Clean Techn Environ Policy (2012) 14:357–367
DOI 10.1007/s10098-011-0407-8

ORIGINAL PAPER

Toward clean environment: evaluation of solar electric power technologies using fuzzy logic

Omar Badran · Rustom Mamlook · Emad Abdulhadi

Received: 31 May 2011 / Accepted: 13 July 2011 / Published online: 26 July 2011

Abstract The rapid expansion of the use of solar energy power plants worldwide is a subject that is being followed with interest. Fuzzy logic methodology is used for evaluating the solar thermal power technology, it compresses huge amount of data into smaller sets, and it has the ability to decide between different solar technologies on the basis of their benefits and costs. The most often considered solar technologies were parabolic trough, central receiver, dish sterling engine, compact linear Fresnel reflector (CLFR), solar chimney, photovoltaic (PV), and solar pond. The aim of our research is to provide the needed information to make a judgment or a decision of adopting the most preferred solar technology in terms of installation and development using fuzzy set methodology. The criteria of the evaluation were based on different parameters, i.e., power capacity, efficiency, availability, capacity factor, storage capability, cost, maturity, water usage, land usage, and safety. The key barriers and features for each technology on the basis of benefit-to-cost ratios are addressed. The results showed that CLFR was found to be the best choice in terms of research, development, and implementation, followed by parabolic trough technology, then the central receiver technology, dish sterling engine, solar chimney, PV, and solar pond, according to the order of preference.

O. Badran · E. Abdulhadi
Mechatronics Engineering Department, Faculty of Engineering Technology, Al-Balqa Applied University, Amman, Jordan

R. Mamlook (✉)
Department of Computer Engineering, College of Computer Engineering and Sciences, Al-kharj University,
Al-kharj, Saudi Arabia
e-mail: rstmamlk@hotmail.com

Keywords Fuzzy sets methodology · Solar electric power · Control technology

Introduction

Electricity production using solar thermal energy is currently one of the main research areas in the field of renewable energies. The significant price fluctuations that are seen for the fossil fuel on one hand, and the trend toward privatization that dominates the power markets these days on the other hand, will drive the demand for solar technologies in the near future.

Different types of solar power plants need further improvements and cost reduction to be competitive with fossil fuel power plants in future power markets. Price and Kearney (2003) reviewed the current cost of energy and the potential for reducing the cost of energy from parabolic trough solar power plant technology based on the latest technological advancements and projected improvements proposed from industry and sponsored research and development (R&D) institutions.

Another study has been made by the National Renewable Energy Laboratory (NREL) to evaluate the potential for the emerging photovoltaic (PV) technologies to meet the solar program's technical and economic targets. They also discussed the current structure, capabilities, and assumptions, and made a linear programming model of capacity expansion for the concentrating solar power (CSP). The results are presented for the impact of continued R&D for the CSP to drive down the solar electric power (Braun and Skinner 2007; Blair et al. 2006).

The solar energy flux reaching the Earth's surface represents a few thousand times the current use of primary energy by the humans. Earth receives 174 petawatt of incoming solar radiation at any given time; unfortunately, this huge amount of energy has not been well utilized till now. There are many advantages for solar power plants. They can be used in large scale power generation. The modular character of the solar field enables it to start at any power level. Off-grid solar power for remote locations maybe competitive to fossil fuel power, because the energy at remote locations becomes costly because it requires to be distributed over very long distances (Schott 2006).

The independence of the operating costs from fuel prices fluctuation and the unlimited availability constitute important factors of merit for the solar power plants. Solar power plants have the advantage of generation at peak load hours; the hot-climate countries, such as Jordan, have the highest electricity peak load consumption for meeting cooling demands during the hot summer days (Amman and Jordan 2007).

Solar power plants play an important role in decreasing the environmental pollution; they contribute directly to the reduction in CO_2 emission that is caused by the conventional fossil fuel power plants. According to a Greenpeace study, the use of solar power plants can avoid 362 million tons of CO_2 emissions worldwide from 2002 to 2025 (Brakmann et al. 2005).

