, 2.00, 2.00)	(1.50, 1.50, 2.20, 2.20)	(2.30, 2.30, 3.30, 3.30)			
Political acceptance	E1	(0.9, 1)	(0.9, 0.9, 1, 1)	(0.9, 1)	(0.9, 0.9, 1, 1)			
	E2	(0.75, 1)	(0.75, 0.75, 1, 1)	(2, 3)	(2, 2, 3, 3)			
	E3	1	(1, 1, 1, 1)	(2, 3)	(2, 2, 3, 3)			
	Aggregation	1.00	(0.89, 0.89, 1.00, 1.00)	(1.56, 1.56, 2.20, 2.20)				
Social acceptance	E1	1	(1, 1, 1, 1)					
	E2	(3, 4)	(3, 3, 4, 4)					
	E3	(2, 3)	(2, 2, 3, 3)					
	Aggregation	1.00	(1.90, 1.90, 2.50, 2.50)					
Labour impact	E1							
	E2							
	E3							
	Aggregation			1.00				

1.00

For example, the STFNN scale of comparing “Political Acceptance” with “Social Acceptance” is aggregated as follows:

$$\begin{aligned}\tilde{a}_{23} &= [(0.9, 0.9, 1.0, 1.0) \otimes 0.4] \oplus [(0.75, 0.75, 1.0, 1.0) \otimes 0.3] \oplus [(1, 1, 1.0, 1.0) \otimes 0.3]; \\ \tilde{a}_{23} &= (0.885, 0.885, 1.00, 1.00).\end{aligned}$$

Then STFNN scale of comparisons should be defuzzified. By using Eq. (5) in Appendix-B, the STFNN scale of comparing “Political Acceptance” with “Social Acceptance” is defuzzified as:

$$a_{2,3} = \frac{0.885 + 2(0.885 + 1) + 1}{6} = 0.9425.$$

The pairwise comparisons matrix of “Socio-Political” is obtained by using Eqs. (5) and (6) in Appendix B as follows:

$$A_{\text{Socio-Political}} = \begin{bmatrix} 1.00 & 1.65 & 1.85 & 2.80 \\ 0.61 & 1.00 & 0.94 & 1.88 \\ 0.54 & 1.06 & 1.00 & 2.20 \\ 0.36 & 0.53 & 0.46 & 1.00 \end{bmatrix}.$$

By taking into account this matrix and using Eq. (7) in Appendix B the weights of the sub-criteria of “Socio-Political” are calculated as follows:

$$w = \{0.395, 0.235, 0.244, 0.126\}.$$

The final weights of the criteria are calculated by using Eq. (8) in Appendix B. Then the \tilde{FS} of Solar Energy is calculated by using Eq. (9) in Appendix B as follows:

$$\tilde{FS}_{\text{Solar}} = (5.83, 8.27, 8.27, 9.59).$$

\tilde{FS} values of the other renewable energy alternatives are also calculated and the results are shown in Table 3.

Table 3. Fuzzy scores of renewable energy alternatives

Energy	\tilde{FS}
Wind	(6.24, 8.74, 8.74, 9.97)
Solar	(5.83, 8.27, 8.27, 9.59)
Biomass	(5.25, 7.75, 7.75, 9.78)
Geothermal	(4.14, 6.64, 6.64, 8.92)
Hydropower	(4.05, 6.32, 6.32, 8.69)

The membership functions (MFs) of these fuzzy scores are shown in Figure 6.

In the last step of the proposed methodology the fuzzy scores need to be ranked. The method explained in Appendix B is used to rank the fuzzy scores and the ranking results are summarized in Table 4.

