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A neuro-fuzzy program approach for evaluating electric power generation systems

Rustom Mamlook [a,*], Bilal A. Akash [b], Mousa S. Mohsen [c]

[a] Department of Electrical and Computer Engineering, Applied Science University, Amman, 11931, Jordan
[b] College of Technology, University of Qatar, Doha, Qatar
[c] Department of Mechanical Engineering, Hashemite University, Zarqa, Jordan

Abstract

This paper uses neuro-fuzzy programming to perform a comparison between the different electricity power generation options for Jordan. Different systems are considered: in addition to fossil fuel power plants, nuclear, solar, wind, and hydropower systems are evaluated. Based on cost-to-benefit ratios, results show that solar, wind, and hydropower are considered to be the best systems for electricity power generation. On the other hand, nuclear electricity turns out to be the worst choice, followed by fossil fuel electric power.

1. Introduction

Nearly all the generated electric power in Jordan is produced from power plants that use fossil fuels. The most popular fuels are heavy fuel oil and diesel fuels, which are imported petroleum products. However, this option is not very attractive since Jordan's spending on petroleum is more than 50% of its export earnings. Unlike other countries of the Middle East, Jordan is non-oil producing country and oil must be imported. Also, using foreign fossil fuels escalates environmental and unemployment issues that Jordan must face.

This paper uses the neuro-fuzzy approach to determine the most suitable option or options for electricity production and to provide solutions to some of the current or future energy issues that Jordan faces. These options may include nuclear, solar, wind, or hydroelectric power generation systems.

Our research using a neuro-fuzzy method is aimed to direct the energy decision-makers in Jordan to the most appropriate system for electric power generation.

* Corresponding author. Tel.: +962-6523-7181; fax: +962-6523-2899.
E-mail address: rstmamlk@asu.edu.jo (R. Mamlook).

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2. Electric power generation for Jordan

The annual electrical energy consumption in Jordan is roughly 6000 GWh. The National Electric Power Company (NEPCO), which is the main electricity supplier in Jordan, supplies about 93% of this amount [1]. Other energy sources for electric power generation must be considered. In general, fossil fuels are non-renewable. They originate from the earth as a result of decomposition and chemical conversion of organic materials. Coal represents the largest fossil fuel energy resource in electric power generation [2]. Oil shale is a fossil fuel that exists in Jordan in abundance, but with unattractive physical and chemical properties. Firstly, like all oil shale, it has a low heating value due to its high ash content [3]. Secondly, Jordanian oil shale has a high sulfur content, ranging from 4 to 6% on mass basis [4]. Due to low petroleum prices worldwide, the utilization of solid fossil fuels, such as oil shale, is not presently feasible. Therefore, oil shale power plants can not be considered a competitive option [2]. Petroleum and natural gas (which is locally available in small amounts) are the main fuels used for electric power generation in Jordan in addition to small hydro-powered electricity generation plants.

Since the 1970s, solar energy has received the greatest attention of all renewable energy sources throughout the world. Many regard it as the primary solution for a cleaner environment and a possible alternative to fossil and nuclear fuels.

The Jordanian experience with electricity generation using solar and wind energies has been on the small and experimental scale. Many studies and experiences have shown that solar thermal power plants are some of the most economic forms of solar electricity generation. Solar energy can also be converted into electricity by photovoltaic cells, but this process is mostly convenient and suitable only for small applications. Stand-alone photovoltaic power systems have been proposed for electrification of remote areas located outside the electricity grid-connection supply system [5]. On the other hand, solar energy can be converted into thermal energy by means of solar collectors or concentrators. A working fluid is used to convert the thermal energy into mechanical energy, which is then converted into electricity. Unlike photovoltaics, large amounts of electrical power can be generated from such plants.

Like most countries in the Middle East, Jordan enjoys long periods of sunshine. The local weather has over 300 cloudless days per year. Future technology suggests that, for example, the Dead Sea itself can be used as a 450-km^2 solar lake, operating a 2500 MW power plant, if utilized properly [6]. There are a number of solar thermal power plants in operation around the world and they are found to be one of the most economical systems for generating electricity [7,8].