Many researchers have studied different types of solar power plants. Shinnar and Citro (2007) found that solar thermal energy, particularly trough technology, proved to be already competitive compared with any other power plants for intermediate loads, including old-fashioned coal power plants equipped with scrubbers.

A study on the performance and economy of integrated solar combined cycle systems (SCCS) for parabolic trough power plants were made by Dersch et al. (2004) to show the potential environmental and economical benefits of solar energy generating systems (SEGS) and the SCCS.

Onyango and Ochieng (2006) considered the appropriateness of a solar chimney to rural villages and highlight some features of such a power-generating plant.

An evaluation study of the compact linear Fresnel reflector (CLFR) has been made by Mills and Morrison (2000). They found that CLFR is suitable for large-scale solar thermal electricity generation plants. The improved ability to use the Fresnel approach has many benefits over solar technologies, namely small reflector size, low structural cost, fixed receiver position without moving joints, and non-cylindrical receiver geometry. The modeled array also uses low-emittance all-glass evacuated Dewar tubes as the receiver elements (Mills and Morrison 2000, 1999). Another advantage for CLFR plants gained due to low-temperature operation derives from an unusual combination of low-cost and low-temperature large turbines (Mills et al. 2004)

Mills et al. (2006) proposed Fresnel with multitowers that do not require a tracking system; each field of reflectors is directed into a single tower, which in turn decreases the overall cost.

An evaluation study for the new solar technologies was made by Mills (2004) which includes parabolic trough technology, CLFR, sterling engines, central receiver (solar tower), and solar chimney, in terms of new market approaches, in the medium and long terms.

Another evaluation study for different power production systems using fuzzy set methodology was conducted by Mamlook (2006). He showed that the solar power production is the best preferable option under the Jordanian climate on the basis of cost to benefit ratio. He also used the same mechanism under the same Jordanian climate for solar utilization applications; he showed that the solar power production is the second-best choice that comes after the solar distillation (Mamlook et al. 2001).

Badran (2001) has studied different solar thermal power cycles, namely low-, medium-, and high-temperature solar thermal power cycles and suggested that the Jordanian government should take more serious steps toward the utilization of industrial solar energy systems for power generation applications to reduce the energy bill.

Fuzzy methodology has been utilized for many evaluation applications, as it aids researchers to make the right decisions for improvement and development purposes in many engineering applications (Mamlook and Al-Rawajfeh 2008; Al-Rawajfeh and Mamlook 2008; Mamlook et al. 2009; Badran et al. 2009).

The present study uses fuzzy logic methodology to compare between different solar electric power technologies, which are available or being developed, on the basis of benefit-to-cost ratio to make a judgment or a decision to adopt the higher priority solar technology in terms of installation, development and efficient production.

Solar electric power technologies

Solar power technologies can be divided into two sections; direct and indirect electricity conversion. The indirect solar system can be classified into concentrating and non-concentrating solar power (non-CSP) systems (Fig. 1). The CSP systems are sub-classified by focus and tracking type: the solar system that concentrates the sunlight to a focal line or focal point, has a parabolic shape; the one-axis tracking system that concentrates the sunlight onto an absorber tube in the focal line, such as in parabolic trough technology or CLFR technology; and the two-axis tracking system that does so onto a relatively small absorber surface near the focal point, such as in central receiver technology

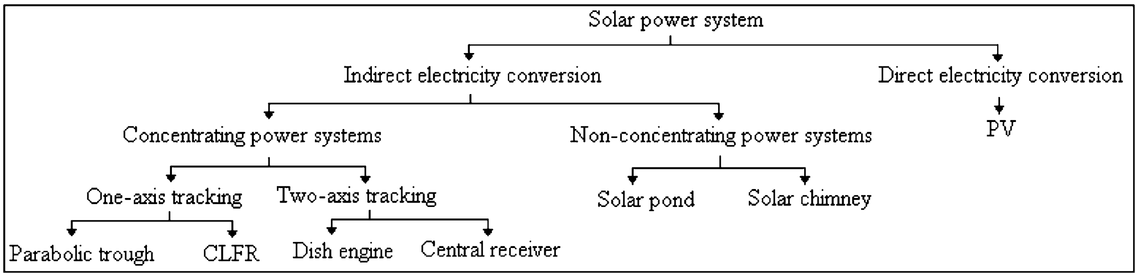


Fig. 1 Solar power technology classification (Renewable Energy World 2003)

or dish sterling engine technology (Renewable Energy World 2003).

