PERGAMON

Energy Conversion and Management 42 (2001) 1717–1726

ENERGY CONVERSION & MANAGEMENT

www.elsevier.com/locate/enconman

Fuzzy sets programming to perform evaluation of solar systems in Jordan

Rustom Mamlook [a,*], Bilal A. Akash [b], Salem Nijmeh [c]

[a] Department of Electrical and Computer Engineering, Applied Science University, Amman 11931, Jordan
[b] Department of Mechanical Engineering Technology, University of Qatar, P.O. Box 2713, Doha, Qatar
[c] Department of Mechanical and Industrial Engineering, Applied Science University, Amman 11931, Jordan

Received 22 June 2000; accepted 15 November 2000

Abstract

This paper uses fuzzy set methodology to perform the comparison between different solar systems for various applications. The aim of the paper is to determine the order in which solar systems should be given higher priority to be used in Jordan. The systems considered are solar distillation, solar water heating, solar space heating and ventilation, solar water pumping, photovoltaics and solar electric power production. They were compared according to their benefits and costs. Based on benefit to cost ratios, the results show that solar distillation is found to be the best choice and should be given the highest priority in terms of research and development. It is followed by the solar pond for electric power production, then, solar water pumping followed by solar space heating and photovoltaics. Finally, solar water heating may not need further development. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Fuzzy sets methodology; Multi-criteria selection; Fuzzy decision making; Solar energy; Benefit to cost ratios; Jordan

1. Introduction

About all the needed systems of society in Jordan use electrical power, which is produced from power plants that use fossil fuels. The most popular fuels used in electricity generation are heavy fuel oil and Diesel fuel, which are imported petroleum products. However, since Jordan's spending on petroleum is more than 50% of the export earnings, using foreign fossil fuels escalates not only energy and economical issues but also environmental issues facing Jordan. Therefore,

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

PII: S0196-8904(00)00152-7

looking for renewable energy sources as an alternative is essential and can be a solution to environmental and energy issues. Energy consumption was limited throughout the 20th century to resources such as nuclear energy, natural gas, oil and coal. However, these resources are depleting. Therefore, it is necessary to look for other sources of energy, like solar energy. Solar energy is a non-polluting energy form, which is environmentally safe and known to be a renewable source that can meet the necessary society needs. Solar energy can be the best alternative for the electrical power production option.

Researchers indicate that the energy which reaches earth from the sun in a time period of 96 h (four days) equals all the reserves of the non-renewable depleting sources of energy [1]. Also, it has been known that the yearly global needs of energy is equal to the solar energy reaching the earth in 1 h if 100% efficiency conversion is assumed.

Usually, governments provide financial support which enables researchers to carry on research and development. This paper uses fuzzy set programming to determine the best suitable solar energy options that need to be supported. This would allow governments and decision makers to decide on which area must be given the highest priority for future needs. Some solutions to the environmental and energy consumption issues may be resolved.

2. Solar systems in Jordan

Jordan is a developing non-oil producing country. Because of the increasing energy demand, the country's energy requirements are becoming a real burden on its national economy. In the next few years, the cost of primary energy imported in the form of crude oil is expected to exceed 10% of the GNP. In light of reducing the burden of the cost of imported energy, an initiative was taken in the 1970s to utilize solar and wind energy [2]. Jordan is blessed with good solar energy resources. In the desert, which covers 87% of the land, the average daily solar radiation is about 5.5 kW h/m^2, and the sunshine duration is about 3000 h per year. Research and development activities in this field are led by the Royal Scientific Society (RSS) in cooperation with the German Agency for Technical Cooperation (GTZ). Their work included the installing and testing of two water desalination systems in Aqaba [3]. These systems use the solar still and solar heat pipe principles. This application could be one of the few available choices to solve Jordan's severe fresh water shortage problems. A number of studies were conducted using different types of solar stills [4–6]. Other new methods considered are reverse osmosis or electrodialysis operated by photovoltaic systems.