It is well established that wind energy resources are large for many different applications and globally widespread. It is clear that wind energy can be competitive in many locations [9] such as water pumping [10] and water desalination [11]. It can also be used for electrical power generation using a wind energy conversion system [12]. Wind power is expected to be one of the least expensive forms of new electrical generation in the twenty-first century [13]. With global efforts to restrict fossil fuel related energy systems and to reduce CO_2 emissions. Therefore, it will most likely encourage low cost wind systems. For example, large wind power plants at good wind sites using emerging technologies can deliver electricity into the utility grid at low prices that are becoming competitive with those of conventional power generation. Wind power plants can use hundreds of wind turbines that range in size from 50 to 500 kW each, and they can be located in certain remote areas. This plant's computerized and control center operates similar to that of fossil fuel plants, except it does not have to be in sight of its turbines. In a recent study, a model of a wind power plant for an isolated location was presented [14].

There are a number of sites in Jordan with potentially high wind speeds that can be utilized for this purpose [15]. Eleven wind sites were considered covering the entire country. The three most likely sites in Jordan are found to be Ras Muneef, Mafraq, and Aqaba. They have wind speeds that range from 4 to 23 m s^{-1} throughout 80% of the year.

Hydroelectric power plants can provide a basis for evaluating the potential of renewable sources of energy. When compared to other thermal power plants, they are found to be conventional and reliable. Some countries utilize this form of free natural energy into useful type of electrical power. For example, 11% of the electric power produced in the USA was provided by hydroelectric power as reported by Fraas in 1982 [16]. Egypt and Turkey, countries in the same general region as Jordan, also utilize this type of power for generating electricity at low costs. Therefore, Jordan must consider such source of energy. A number of studies were involved in utilizing hydro-power in Jordan for the purpose of electricity production [17], water desalination [18,19], or both [20]. These studies, primarily, considered the linkage of the Red and Dead Seas with a canal to generate hydropower. The Dead Sea is about 400 m below sea level (BSL) and is roughly 200 km to the north of the Gulf of Aqaba. It is an extension of the Red Sea with no outlet; its water level is a result of inflow and evaporation of water. For thousands of years the Dead Sea maintained equilibrium with the annual inflow and evaporation of water which resulted in a constant sea level. For example, in 1930 the surface of the Dead Sea was measured at its historical elevation of about 390 m B. Over the years, due to increase in population and agricultural development, water was diverted from its main tributary, the Jordan River, for irrigation neighboring regions. Therefore, its elevation was dropped, drastically to 408 m BSL in 1993. To halt this trend, it will be necessary to introduce a substantial amount of new water to the sea. Seawater from the Red Sea can be used as a source of water needed for diversion into the Dead Sea. This diversion can be used to both maintain the sea at its current level and thus stop its dropping, or even to bring it back to its level.

It is very well known fact that for those countries that rely on but do not have oil, nuclear power becomes a strategic as well as economic necessity [2]. Nuclear power plants can pay for their capital cost in a few short years. Thus, a less expensive electric power can be produced without relying on importing foreign oil, or at least the reduction in oil import. Some believe that one day oil will be depleted, and nuclear power becomes a must. Therefore, it is important to start this technology now in order to assure the country would not be left behind when the time comes to have to use nuclear technology.

Thus, nuclear power is bound to become the choice of power for the future. There are some difficulties that are associated with nuclear power, namely, waste disposal and safety. If this kind of energy becomes popular in most countries around the world, solutions to these problems become a must and thus are found.

3. The decision making methodology

3.1. Fuzzy logic

After Zadeh's work on fuzzy sets [21], many theories in fuzzy logic were developed in Japan, Europe, United States, and elsewhere. Since the 1970s Japanese researchers have been advancing the practical implementation of the fuzzy logic theory. They have been commercializing this technology and currently, there are over 2000 patents in the area from fuzzy air conditioner, to fuzzy washing machine, fuzzy toasters, fuzzy rice cookers, fuzzy vacuum cleaner, and many other industrial fuzzy control processes. They have a subway system that is totally controlled by fuzzy computer. It is smooth enough that riders do not need to hold straps and the controller makes 70% fewer judgmental errors in acceleration and braking than human operators are. The US Space Administration has been involved in the use of fuzzy logic in space control decision making. Energy consumption could be analyzed using fuzzy set [22]. Also systems could be controlled using fuzzy rules [23].