Parabolic trough

The collector in the parabolic trough technology consists of a large field of single-axis tracking parabolic trough solar collectors. The solar field is modular and is composed of many aligned parallel rows of solar collectors. Each solar collector has a linear parabolic-shaped reflector that focuses the sun's direct beam radiation onto a linear receiver located at the focus of the parabola. The collectors track the Sun from east to west during the day to ensure that the sun is continuously focused on the linear receiver. A heat transfer fluid is heated as it circulates through the receiver and returns to a series of heat exchangers in the power block, where the fluid is used to generate high-pressure superheated steam. The superheated steam is then fed to a turbine that is attached to generator to produce electricity (Wibberley et al. 2006) as shown in Fig. 2.

Parabolic trough technology is a proven technology since mid eighties, it is considered to be very interesting technology in the near term option (Badran and Eck 2006).

Compact linear Fresnel reflectors (CLFRs)

CLFR was patented in 1995 by Mills (Mills et al. 2002) and is classified under one-axis tracking systems. It uses flat or elastically curved reflectors instead of costlier sagged glass reflectors. Unlike the trough technology, the heat transfer loop is separated from the reflector field and fixed in space thus avoiding the high cost of flexible high-pressure lines or high-pressure rotating.

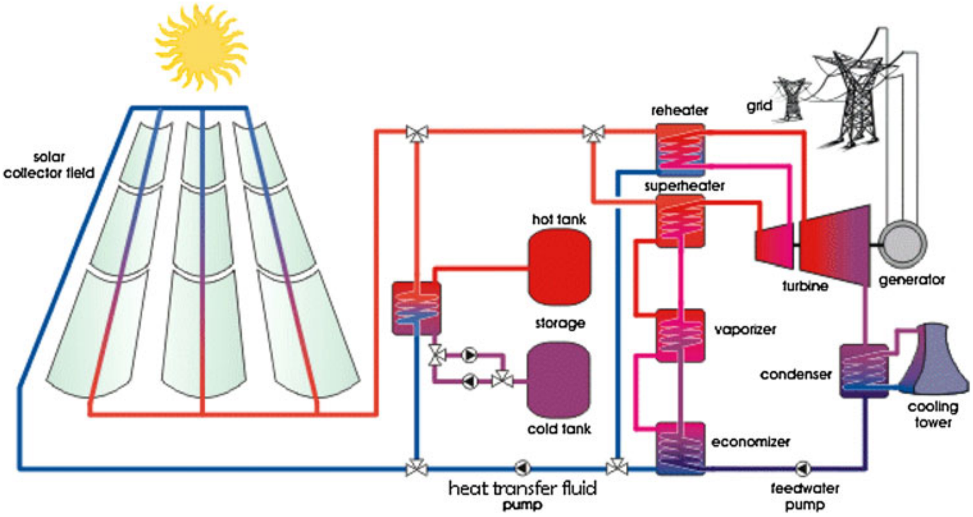
The heat transfer fluid is water, which avoids the losses and the high-cost equipments that are used in other technologies using oil as a transfer fluid. CLFR is characterized by low maintenance cost because of its simple structure (Fig. 3). It also has excellent ground utilization due to the nature of the flat-shape reflectors (Mills et al. 2002).

The CLFR has the lowest level of electricity cost in solar technologies, which amounts to 0.05$ per kWh. It is expected to be competitive compared with fossil fuel in Australia within the next five years (Wibberley et al. 2006).