Another very promising utilization is the use of solar energy for space heating and cooling. A solar house was designed to utilize passive and active means to achieve thermal comfort [7–9]. Flat plate collectors and an under-floor heating system are used for space heating, while a desert cooler operated by a photovoltaics generator is used for space cooling.

The use of solar energy for domestic water heating is quite popular in Jordan. Recent studies have shown that about 30% of the dwellings in Jordan use solar water heating systems [10,11]. Photovoltaic water pumping systems are currently used as an alternative to Diesel powered engines in remote areas in Jordan [12,13]. This could reduce the running cost, maintenance problems and pollution. A recent study has shown that the substitution for Diesel powered engines will be cost effective [14]. Photovoltaic systems are also used to generate power for individual applications, such as clinics, lighting and educational television, for remote villages. Also, they are used to supply power to communication systems in isolated areas.

Solar energy can also be used in the production of electricity [15–17]. Technology suggests that the Dead Sea can be used as a 450 km^2 solar lake, producing 2500 MW [18]. Other areas which deserve further studies are solar cookers, solar architecture, green houses and solar drying.

3. The decision making methodology

After Zadeh's work on fuzzy sets [19], 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 fuzzy logic theory. They have been commercializing this technology, and they have now over 2000 patents in the area for the fuzzy air conditioner, 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 a 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. 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 sets [20]. Also, systems could be controlled using fuzzy rules [21].

Fuzzy rule based models are easy to comprehend because it uses linguistic 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.

In order to compare objects (options) which are fuzzy, vague or ambiguous, we introduce a special notion of relativity [22]. 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 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 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 preferring p to q. For more than two variables, we define variables $p_1, p_2, \ldots, p_i, p_{i+1}, \ldots, p_m$ on the universe U, let these variables be collected on the set S; $S = \{p_1, p_2, \ldots, p_i, p_{i+1}, \ldots, p_m\}$ and form a matrix of relativity values, $f(p_i|q_j)$ where $i, j = 1, 2, \ldots, m$ and p_i and q_j are defined on the universe U. This matrix will be an m by m matrix, 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.,

$$C'_j = \max f(p_j|S), \quad j = 1, 2, \ldots, m \tag{2}$$

or

$$C''_j = \min f(p_j|S), \quad j = 1, 2, \ldots, m \tag{3}$$

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 fuzzy logic decision selection of best solar systems to be used in Jordan was applied according to their costs and benefits. Separately, we considered the benefits and costs. The benefit to cost ratios were also obtained. Our objective is to make the decision selection of the best solar system that costs less and has the most benefits.

The fuzzy logic method (Appendix A) was used to compare the benefits of the electrical production options (P_1 = solar water heating (SWH), P_2 = solar distillation (STILL), P_3 = solar water pumping (SWP), P_4 = solar space heating and ventilation (SSH/VENT), P_5 = solar photovoltaics (PV), P_6 = solar pond (POND)) in Jordan to decide which option has the preferable benefits. Many factors affect this decision (Fig. 1). They include F_1 = efficiency, F_2 = reliability, F_3 = social benefits and F_4 = safety. First, pairwise membership functions $fp_i(p_j)$, $i, j = 1, 2, 3, 4, 5$ and 6 were determined using five fuzzy values [23] as shown in Fig. 2. These values represent the subjective benefits of the appropriateness of each solar system 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 of the rows (relative weights); $C'_j, j = 1, 2, 3, 4, 5, 6$ in Eq. (2). Table 6 is determined using pairwise membership functions for all benefits criteria with respect to each other. Table 7 is determined by using Eqs. (1) and (2) to obtain the relative weights. The overall relative weight factor was then obtained using the results of Tables 5 and 7. Table 1 shows how these relative weight factors were used to make the decision.