3.2. Neural networks

Neural networks are considered to be computational models, which consists of links connected nodes. Their structure is analogous to that of neural system in human brain, by which nodes correspond to neurons and links correspond to synapses that transmit signals between neurons. One of the major features of a neural network is its learning capability. Developing an insight about the meaning associated with each neuron and each weight is somewhat difficult. Therefore, neural networks are often presented as a black box. One may understand what the box does, but not necessarily how it is done, conceptually [24].

3.3. Neuro-fuzzy logic

Fuzzy rule based models are easy comprehend because it uses linguist terms and the structure of IF–THEN rules. Fuzzy logic does not come with a learning algorithm. The learning and identification of fuzzy models must have the capability to adopt techniques from other areas such as, linear system identification, statistics, etc. Since neural networks have the ability to learn, it natural to be engaged with fuzzy logic. This engagement has created a new terminology called 'neuro-fuzzy' method.

The neuro-fuzzy networks are not adoptive, and each must be built specifically for its intended use. Takagi and Hayashi made pioneer augmentation in development of neuro-fuzzy technology in the last decade [25,26]. Similarly, Jang developed ANFIS neuro-fuzzy system in the early 90s [27].

In order to compare objects (options) which are fuzzy, vague, or ambiguous we introduce a special notion of relativity [28]. Let p and q be variables defined on universe U, and define two pairwise functions, $f_q(p)$ and $f_p(q)$ as the membership functions of q with respect to p and also, p with respect to q, respectively. Then to do the measurement of the membership value of choosing p over q, we use the relativity function that is defined such as:

$$f(p|q)=\frac{f_q(p)}{\max[f_q(p),f_p(q)]} \tag{1}$$

This relative function $f(p|q)$ can be used as the membership of preferring p to q. For more than two variables, we define variables p_1, p_2,..., p_i, p_{i+1},..., p_m on the universe U. Let these variables be collected on the set S; where S=$p_1,p_2,...,p_i,p_{i+1},...,p_m$, and form a matrix of relativity values, $f(p_i|q_j)$ where i,j=1,2,..., m and p_i and q_j are defined on the universe U. This matrix will be an m by m matrix, and called the C matrix (C for comparison). This matrix can be used to rank many different fuzzy sets.

In order to determine the overall ranking, we find the largest or smallest values in each of the rows of the C matrix; i.e.,

$$C_j' = \max f(p_j|S), j = 1,2,...,m \tag{2}$$

or

$$C_j'' = \min f(p_j|S), j = 1,2,...,m \tag{3}$$

where C_j' or C_j'' is the membership ranking value for the jth variable. We use the maximum function when we are ranking different objects (options) in terms of their benefits, and on the other hand the minimum function is used when different objects (options) are ranked in terms of their costs.

The neuro-fuzzy logic decision selection of best electrical production option(s) in Jordan was applied according to their costs and benefits (Tables 1 and 2 in Appendix A). Data in Tables 1 and 2 are actual data obtained from National Electrical Power Company in Jordan [29]. Separately, we considered the benefits and costs. The cost-to-benefit ratios were also obtained. Our objective is to make the decision selection of the best electrical production options that cost less and have the most benefits.

The fuzzy logic method (Appendix B) was used to compare benefits (Table 1) of the electrical production options (P_1=nuclear; P_2=wind; P_3=solar; P_4=hydro; P_5=fossil fuel) in Jordan to decide which option has the preferable benefits. Many factors affect this decision. They include F_1=efficiency, F_2=reliability, F_3=availability of fuel, F_4=national economy, F_5=social benefits and F_6=safety. First, pairwise membership functions $fp_i(p_j)$, i,j=1, 2, 3, 4, 5, were determined using five fuzzy values [30] as shown in Fig. 1. These values represent the subjective benefits of appropriateness of each electrical production option when compared only one to another (Table 4).