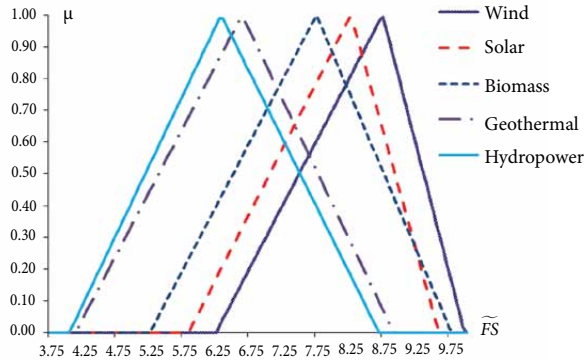


Fig. 6. Membership functions of fuzzy scores for renewable energy alternatives

Table 4. The ranking results for renewable energy alternatives

Energy Alternative	Fuzzy Scores	D_{max}	D_{min}	Ranking
Wind	(6.24, 8.74, 8.74, 9.97)	1.704	8.449	1
Solar	(5.83, 8.27, 8.27, 9.59)	2.109	8.019	2
Biomass	(5.25, 7.75, 7.75, 9.78)	2.483	7.673	3
Geothermal	(4.14, 6.64, 6.64, 8.92)	3.509	6.631	4
Hydropower	(4.05, 6.32, 6.32, 8.69)	3.735	6.394	5

According to Table 4 the “Wind Energy” is determined as the most appropriate renewable energy alternative for Turkey in the future. The “Solar Energy” alternative is determined as the second most suitable alternative. The ranking of energy alternatives is determined as follows: {Wind – Solar – Biomass – Geothermal – Hydropower}.

2.3. Sensitivity analysis

Since the final ranking of the alternatives are highly dependent on the weights of the experts, a sensitivity analysis based on experts’ weight is performed in this section. For this aim some different cases are considered. For this purpose, the weights of the experts are separately altered, between 0.1 and 0.8. The results for these cases with respect to ranking of the renewable energy alternative are summarized in Table 5.

Table 5. Results of sensitivity analysis based on experts’ weights

Case-1 ($E_1 = 0.8; E_2 = 0.1; E_3 = 0.1$)			Case-2 ($E_1 = 0.6; E_2 = 0.2; E_3 = 0.2$)		
Energy	Fuzzy Scores	Ranking	Energy	Fuzzy Scores	Ranking
Wind	(6.42, 8.92, 8.92, 9.96)	1	Wind	(6.32, 8.82, 8.82, 9.97)	1
Solar	(6.12, 8.56, 8.56, 9.64)	2	Solar	(5.98, 8.42, 8.42, 9.62)	2
Biomass	(5.2, 7.7, 7.7, 9.89)	3	Biomass	(5.22, 7.72, 7.72, 9.83)	3
Geothermal	(3.87, 6.37, 6.37, 8.79)	5	Geothermal	(4, 6.5, 6.5, 8.85)	5
Hydropower	(4.34, 6.78, 6.78, 9.07)	4	Hydropower	(4.2, 6.56, 6.56, 8.89)	4