Central receiver (power tower)

In the central receiver system, an array of field mirrors (called heliostat) focuses the sunlight to a focal point on the central receiver mounted on a tower as shown in Fig. 4. To

Fig. 2 Parabolic trough power plant with thermal storage (Wibberley et al. 2006)



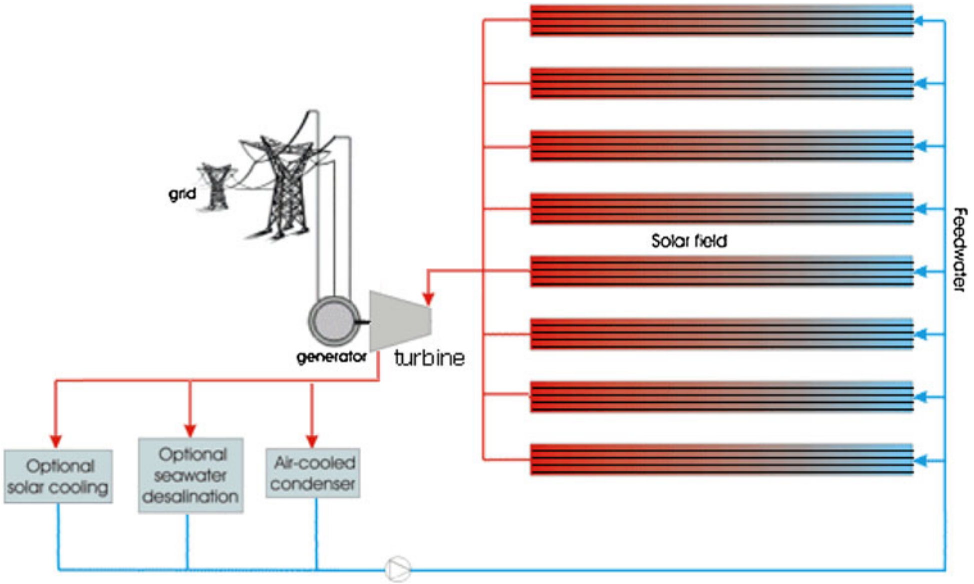


Fig. 3 Compact linear Fresnel reflector power plant (Mills et al. 2002)

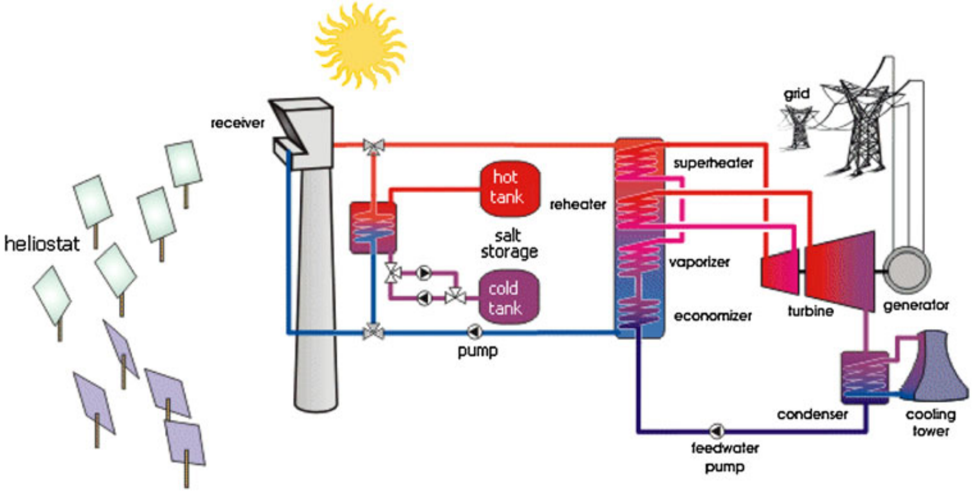


Fig. 4 Central receiver power plant schematic for generating electricity (Berenguel et al. 2004)

focus the sun on the central receiver at all times, each heliostat is mounted on the two-axis sun tracker attached to artificial vision-based control system (Berenguel et al. 2004) to seek position in the sky that is midway between the receiver and the sun. Comparing to the parabolic trough, this technology has higher concentration ratio, and hence, higher-temperature working medium. Consequently, it yields higher thermal efficiency, and is well suited for utility scale power plants of tens or hundreds of megawatt capacity (Mukund 1999). It is characterized with the high capability of storing heat energy for long duration reaching up to 16 h without exposure to sunshine.