Then we used Eq. (1) to calculate all of the relative values, Table 5 expresses these calculations, and this is the comparison (C) matrix. The additional column to the right of the C matrix is the maximum value of each rows (relative weights); C_j', j=1, 2, 3, 4, 5 in Eq. (2). Table 6 is determined using pairwise membership functions for all benefits criteria with respect to each other. Table

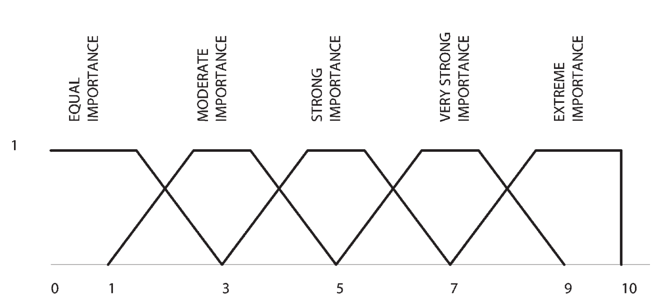

Fig. 1. Fuzzy pairwise comparison values.

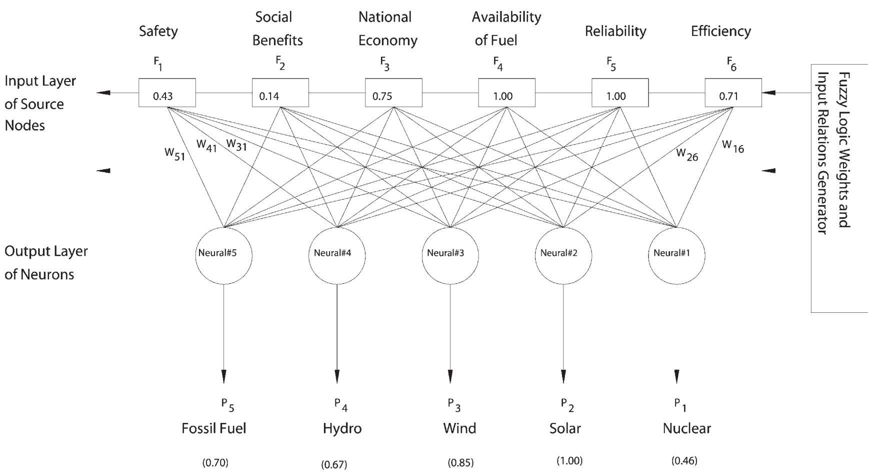

Fig. 2. Neuro-fuzzy network to make decision on best system based on benefit factors.

7 is determined using Eqs. (1) and (2) to obtain the relative weights. The overall relative weight factor was then obtained by using the results of Tables 5 and 7 (Table 8). Fig. 2 shows how these relative weight factors were used in neuro-fuzzy network to make the decision. In the figure each neural has a computational property that is introduced in Fig. 3. The neural is used as a fan out feedforward which makes it fast and does not require training [31]. 'Fan out' is a term used by Skapura [31] where each neural input must be distributed unaltered to other neural elements. The fuzzy logic was then used to compare costs (Table 2) of the electrical production options (P_1=nuclear; P_2=wind; P_3=solar; P_4=hydro; P_5=fossil fuel) in Jordan to decide which option has the lowest cost. Many factors affect this decision, including F_1=cost of fuel, F_2=hardware, F_3=maintenance and service, F_4=auxiliary system, and F_5=environmental constraints. First, pair-wise membership functions $fp_i(p_j)$, i,j=1, 2, 3, 4, 5, were determined using five fuzzy values (Fig. 1). These values represent the subjective cost appropriateness of each electrical production option when compared one to another (Table 4). Eq. (1) was then used to calculate all of the relative values. Table 5 expresses these calculations, this is the comparison (C) matrix. The extra column

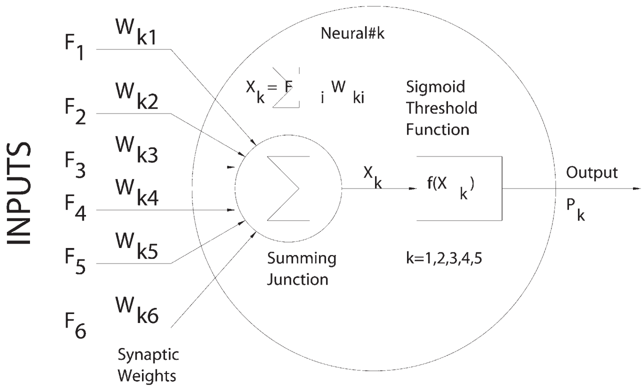

Fig. 3. Neuron computation structure.

to the right of the C matrix is the minimum value of each row; C_j'', j=1, 2, 3, 4, 5 in Eq. (3). Table 6 is determined using pairwise membership functions for all costs criteria with respect to each other. Table 7 is determined using Eqs. (1) and (3) to obtain the relative weights. The overall relative weight factor was then obtained using the results of Tables 5 and 7 (Table 9). Fig. 4 shows how these relative weight factors were used in neuro-fuzzy network to make the decision.