Continued Table 5

Case-3 ($E_1 = 0.3; E_2 = 0.4; E_3 = 0.3$)			Case-4 ($E_1 = 0.1; E_2 = 0.6; E_3 = 0.3$)		
Energy	Fuzzy Scores	Ranking	Energy	Fuzzy Scores	Ranking
Wind	(6.18, 8.68, 8.68, 9.98)	1	Wind	(6.05, 8.55, 8.55, 9.99)	1
Solar	(5.75, 8.19, 8.19, 9.58)	2	Solar	(5.56, 8, 8, 9.56)	2
Biomass	(5.25, 7.75, 7.75, 9.73)	3	Biomass	(5.26, 7.76, 7.76, 9.64)	3
Geothermal	(4.18, 6.68, 6.68, 8.93)	4	Geothermal	(4.28, 6.78, 6.78, 8.97)	4
Hydropower	(3.99, 6.22, 6.22, 8.6)	5	Hydropower	(3.86, 5.97, 5.97, 8.35)	5
Case-5 ($E_1 = 0.1; E_2 = 0.8; E_3 = 0.1$)			Case-6 ($E_1 = 0.2; E_2 = 0.4; E_3 = 0.4$)		
Energy	Fuzzy Scores	Ranking	Energy	Fuzzy Scores	Ranking
Wind	(5.93, 8.43, 8.43, 9.99)	1	Wind	(6.17, 8.67, 8.67, 9.98)	1
Solar	(5.52, 7.97, 7.97, 9.57)	2	Solar	(5.68, 8.11, 8.11, 9.57)	2
Biomass	(5.12, 7.62, 7.62, 9.54)	3	Biomass	(5.31, 7.81, 7.81, 9.73)	3
Geothermal	(4.18, 6.68, 6.68, 8.88)	4	Geothermal	(4.28, 6.78, 6.78, 8.99)	4
Hydropower	(3.96, 6.07, 6.07, 8.42)	5	Hydropower	(3.88, 6.05, 6.05, 8.45)	5
Case-7 ($E_1 = 0.2; E_2 = 0.2; E_3 = 0.6$)			Case-8 ($E_1 = 0.1; E_2 = 0.1; E_3 = 0.8$)		
Energy	Fuzzy Scores	Ranking	Energy	Fuzzy Scores	Ranking
Wind	(6.29, 8.79, 8.79, 9.97)	1	Wind	(6.37, 8.87, 8.87, 9.96)	1
Solar	(5.71, 8.13, 8.13, 9.56)	2	Solar	(5.64, 8.05, 8.05, 9.53)	3
Biomass	(5.44, 7.94, 7.94, 9.81)	3	Biomass	(5.58, 8.08, 8.08, 9.85)	2
Geothermal	(4.36, 6.86, 6.86, 9.07)	4	Geothermal	(4.5, 7, 7, 9.18)	4
Hydropower	(3.79, 5.96, 5.96, 8.39)	5	Hydropower	(3.63, 5.73, 5.73, 8.2)	5
Case-9 ($E_1 = 0.1; E_2 = 0.2; E_3 = 0.7$)			Case-10 ($E_1 = 0.7; E_2 = 0.1; E_3 = 0.2$)		
Energy	Fuzzy Scores	Ranking	Energy	Fuzzy Scores	Ranking
Wind	(6.3, 8.8, 8.8, 9.97)	1	Wind	(6.39, 8.89, 8.89, 9.96)	1
Solar	(5.63, 8.05, 8.05, 9.54)	3	Solar	(6.06, 8.5, 8.5, 9.63)	2
Biomass	(5.51, 8.01, 8.01, 9.81)	2	Biomass	(5.24, 7.74, 7.74, 9.88)	3
Geothermal	(4.46, 6.96, 6.96, 9.14)	4	Geothermal	(3.96, 6.46, 6.46, 8.84)	5
Hydropower	(3.67, 5.78, 5.78, 8.23)	5	Hydropower	(4.24, 6.64, 6.64, 8.97)	4

The sensitivity results are also summarized as in Fig. 7. The five cases for this analysis are graphically illustrated in Fig. 7. Case-0 represents the current situation of the results where the ranking is {Wind – Solar – Biomass – Geothermal – Hydropower}. When the experts' weights are changed as shown in Case-1 ($E_1 = 0.8; E_2 = 0.1; E_3 = 0.1$), the renewable energy alternative *Geothermal*, is determined as the worst alternative for Turkey. As it seen from Fig. 7, the alternative *Hydropower*, is determined as the worst renewable energy alternative for Turkey except from Case-1.

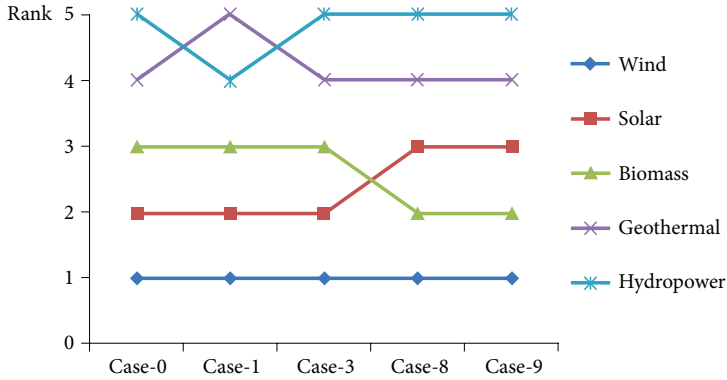


Fig. 7. The ranking of renewable energy alternatives based on sensitivity cases

Wind energy alternative is always determined as the best alternative whatever the weights for experts are. When the experts' weights are changed as shown in Case-8 ($E_1 = 0.1; E_2 = 0.1; E_3 = 0.8$) and Case-9 ($E_1 = 0.1; E_2 = 0.2; E_3 = 0.7$), the renewable energy alternative *Biomass* is more preferable than *Solar* energy. The ranking of the renewable energy alternatives is obtained as $Wind > Biomass > Solar > Geothermal > Hydropower$ for these cases.