Solar dish engines

Parabolic dish systems are primarily designed to operate as stand-alone systems, with highly concentrated heat energy being used in a variety of engines—steam, gas turbine, or sterling engines. The systems use either a single minor, or an array of parabolic dish-shaped minors (stretched membrane or flat glass facets), to focus solar energy onto a receiver located at the focal point of the dish Fig. 5.

The parabolic dish tracks the sun to rise to very high temperatures up to 1,200°C, which drives a sterling heat engine–generator unit. This technology has applications in relatively small capacity (tens of kW) due to the limited sizes of the available engines and wind loads on the dish collectors. Because of its small size, and being more modular than other solar thermal power systems, these systems can be assembled to produce units with a few hundred kW to few MW capacities. This technology is particularly attractive for small stand-alone remote applications (Mukund 1999).

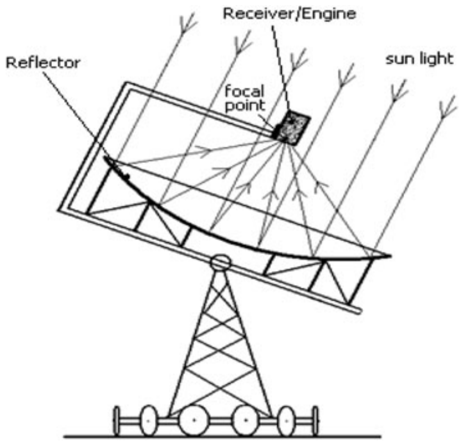


Fig. 5 Dish sterling engine (Mukund 1999)

Parabolic dish systems are the most efficient of all the systems based on solar technology, with peak solar-to-electricity efficiencies up to 29% and thermal efficiencies 80%, compared with the other solar thermal technologies; however, they supply expensive electricity which costs up to 33 cent/kWh (Porta 2005).

Solar chimney

This technology involves using wide collector for heating air over a large area, which generates an upward flow of air via a chimney. Heating is accomplished when the collector is exposed to sunshine with a transparent material, such as clear plastic or glass, which causes the air underneath to get heated up. This heated air can rise through a chimney installed at the center, causing a continuous natural draft. This air drives a vertical-axis wind turbine, placed at the base of the chimney. Since the only moving object in the solar chimneys is the turbine, they are particularly reliable and not prone to breakdown, in comparison with other solar generating plants.

The larger the temperature difference between the heated air underneath the collector and the ambient air at the top of the chimney, the greater the pressure drop over the height of the chimney, and the greater the potential to convert kinetic energy to electrical energy, justifying the greater chimney's height (reaching up to 1 km). The heat absorption capacity process can also be important. The solar chimney technology provides for inbuilt thermal storage as shown in Fig. 6. It has the longest duration of heat storage of all the solar technologies. It could generate electricity continuously for 24 h even in the absence of sunlight.

Unlike many solar technologies, solar chimneys do not consume cooling water. This is a key advantage in the Sun Belt countries that already have major problems of drinking water scarcity (Schlaich and Schiel 2001).

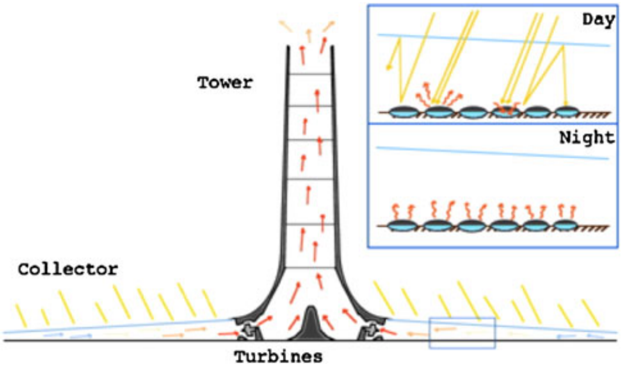


Fig. 6 Schematic of solar chimney (Schlaich and Schiel 2001)

A 200-MW solar chimney has been proposed by EnviroMission for Australia. The heated skid is 5 km in diameter, with a chimney height of 1 km (Wibberley et al. 2006).