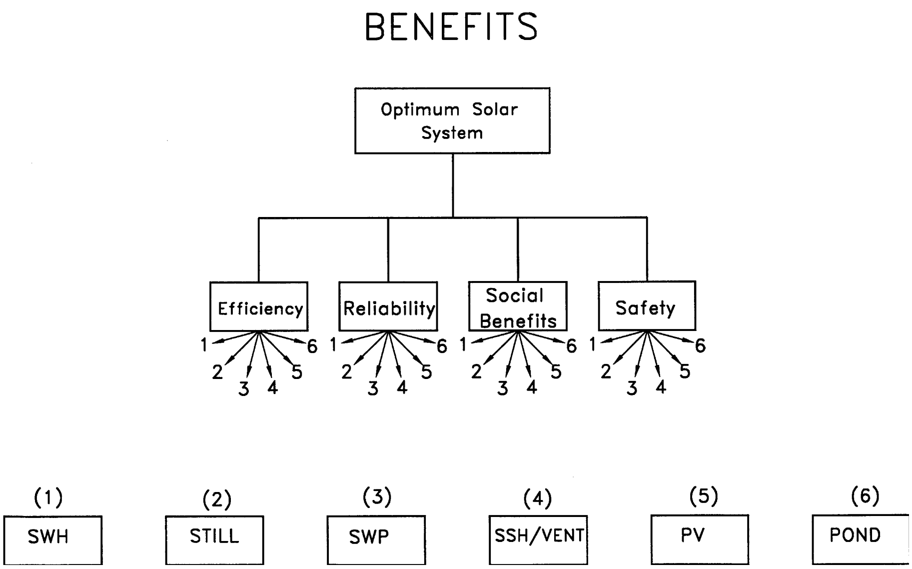

Fig. 1. Benefits fuzzy structure.

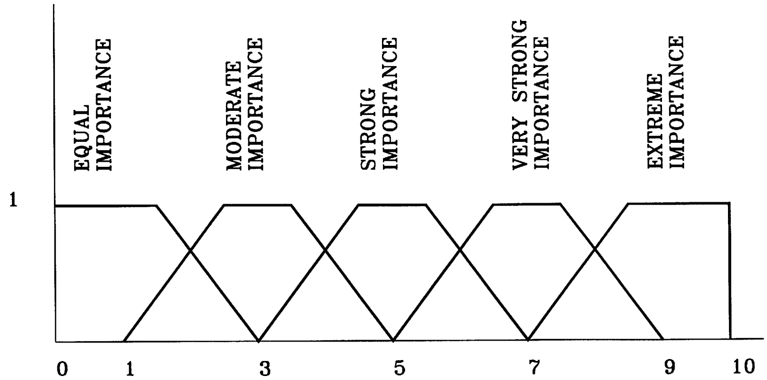

Fig. 2. Fuzzy pairwise comparison values.

Fuzzy logic was then used to compare the costs of the electrical production options (P_1 = SWH; P_2 = STILL; P_3 = SWP; P_4 = SSH/VENT; P_5 = PV; P_6 = POND) in Jordan to decide which solar system has the lowest cost (Fig. 3). Many factors affect this decision, including F_1: hardware cost, F_2: maintenance and service, F_3: added cost of auxiliary system and F_4: environmental constraints. First, pairwise membership functions $fp_i(p_j)$, $i, j = 1, 2, 3, 4, 5, 6$ were determined using five fuzzy values (Fig. 2). These values represent the subjective cost appropriateness of each solar system when compared one to another (Table 4). Eq. (1) was then used to calculate all of the relative values. Table 5 expresses these calculations, and this is the comparison (C) matrix. The extra column to the right of the C matrix is the minimum value of each row; C''_j, $j = 1, 2, 3, 4, 5, 6$ in Eq. (3). Table 6 is determined using pairwise membership functions for all the 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 2 shows how these relative weight factors were used to make the decision.