4. Results and conclusions

The fuzzy sets enabled us to condense large amount of data, collected to compare between the five electrical production systems in Jordan, into a smaller set of variable rules (see Appendix BFig. 1). From the results as presented in Figs. 2 and 4, one can note that the preferable option is to use solar system to produce electricity in Jordan. It has the maximum benefit factor of 1.00, while its cost factor is 0.20. Cost-to-benefit ratios are obtained and presented in Fig. 5. The minimum value is for solar energy at 0.200, followed by hydropower and wind energy, which have values of 0.27 each. Therefore, the next two options are the use of hydro and wind systems. Solar, wind, hydro, or all these three options could be used to produce electricity in Jordan with minimum cost, as presented by Fig. 4, and optimum benefits in terms of issues related to availability of fuel, national economy, social benefits, and safety (see Fig. 2). The worst option is found to be nuclear due to its high initial cost and safety factor. It is followed by fossil fuels.

One of the advantages of the neuro-fuzzy decision-maker (NFDM) method is presented. It uses fuzzy sets to condense large amount of data into smaller set of variable rules. NFDM uses minimum and maximum operations, which are easier and faster than average and sum operations that are used by other methods. Also, NFDM uses neural network to reach the decisions. Based on this method, the solar electrical production option was the best preferable option for Jordan. The second and third options were wind and hydro systems. In conclusion Jordan has the option of using solar, wind, and hydro to produce electricity. These results agreed with those obtained in a recent study by the authors using a different methodology known as the analytical hierarchy

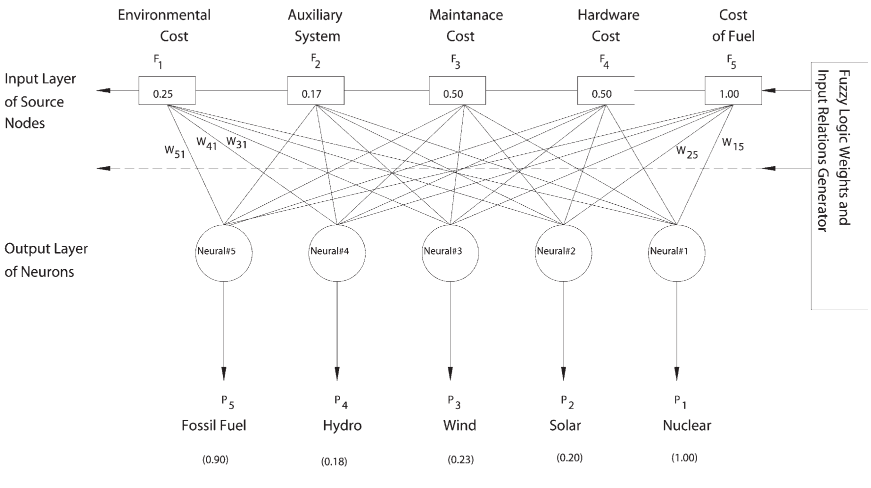

Fig. 4. Neuro-fuzzy network to make decision on best system based on cost factors.