Solar pond

A solar pond does not concentrate solar radiation, but the pond's water collects solar energy by absorbing both the direct and diffuse components of sunlight. This is ideal for countries where the sky is frequently overcast. Solar ponds contain salt in high concentrations near the bottom, with decreasing concentrations closer to the surface (Fig. 7). This variation in concentration, known as a salt-density gradient, suppresses the natural tendency of hot water to rise, thus allowing the heated water to remain in the bottom layers of the pond, while the surface layers stay relatively cool. Temperature differences between the bottom and top layers are sufficient to drive an organic Rankine-cycle engine that uses a volatile organic substance as the working fluid instead of steam. Temperatures up to 90°C are routinely achieved in the pond bottom, and solar ponds are sufficiently large to provide some degree of energy storage. The potential of solar ponds to provide fresh water, heat, and electricity, especially for island communities and coastal desert regions, appears promising, but has not been fully investigated (Zumerchik 2001). Dead Sea is considered a perfect place for solar pond power plants because of its high salinity; a 5-MWe solar pond had been constructed by Ormat in the Dead Sea in 1982. Khalil et al. presented a 5-MWe electric solar pond power plant in the Dead Sea in Jordan with a surface area of 1.5 km^2 (Khalil et al. 1997).

Photovoltaic (PV)

The PV cells (photo for light, voltaic for electricity) converts sunlight directly to electricity. Modules are mounted on a stationary array or on single- or dual-axis sun trackers. Arrays can be ground mounted on all types of buildings and structures. The DC output from PV can be conditioned

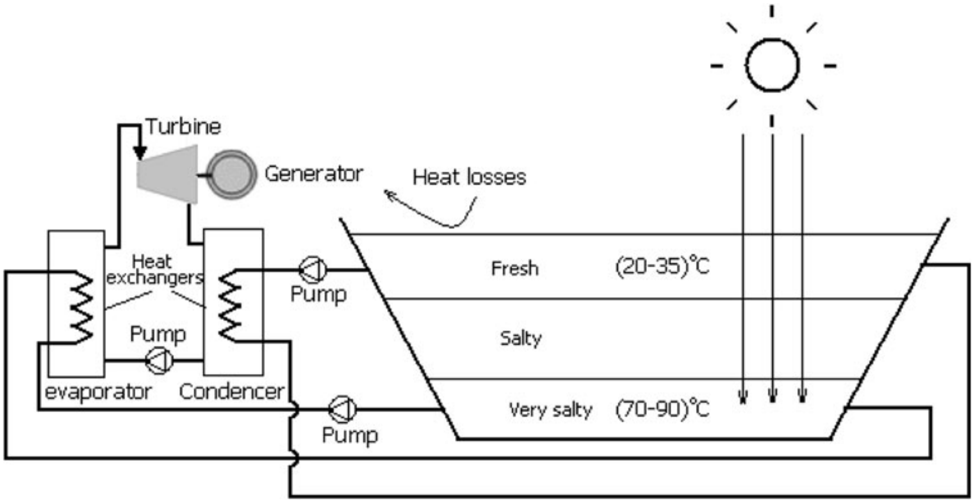


Fig. 7 Solar pond power plant schematic for generating electricity (Khalil et al. 1997)