Table 1
Overall fuzzy relative weights for solar systems based on benefits

Solar system	Efficiency (0.714)	Reliability (1.000)	Social benefits (0.143)	Safety (0.429)	Relative weight[a]	Normalized relative weight[b]
SWH	0.60	0.20	0.33	0.25	0.78	0.34
STILL	1.00	1.00	1.00	1.00	2.29	1.00
SWP	0.60	0.60	1.00	0.50	1.39	0.61
SSH/VENT	0.40	0.60	0.50	0.25	1.06	0.46
PV	0.20	0.25	0.25	0.25	0.54	0.24
POND	1.00	0.60	0.67	0.50	1.62	0.71

[a] Relative weight can be calculated as the following example: relative weight for SWH: $0.714 \times 0.60 + 1.000 \times 0.20 + 0.143 \times 0.33 + 0.429 \times 0.25 = 0.78$.

[b] Normalized relative weight = relative weight/maximum relative weight.

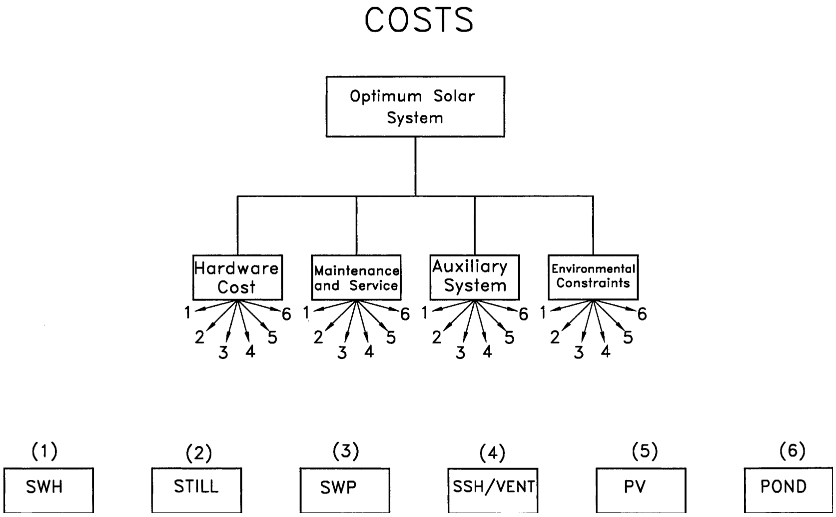

Fig. 3. Costs fuzzy structure.

4. Results and discussion

The fuzzy sets enabled us to condense large amounts of data, collected to compare between the six solar systems in Jordan, into a smaller set of variable rules (see Appendix A and Fig. 2). The final results are shown in Fig. 4. Based on benefits, solar distillation must be given the highest priority. It is followed by electric power generation from a solar pond (Dead Sea), solar water pumping and solar space heating and ventilation. Further development and spending on solar water heating and photovoltaic application should be limited to a minimum. On the other hand, based on costs, solar water heating development is the least attractive. It is followed by photovoltaics, solar water pumping and solar space heating. Solar distillation and the solar pond are the

Table 2
Overall fuzzy relative weights for solar systems based on costs

Solar system	Hardware cost (0.500)	Maintenance (1.000)	Auxiliary system (0.167)	Environmental constraints (0.250)	Relative weight[a]	Normalized relative weight[b]
SWH	1.00	1.00	0.17	1.00	1.78	1.00
STILL	0.10	0.25	0.50	0.11	0.41	0.23
SWP	0.22	0.08	1.00	1.00	0.61	0.34
SSH/VENT	0.13	0.13	0.25	1.00	0.49	0.28
PV	0.44	0.20	0.25	1.00	0.71	0.40
POND	0.06	0.10	0.50	1.00	0.46	0.26

[a] Relative weight can be calculated as the following example: relative weight for STILL: $0.500 \times 0.10 + 1.000 \times 0.25 + 0.167 \times 0.50 + 0.250 \times 0.11 = 0.41$.
[b] Normalized relative weight = relative weight/maximum relative weight.