Conclusions

It is well accepted that renewable energy alternatives have advantages over conventional energy systems in terms of environmental acceptability. Renewable energy investments have been increasing in Turkey. The selection of the suitable renewable energy alternative is very important to plan future's energy consumption. Since the most forms of renewable energy alternatives are dependent on multicriteria decision making, this paper is concerned with using MACBETH and fuzzy AHP multicriteria methods to evaluate renewable energy resources for Turkey.

In this paper, we evaluated the renewable energy alternatives *Wind, Solar, Biomass, Geothermal* and *Hydropower* by using two multicriteria decision making methodologies based on linguistic evaluations. The ranking order of the alternatives has been obtained by using MACBETH as follows: When Technological criterion is considered, the ranking order of alternatives is $Wind > Solar > Biomass > Geothermal > Hydropower$. When Environmental criterion is considered, the ranking order of alternatives is the same as those of technological criterion. However, *Wind* energy alternative is more dominant to the others in this case. When Socio-political criterion is considered, the ranking order is $Wind > Solar > Biomass > Hydropower > Geothermal$. And finally when Economical criterion is considered, the ranking order becomes $Hydropower > Wind > Solar > Biomass > Geothermal$.

The judgments of experts are usually vague in energy decision making problems. As it is relatively difficult for experts to provide exact values for the criteria, the evaluation for the alternative energy policies should be expressed in linguistic terms. In this paper these methods are applied to the selection problem for renewable energy alternatives by using

only linguistic evaluations. The proposed fuzzy AHP based multicriteria decision making methodology determined the ranking of renewable alternative as {Wind – Solar – Biomass – Geothermal – Hydropower}. Wind and Solar Energy alternatives are determined as the most suitable renewable alternatives, respectively for Turkey. This result confirms that wind energy causes no emissions and will be the most suitable alternative to resolve Turkey's energy problem in the future. One of the major contributions of wind energy to environmental protection is the decrease in CO₂ emission.

In the application, MACBETH and Fuzzy AHP have given the same ranking order of energy alternatives, even though the two methods are based on different evaluation approaches. This result will cause decision makers to give more reliable and confident decisions in selecting an energy alternative. If we had a different ranking order, decision makers would need a deeper analysis by examining the sources of differences.

In the future research, we suggest the other fuzzy MCDM approaches such as TOPSIS, VIKOR, PROMETHEE, ELECTRE, etc. to test and compare their results with ours.

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Appendix A

MACBETH multicriteria method

The MACBETH method (Measuring Attractiveness by a Categorical Based Evaluation Technique) has been recently proposed by Bana e Costa *et al.* (2003). This method has been widely implemented in consulting projects in the field of the evaluation of public policies, quality management, and investment strategies. This method appears particularly adapted for the aggregation of evaluation criteria when both absolute and relative information are required (positioning the alternatives taking into account specific targets) and when various types of quantitative and qualitative data have to be processed. Additionally the MACBETH method is associated to a user friendly decision support system called M-MACBETH which helps with the implementation of the whole multicriteria evaluation-aiding process. The method relies on a cardinal multi-criteria aggregation procedure. At first its aim is to translate the performance of an alternative regarding each criterion into a new performance representing the attractiveness of the alternative on a normalized scale. Secondly “scale constants” (weights) are determined for each evaluation criterion in order to proceed to a weighted sum of the normalized scales. One of the particularities of the MACBETH method is the introduction of

two reference levels that have to be defined for each evaluation criterion. One level is called “acceptable” and the other level is called “satisfying”. In the case of the evaluation of renewable energy alternatives, the following definitions are chosen for these two levels: acceptable level which means that the level below that an important renewable energy selection effort will be required to select an alternative. Satisfying level, which means that the level above that criterion is a strong point of the technology and renewable energy selection for improving the performance regarding the studied criterion is not a priority. In MACBETH method, 7 semantic categories are used for qualifying the differences of attractiveness between alternatives: “extreme”, “very strong”, “strong”, “moderate”, “weak”, “very weak”, “no difference” (Roubens *et al.* 2006; Clivillé *et al.* 2007).