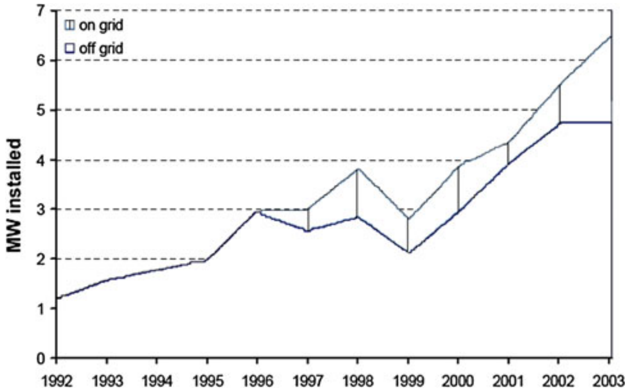


Fig. 8 PV installation annually in Australia

into grid-quality AC electricity, or DC can be used for charging batteries or for splitting water to produce hydrogen (electrolysis of water) (Aabakken 2006).

The PV power generation is highly more expensive than other forms of electricity generation; consequently, the world production of electricity by PV has been comparatively low, but it is shown to be rapidly growing as seen in Fig. 8.

However, PV technology is not expected to contribute in base load generation in Australia at least for the next 25 years (Wibberley et al. 2006).

Fuzzy methodology

Over the last two decades, the tremendous growth in the use of fuzzy logic controllers in power system applications is an evidence of its growing significance in the power field.

Also, Fuzzy methodology has been utilized for evaluation purposes; it has been used for evaluation of factors that affect the solar still production, energy conservation programs in residential sector, and the parameters that affect leakage in infrastructure systems (Mamlook and Badran 2006; Jaber et al. 2005; Mamlook and Al-Jayyousi 2003).

After Zadeh's study on fuzzy sets (Zadeh 1965), many theories in fuzzy logic were developed in Japan, Europe, the 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 they have now over 2,000 patents in the areas, such as 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 fuzzy computer. It is smooth enough such that riders do not need to hold straps, and the controller makes 70% fewer judgmental errors in acceleration and braking than human operators. The U.S. Space Administration has been involved in the use of fuzzy logic in space control decision making. Energy consumption could be analyzed using fuzzy sets (Oder et al. 1993). Also, systems could be controlled using fuzzy logic (Mamlook et al. 1998).

Fuzzy implementation steps

Mainly, the fuzzy implementation consists of four steps (Negnevitsky 2005):

1 Determining the linguistic variables and the fuzzy sets.
2 Constructing fuzzy rules.
3 Performing fuzzy inference into the system.
4 Evaluating and tuning the system.

Determining the linguistic variables and the fuzzy sets

In order to decide between parameters which are fuzzy, vague, or ambiguous, a software package (MATLAB) fuzzy toolbox was employed to generate decision based on the benefit and the cost for each solar technology.

The fuzzy logic decision selection of the solar technology options was applied according to benefits, namely, (B1 = power plant capacity or size (MW), B2 = Annual solar to electric efficiency, B3 = Thermal efficiency, B4 = Peak solar to electric efficiency, B5 = Availability, B6 = Annual capacity factor (CF), B7 = storage hours, B8 = maturity or popularity, B9 = Temperature, B10 = Safety, and B11 = Concentration ratio (CR)) to enable making decision for selection, from different solar technologies, of the one that costs less and have many benefits; many factors affect this decision making (according to costs that include C1 = Hardware cost, C2 = Electricity cost, C3 = Water usage, C4 = Land usage, C5 = Maintenance cost, and C6 = environmental constrains).

The Fuzzy input/output combination is shown in the Fig. 9 as follows:

The fuzzy logic decision selection of the best solar technology options was applied according to their costs and benefits (Tables 1, 2).

Data in Tables 1 and 2 are the actual data obtained from different studies in the literature (Price and Kearney 2003; Braun and Skinner 2007; Blair et al. 2006; Schott 2006), (Brakmann et al. 2005), (Dersch et al. 2004), (Mills and Morrison 2000, 1999; Mills et al. 2004, 2006; Mills 2004), (Wibberley et al. 2006), (Mukund 1999; Porta 2005; Schlaich and Schiel 2001; Zumerchik 2001), (Aabakken 2006), and (Groenendaal 2002; Lovegrove 2003; Trieb F et al. 2005).