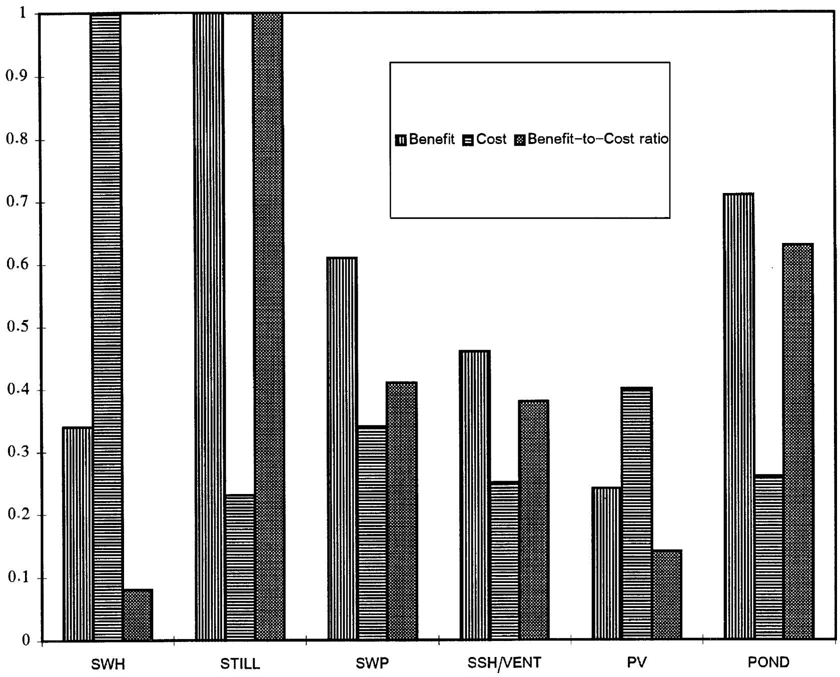

Fig. 4. Comparison of benefits, costs, and normalized cost to benefit ratios.

most attractive. Benefits and cost are then combined as benefit to cost ratios (Fig. 4). Based on benefit to cost ratio, one can note that the preferable option is the use of solar distillation in Jordan. The use of solar energy with 21st century technology can be utilized in desalting brackish water in many parts of the country [24]. Combining both energy and water, which are the main issues for Jordan, it can be shown that an immediate solution must be obtained. Otherwise, a severe problem could arise in the very near future. Additional research and development as well as more financial support by the government must be provided.

5. Conclusions

One of the advantages of the fuzzy decision maker (FDM) method is presented. It uses fuzzy sets to condense large amounts of data into a smaller set of variable rules. The FDM uses minimum and maximum operations, which are easier and faster than the average and sum operations that are used by other methods. Based on this method, solar distillation was the most preferable system to be used in Jordan for utilizing solar energy. The second option was electricity production by use of the solar pond (Dead Sea). They are followed by solar water pumping and solar space heating and ventilation. Any further development on solar water heating and photovoltaics may not need to be immediate.

Appendix A. 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) that will be used for 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.

In this matrix, compare the element P_1 in the column on the left with P_1, P_2, P_3, and so on in the row on 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 contribute 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. 2. When comparing one element in a matrix with itself, the comparison must give unity (1), which represents the values in the diagonal of the matrix.

To illustrate how to form a normalized matrix and to come up with relative weights in a generalized form, the following numerical example is presented:

Suppose that the outcome of the pairwise comparisons was made for three elements P_1, P_2, and P_3 with respect to factor F as shown in Table 4:

Table 3
Sample matrix for fuzzy pairwise comparison

F	P_1	P_2	$\cdots$	P_M
P_1	1			
P_2		1		
$\vdots$			1	
P_M				1

Table 4
Simple 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

To harmonize our judgments so as to get relative weights, the following steps are to be taken:

(a) Divide each entry in each column by the maximum value of that column to obtain the normalized matrix as shown in Table 5.

(b) Determine the minimum (maximum) value in each row, depending on finding weights based on cost (benefit). This yields the percentages of the overall relative priorities of the elements P_1, P_2, and P_3. Hence, we make deductions with reference to relative weights as calculated above.