MACBETH procedure consists of four main steps (Bana e Costa *et al.* 1999, 2003, 2004; Bana e Costa, Manuel 2004):

1. Context definition;
2. Identification of the Objective, Criteria and Alternatives;
3. Quantification in parallel with:
 - i. The vector of elementary expressions.
 - ii. The weights of the weighted arithmetic mean (WAM);
4. Calculation of the aggregated performance associated to different situations (alternatives).

The verification of judgments’ consistency is made in Step 3. In the first step, the DM is asked to determine the preferences of the alternatives for each criterion i of the context and then, the DM is asked to express the strength of the judgments that he/she provided in the previous stage. Let p_i^k be the performance expression of the k^{th} alternative for criterion i . Suppose the DM prefers the alternative k to the alternative l , for criterion i . Therefore, it means: $A^k \succ A^l \Leftrightarrow p_i^k \succ p_i^l$. And if the DM finds the two alternatives equivalent for the criterion i , then $A^k \approx A^l \Leftrightarrow p_i^k = p_i^l$. In addition to that information, DM will characterize the strength of his judgments with a level of strength that can take values from zero to six (from the least to the strongest level) according to the seven semantic categories of difference of attractiveness and zero for a null strength. This level will be denoted with h . Therefore, if the DM prefers alternative k to alternative l for criterion i , with a strength h , then this will give the following equation where α is a coefficient necessary to meet the condition p^k and $p^l \in [0;1]$ $A^k \succ^h A^l \Leftrightarrow p_i^k - p_i^l = h\alpha$.

Suppose that the DM gives the following preferences and the strength of preferences for three alternatives according to some criteria (Bana e Costa *et al.* 1999, 2003, 2004; Bana e Costa, Manuel 2004):

$$Good \succ^3 A^3 \succ^2 A^2 \succ^1 A^1 \succ^2 Neutral$$

Therefore, the following system of independent equations can be retrieved:

$$\begin{cases} p^{Good} - p^3 = 1 - p^3 = 3\alpha; \\ p^3 - p^2 = 2\alpha; \\ p^2 - p^1 = \alpha; \\ p^1 - p^{Neutral} = p^1 - 0 = 2\alpha. \end{cases}$$

Hence the following results of the elementary performance expressions are defined along interval scales defined on the interval $[0;1]$ in a commensurate way:

$$p^1 = \frac{1}{4}, p^2 = \frac{3}{8}, p^3 = \frac{5}{8}, \left(\alpha = \frac{1}{8} \right).$$

In order to determine the Weighted Arithmetic Means (WAM), MACBETH proposes to consider some particular and possibly fictive situations, S , in which associated the elementary expression vectors are so that the aggregated performance expression is reduced simply to $p_{Ag}^i = w_i$ where p_{Ag}^i is aggregated performance from the vector where only $p_i = 1$ and all other $p_j = 0$ with $j \neq i$. The DM will give the preference relations and their strengths that each of them will be as follows and all together they will provide us a system of n independent equations:

$$p_{Ag}^i - p_{Ag}^g = ha = w_i - w_g.$$

Suppose that the DM provided the following information:

$$S^{(0,1,0)} \succ \text{moderate } S^{(1,0,0)} \succ \text{strong } S^{(0,0,1)} \succ \text{weak } S^{(0,0,0)}.$$