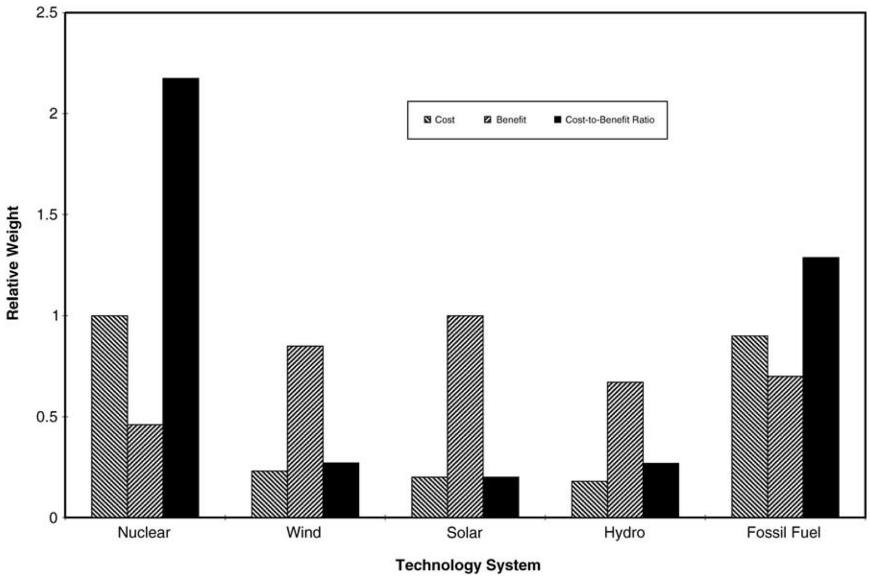

Fig. 5. Comparison of weight costs, weight benefits, cost-to-benefit weight ratios.

process (AHP) [32]. Similarly, the fuzzy sets methodology outlined in this paper (Appendix B) was also used in another paper on the evaluation of solar systems [33]. The results of this paper show that this method can be used in number of applications and it is not sensitive to the real input data. On the other hand they are sensitive to the relationship of one cost (or benefit) relative to the other.

Appendix A

A.1. Real data concerning cost and benefit of the systems

Actual data as obtained from National Electrical Company in Jordan [30] for the costs of the five electricity generating systems are shown in Table 1 below and the following two lists:

Table 1
Actual data for cost of the electricity generating systems in Jordan

Generating system	Cost of fuel	Hardware cost ($/kW)	Maintenance and service cost
Fossil fuel (diesel engine)	85 $/ton	450	0.042 $/kWh
Fossil fuel (fuel oil)	85 $/ton	750	0.035 $/kWh
Fossil fuel (gas)	174 $/ton	280	0.021 $/kWh
Fossil fuel (oil shale)	5 $/ton	1500	0.050 $/kWh
Wind	Zero	1000	0.010 $/kWh
Hydro	Zero	500	0.014 $/kWh
Solar	Zero	1500	0.040 $/kWh
Nuclear	Estimated very low	Estimated very high	Estimated very high

A.1.1. Auxiliary Systems:

The eight electricity generating systems are listed below based on the higher need of auxiliary systems:

- Wind and Solar
- Hydro
- Diesel Power Generation Systems and Gas Turbine
- Nuclear
- Fuel Oil Thermal Power Plants and Oil Shale

A.1.2. Environmental Constraints:

The eight electricity generating systems are decently listed below based on environmental constraints:

- Wind, Solar, and Hydro
- Gas Turbine
- Diesel Generation Sets
- Oil Shale
- Thermal Power Stations
- Nuclear

Actual data as obtained from National Electrical Company in Jordan [30] for the benefit of the eight electricity generating methods are shown in Table 2 below and the following three lists:

A.1.3. National Economy:

The eight electricity generating methods are listed below based on their higher effect on the national economy:

- Hydro, Wind and Solar
- Oil Shale

Table 2
Actual data for benefit of the electricity generating systems in Jordan

Generating system	Efficiency (%)	Reliability (%)
Fossil fuel (diesel engine)	36	85
Fossil fuel (fuel oil)	34	88
Fossil fuel (gas)	28	90
Fossil fuel (oil shale)	50	85
Wind	35	95
Hydro	40	80
Solar	30	40
Nuclear	43	Low

- Nuclear
- Thermal Power Stations, diesel Generation Sets, and Gas Turbine

A.1.4. Social Benefits and Safety:

The eight electricity generating systems are listed below based on their higher social benefits and safety:

- Wind, Solar, and Hydro
- Gas Turbine
- Diesel Generation Sets
- Oil Shale
- Thermal Power Stations
- Nuclear

A.1.5. Availability of Fuel:

The eight electricity generating systems are listed below based on fuel availability:

- Oil Shale
- Wind and Solar
- Nuclear
- Gas Turbine
- Hydro
- Diesel Generation Sets, and Thermal Power Station

Appendix B

B.1. Explaining fuzzy set methodology

A brief description of fuzzy sets, as a methodology for evaluating alternatives is outlined below:

1. The first step involves the composition or sustaining of the components of the problem or issue to be analyzed. This phase may involve a group decision making to explore the various perspectives of the problem. In this paper, the fuzzy method was composed of the following levels: goals, systems, and factors. However, these components are by no means exhaustive; other levels may be incorporated into the method such as strategies, scenarios, and/or characteristics.
2. The second step is to make pairwise comparisons; i.e., to compare the elements of a problem in pairs (as will be shown in the numerical example below) against a given goal or criterion. To perform pairwise comparisons, a matrix is used to compare different variables; this is done as follows:
   - Start at the top of the problem's structure to select the factor (F), which will be used for

Table 3
Sample matrix for fuzzy pairwise comparison

F	P_1	P_2	...	P_M
P_1	1			
P_2		1		
.			1	
P_M				1

Table 4
Sample fuzzy matrix comparing three elements for factor F

F	P_1	P_2	P_3
P_1	1	1/5	1/3
P_2	5	1	1/2
P_3	3	2	1
Column max value	5	2	1

making the first comparison. Then, from the level immediately below, take the elements to be compared for example, P_1, P_2, P_3,..., P_M. Considering that we have M elements.

- Arrange these elements in a matrix as shown in Table 3 below
- In this matrix compare the element P_1 in the left column with P_1, P_2, P_3, and so on, in the row at the top with respect to factor F in the upper left-hand corner. To compare elements, one should ask: 'How much more strongly does this element possesses or contributes to influence, satisfy, or benefit the property than does the element with which it is being compared?'
- To fill the matrix of pairwise comparisons, we may use the five fuzzy values shown in Fig. 1. When comparing one element in a matrix with itself, the comparison must give unity (1) that represents the values in the diagonal of the matrix.
- To illustrate how to form a normalized matrix and to obtain relative weights in a generalized form, the following numerical example is presented: Suppose that the outcome of pairwise comparison was made for three elements P_1, P_2, and P_3 with respect to factor F as shown in Table 4.
- To harmonize our judgments so as to get relative weights, the following steps are to be taken:
  - Divide each entry in each column by the maximum value of that column to obtain the normalized matrix as shown in Table 5.

Table 5
Fuzzy relative weights for three elements

F	P_1	P_2	P_3	Min (max) row value
P_1	1/5	1/10	1/3	1/10 (1/3)
P_2	1	1/2	1/2	1/2 (1)
P_3	3/5	1	1	3/5 (1)

Table 6
Sample fuzzy matrix comparing three elements against each other

–	F_1	F_2	F_3
F_1	1	1/6	1/2
F_2	6	1	1/2
F_3	2	2	1
Column max value	6	2	1

Table 7
Fuzzy relative weights for three factors

–	F_1	F_2	F_3	Min (max) row value
F_1	1/6	1/12	1/2	1/12 (1/2)
F_2	1	1/2	1/2	1/2 (1)
F_3	1/3	1	1	1/3 (1)

Table 8
Fuzzy relative weights for electricity generating systems based on benefits

System	Safety (0.43)	Social benefits (0.14)	National economy (0.75)	Availability of fuel (1.00)	Reliability (1.00)	Efficiency (0.71)
Nuclear	0.11	0.14	0.13	0.14	0.80	1.00
Wind	1.00	1.00	1.00	1.00	0.20	1.00
Solar	1.00	1.00	1.00	1.00	0.20	1.00
Hydro	1.00	1.00	0.67	0.25	0.40	1.00
Fossil fuel	0.67	0.22	0.22	0.75	1.00	0.50

Table 9
Fuzzy relative weights for electricity generating systems based on costs

System	Environmental constraints (0.25)	Auxiliary system (0.17)	Maintenance cost (0.50)	Hardware cost (0.50)	Cost of fuel (1.00)
Nuclear	1.00	0.11	1.00	1.00	0.33
Wind	0.03	1.00	0.11	0.11	0.05
Solar	0.03	0.78	0.11	0.11	0.05
Hydro	0.03	0.89	0.11	0.11	0.05
Fossil fuel	0.20	0.11	0.44	0.33	1.00

- Determine minimum (maximum) value in each row depending on finding weights based on cost (benefit); this yields the overall relative weight priorities of the elements P_1, P_2, and P_3. Hence, we make deductions with reference to relative weights as calculated above.
- Construct the weights of the factors against each other as shown in Tables 6–9.

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