(c) Construct the weights of the factors against each other as shown in Tables 6 and 7.

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
Simple 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	1/10 (1/2)
F_2	1	1/2	1/2	1/2 (1)
F_3	1/3	1	1	1/3 (1)

References

[1] Al-Shafeay SM. New and renewable. Arab Bureau of Education for the Gulf States, Riyadh, 1993 [in Arabic].
[2] The Royal Scientific Society, The potential of solar energy applications in Jordan, Amman, 1982.
[3] Ta'ani R, Schubert K, Samara F, Solar desalination – final report, Royal Scientific Society Publication, Amman, Jordan, 1980.
[4] Hamdan MA, Musa A, Jubran BA. Performance of solar still under Jordanian climate. Energy Convers Mgmt 1999;40:495–503.
[5] Akash BA, Mohsen MS, Osta O, Elayan Y. Experimental evaluation of a single-basin solar still using different absorbing materials. Renew Energy 1998;14(1-4):307–10.
[6] Alsaad M. A sub-atmospheric solar distillation unit. Int J Solar Energy 1987;5:129–41.
[7] Ta'ani R. Renewable Energy Activities in Jordan, Fourth Arab Int Solar Energy Conf, 20–25 November 1995, Amman, Jordan, vol. 2. p. 1077.
[8] Ta'ani R, El-Mulki H, Kabariti M, Batarseh S. Jordan's first solar-heated house. Solar Wind Technol 1986;3:305–13.
[9] Ta'ani R, El-Mulki H, Batarseh S. Jordan solar house-second testing year. Solar Wind Technol 1986;3:315–8.
[10] Akash BA, Mohsen MS. Energy analysis of Jordan's rural residential sector. Energy Convers Mgmt 1999;40(12):1251–8.
[11] Akash BA, Mohsen MS. Energy analysis of Jordan's urban residential sector. Energy 1999;24(9):823–31.
[12] Hammad M. Characteristics of solar water pumping in Jordan. Energy 1999;24(2):85–92.
[13] Hammad M. Photovoltaic, wind and diesel: a cost comparative study of water pumping options. Energy Policy 1995;23:723–6.
[14] Mulki H, Ta'ani R, Mahmoud M. Study on the possibility of utilizing pumping and desalination using solar and wind energy for remote desert wells, Royal Scientific Society Publication, Amman, Jordan, 1989.
[15] Akash BA, Mamlook R, Mohsen MS. Multi-criteria selection of electric power plants using analytical hierarchy process. Electric Power Systems Research Journal 1999;52(1):29–35.
[16] Al-Sakaf OH. Application possibilities of solar thermal power plants in Arab countries, Proc Sixth Arab Int Solar Energy Conf, Muscat, Oman, 1998, p. 1–9.
[17] Trieb F, Nitsch J. Recommendation for the market introduction of solar thermal power stations, Proc Sixth Arab Int Solar Energy Conf., Muscat, Oman, 1998, p. 17–22.
[18] Haj-Khalil R, Jubran BA, Faqir N. Optimization of solar pond for electrical power generation system. Energy Convers Mgmt 1997;38:787–98.
[19] Zadeh L. Fuzzy sets. Inf Control 1965;8:338–53.
[20] Oder C, Haasis HD, Rentz O. Analysis of the Lithuanian final energy consumption using fuzzy sets. Int J Energy Research 1993;17:35–44.
[21] Mamlook R, Tao C, Thompson WE. An advanced fuzzy controller. Int J Fuzzy Sets Systems 1998;103(3):541–5.
[22] Shimura M. Fuzzy sets concepts in rank-ordering objects. Math Anal Appl 1973;43:717–33.
[23] Zadah L. A rationale for fuzzy control. J Dyn Syst Meas Control Trans ASME 1972;94:3–4.
[24] Akash BA, Al-Jayyousi OR, Mohsen MS. Multi-criteria analysis of non-conventional energy technologies for water desalination in Jordan. Desalination 1997;114(1):1–12.