Hence the following system of equations and the WAM weights can be found (Bana e Costa et al. 1999, 2003, 2004; Bana e Costa, Manuel 2004):

$$\begin{cases} p_{Ag}^{(0,0,1)} - p_{Ag}^{(1,0,0)} = 3\alpha = w_2 - w_1; \\ p_{Ag}^{(1,0,0)} - p_{Ag}^{(0,1,0)} = 4\alpha = w_1 - w_3; \\ p_{Ag}^{(0,1,0)} - p_{Ag}^{(0,0,0)} = 2\alpha = w_3; \\ w_1 + w_2 + w_3 = 1. \end{cases}$$

$$w_1 = \frac{6}{17}, w_2 = \frac{9}{17}, w_3 = \frac{2}{17}, \left(\alpha = \frac{1}{17} \right).$$

The aggregated performance of the alternative k is calculated as follows (Bana e Costa et al. 2004):

$$p_{Ag}^k = \sum_{i=1}^n w_i p_i^k. \quad (1)$$

In the above expressed MACBETH Method, the aggregated performance of the alternatives can also be determined by M-MACBETH software, in order to build a scale of attractiveness for each evaluation criterion using linear programming models indicated above, in order to build a scale of attractiveness for each evaluation criterion. These scales are normalized with the acceptable reference level at 0 and the satisfying reference level at 100.

At the end of this step, five new numerical scales of attractiveness are then obtained (corresponding to the five technical evaluation criteria), each one being normalized with the acceptable reference level at 0 and the satisfying reference level at 100 (Bana e Costa et al. 1999, 2003, 2004; Bana e Costa, Manuel 2004).

Appendix B

A fuzzy AHP based multicriteria method

In this subsection, a fuzzy multicriteria decision making procedure proposed by Zeng *et al.* (2007) is reconstructed to select the most appropriate renewable energy alternative. A modified fuzzy AHP method is applied to work out the priority weights of energy alternatives. In a typical AHP method, experts have to give a definite number within a 1–9 scale to the pairwise comparison so that the priority vector can be computed. Assume two factors are equally important, then it has a scale of 1; if a factor is weakly more important than another, then it has a scale of 3; scales of 5, 7 and 9 are used to describe strongly more important, very strongly more important and absolutely more important, respectively. 2, 4, 6 and 8 are used to compromise slight differences between two classifications. The corresponding reciprocals 1, 1/2, 1/3, ..., 1/9 are used for the reverse comparisons. However, factor comparisons often involve some amount of uncertainty and subjectivity. For example, an expert may know one factor is more important than another; however, the expert cannot give a definite scale to the comparison because the expert is not sure about the degree of one factor over another. The expert probably provides a range of 3–7 to describe these two factors. Sometimes, experts cannot compare two factors due to the lack of adequate information. In this case, a classical AHP method has to be discarded due to the existence of fuzzy or incomplete comparisons. A fuzzy AHP which is an important extension of the typical AHP method approach may therefore be expected. In this study, the most appropriate renewable energy alternative for Turkey is determined by the modified fuzzy AHP proposed by Zeng *et al.* (2007) because it includes simplified fuzzy operations and similar steps to classical AHP.

In this method, fuzzy aggregation is used to create group decisions, and then defuzzification is employed to transform the fuzzy scales into crisp scales for the computation of priority weights. The group preference of each factor is then calculated by applying fuzzy aggregation operators, i.e. fuzzy multiplication and addition operators. The steps of the proposed methodology are as follows (Kahraman *et al.* 2009; 2010a; Kahraman, Kaya 2010a, b; Kaya 2011):

Step 1. Measure factors in the hierarchy. The experts are required to provide their judgments on the basis of their knowledge and expertise for each factor at the bottom level in the hierarchy. The experts can provide a precise numerical value, a range of numerical values, a linguistic term or a fuzzy number.

Step 2. Compare factors using pair-wise comparisons. The experts are required to compare every factor pair-wise in their corresponding section structured in the hierarchy and calibrate them on either a crisp or a fuzzy scale.

Step 3. Convert preferences into the standardized trapezoidal fuzzy number (STFN). As described in Steps 1 and 2, because the values of factors provided by experts are crisps, e.g. a numerical value, a range of numerical value, a linguistic term or a fuzzy number, the STFN is employed to convert these experts' judgments into a universal format for the composition

of group preferences. Let U be the universe of discourse, $U = [0, u]$. A STFAN can be defined as $\tilde{A} = (a, b, c, d)$, where $0 \leq a \leq b \leq c \leq d$ as shown in Fig. B1, and its membership function is as follows:

$$\mu_{\tilde{A}}(x) = \begin{cases} \frac{(x-a)}{(b-a)}, & \text{for } a \leq x \leq b; \\ 1, & \text{for } b \leq x \leq c; \\ \frac{(d-x)}{(d-c)}, & \text{for } c \leq x \leq d; \\ 0, & \text{for } \textit{Otherwise}. \end{cases} \quad (2)$$

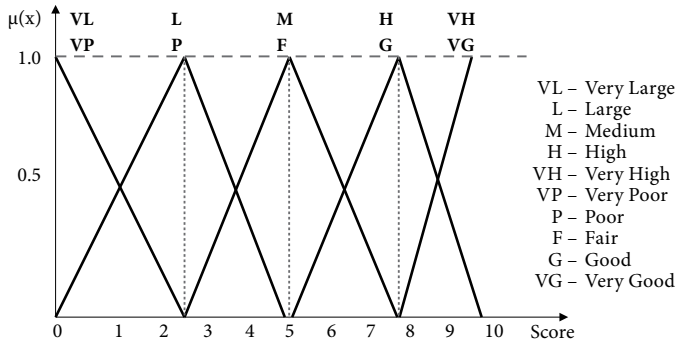


Fig. B1. Membership functions for evaluation

Step 4. Aggregate individual STFANs into group STFANs. The aim of this step is to apply an appropriate operator to aggregate individual preferences made by individual experts into a group preference of each factor. The aggregation of STFAN scores is performed by applying the fuzzy weighted trapezoidal averaging operator, which is defined by:

$$\tilde{S}_i = \tilde{S}_{i1} \otimes c_1 \oplus \tilde{S}_{i2} \otimes c_2 \oplus \dots \oplus \tilde{S}_{im} \otimes c_m, \quad (3)$$

where \tilde{S}_i is the fuzzy aggregated score of the factor F_i , $\tilde{S}_{i1}, \tilde{S}_{i2}, \dots, \tilde{S}_{im}$ are the STFAN scores of the factor F_i measured by m experts E_1, E_2, \dots, E_m , respectively, \otimes and \oplus denote the fuzzy multiplication operator and the fuzzy addition operator, respectively, and c_1, c_2, \dots, c_m are contribution factors (CFs) allocated to experts, E_1, E_2, \dots, E_m and $c_1 + c_2 + \dots + c_m = 1$. Similarly, the aggregation of STFAN scales is defined as:

$$\tilde{a}_{ij} = \tilde{a}_{ij1} \otimes c_1 \oplus \tilde{a}_{ij2} \otimes c_2 \oplus \dots \oplus \tilde{a}_{ijm} \otimes c_m, \quad (4)$$

where \tilde{a}_{ij} is the aggregated fuzzy scale of F_i comparing to F_j ; $i, j = 1, 2, \dots, n$; $\tilde{a}_{ij1}, \tilde{a}_{ij2}, \dots, \tilde{a}_{ijm}$ are the corresponding STFAN scales of F_i comparing to F_j measured by experts E_1, E_2, \dots, E_m , respectively.

Step 5. Defuzzify the STFAN scales. In order to convert the aggregated STFAN scales into matching crisp values that can adequately represent the group preferences, a proper defuzzi-

fication is needed. Assume an aggregated STFN scale $\tilde{a}_{ij} = (a_{ij}^l, a_{ij}^m, a_{ij}^n, a_{ij}^u)$, the matching crisp value a_{ij} can be obtained:

$$a_{ij} = \frac{a_{ij}^l + 2(a_{ij}^m + a_{ij}^n) + a_{ij}^u}{6}, \tag{5}$$

where $a_{ii} = 1, a_{ji} = 1/a_{ij}$.

Consequently, all the aggregated fuzzy scales $\tilde{a}_{ij} (i, j = 1, 2, \dots, n)$ are transferred into crisp scales a_{ij} within the range of $[0, 9]$.

Step 6. Calculate the priority weights of factors. Let F_1, F_2, \dots, F_n be a set of factors in one section, a_{ij} is the defuzzified scale representing the quantified judgment on F_i comparing to F_j . Pair-wise comparisons between F_i and F_j in the same section thus yields a n-by-n matrix defined as follows:

$$A = a_{ij} = \begin{matrix} & \begin{matrix} F_1 & F_2 & \dots & F_n \end{matrix} \\ \begin{matrix} F_1 \\ F_2 \\ \dots \\ F_n \end{matrix} & \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \dots & 1 \end{bmatrix} \end{matrix}, \quad i, j = 1, 2, \dots, n, \tag{6}$$

where $a_{ii}=1, a_{ji}=1/a_{ij}$.

The priority weights of factors in the matrix A can be calculated by using the arithmetic averaging method:

$$w_i = \frac{1}{n} \sum_{j=1}^n \frac{a_{ij}}{\sum_{k=1}^n a_{kj}}, \quad i, j = 1, 2, \dots, n, \tag{7}$$

where w_i is the section weight of F_i . Assume F_i has t upper sections at different level in the hierarchy, and $w_{section}^{(i)}$ is the section weight of the i^{th} upper section which contains F_i in the hierarchy. The final weight w'_i of F_i can be derived by:

$$w'_i = w_i \times \prod_{i=1}^t w_{section}^{(i)}. \tag{8}$$

All individual upper section weights of $w_{section}^{(i)}$ can also be derived by Eq. (7) to prioritize sections within the corresponding cluster in the hierarchy.

Step 7. Calculate final fuzzy scores. When the scores and the priority weights of factors are obtained, the final fuzzy scores (\tilde{FS}) can be calculated by:

$$(\tilde{FS}) = \sum_{i=1}^n \tilde{S}_i w'_i \quad i = 1, 2, \dots, n. \tag{9}$$

Step 8. This step is added into proposed method to compare the (\tilde{FS}) values using an outranking method. In this paper a method proposed by Tran and Duckstein (2002) is used

to rank final fuzzy scores. The method is based on the comparison of distances from fuzzy numbers (FNs) to some predetermined targets: the crisp maximum (*Max*) and the crisp minimum (*Min*). The idea is that a FN is ranked first if its distance to the crisp maximum (D_{max}) is the smallest but its distance to the crisp minimum (D_{min}) is the greatest. If only one of these conditions is satisfied, a FN might be outranked by the others depending upon context of the problem (for example, the attitude of the decision-maker in a decision situation).

The *Max* and *Min* are chosen for STFNs as follows:

$$\begin{aligned} Max(I) &\geq \sup \left(\bigcup_{i=1}^I s(\tilde{A}_i) \right); \\ Min(I) &\leq \inf \left(\bigcup_{i=1}^I s(\tilde{A}_i) \right), \end{aligned} \quad (10)$$

where $s(A_i)$ is the support of FNs A_i , $I = 1, \dots, I$. Then D_{max} and D_{min} of fuzzy number $\tilde{A}(a_1, a_2, a_3, a_4)$ can be computed as follows:

$$D^2(\tilde{A}, M) = \begin{cases} \left(\frac{a_2 + a_3 - M}{2} \right)^2 + \frac{1}{2} \left(\frac{a_2 + a_3 - M}{2} \right) \times [(a_4 - a_3) - (a_2 - a_1)] + \\ \frac{1}{3} \left(\frac{a_3 - a_2}{2} \right)^2 + \frac{1}{6} \left(\frac{a_3 - a_2}{2} \right) \times [(a_4 - a_3) + (a_2 - a_1)] + \\ \frac{1}{9} [(a_4 - a_3)^2 + (a_2 - a_1)^2] - \frac{1}{9} [(a_2 - a_1) \times (a_4 - a_3)] \end{cases}, \quad (11)$$

where M is either *Max* or *Min*, hence:

$$D_{max} = \sqrt{D^2(\tilde{A}, Max)} \quad \text{and} \quad D_{min} = \sqrt{D^2(\tilde{A}, Min)}. \quad (12)$$

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