The inputs for fuzzy implementation in Tables 1 and 2 are considered to be fuzzy variables, each of which can vary over a fixed weight (0–1), the input's and output's sets are shown in Fig. 10 as follows:

The linguistic variables that were used to describe the fuzzy sets in Fig. 10 are very low (VL), low (L), normal (N), high (H), and very high (VH).

The "conversion method" input shown in Fig. 9 is responsible for determining the solar technology type—whether it should be direct solar conversion (PV) or indirect (thermal conversion)—to exclude the factors of "thermal efficiency," "temperature," and "concentration

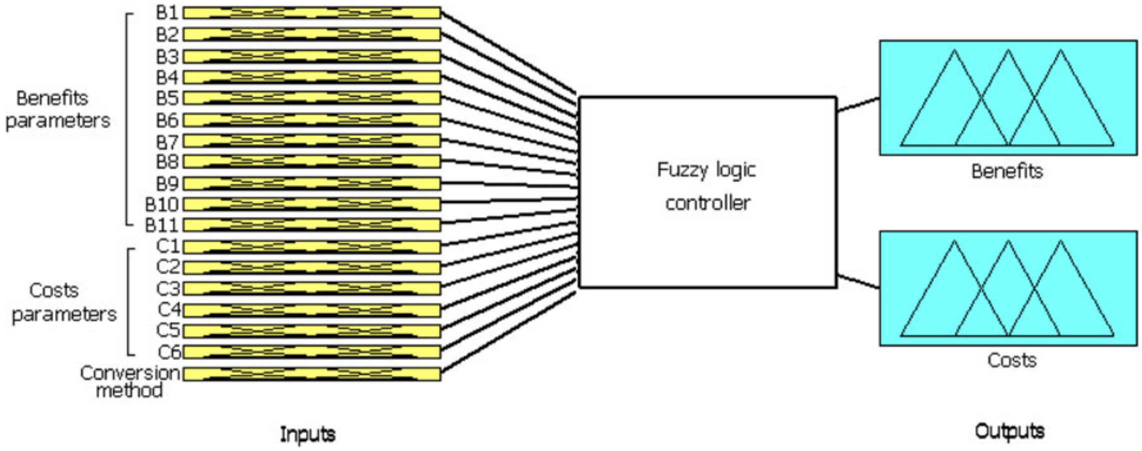


Fig. 9 Fuzzy inputs/outputs combination

Table 1 Overall fuzzy weights for solar technologies (benefits)

	Power	Annual efficiency	Thermal efficiency	Peak efficiency	Availability	Annual CF	Storage h	Maturity	T	Safety	CR	Relative weight	Normalized relative weight
Parameter importance	1.00	0.71	0.71	0.5	1.00	0.50	0.50	1.00	0.71	0.43	0.71	–	–
Trough	1.00	0.67	0.70	0.72	1.00	0.69	0.50	1.00	0.33	0.50	0.40	0.684	1.000
Tower	0.25	0.74	0.91	0.69	0.50	1.00	0.67	0.80	0.67	0.40	0.70	0.651	0.952
Chimney	0.50	0.10	0.21	0.10	0.70	1.00	1.00	0.30	0.06	0.45	0.10	0.399	0.583
Dish	0.13	1.00	1.00	1.00	0.60	0.31	0.00	0.20	1.00	0.60	1.00	0.564	0.825
Pond	0.01	0.10	0.24	0.10	0.80	1.00	1.00	0.20	0.08	1.00	0.10	0.38	0.556
PV	0.05	0.70	–	0.97	1.00	0.19	0.42	0.60	–	0.30	–	0.522	0.763
CLFR	0.44	0.48	0.70	0.69	0.90	0.70	0.50	0.30	0.33	0.70	0.40	0.546	0.798

Normalized relative weight = relative weight/maximum relative weight

Table 2 Overall fuzzy weights for solar technologies (costs)

	Hardware cost	Electricity cost	Water usage	Land usage	Maintenance cost	Environmental constrains	Relative weight	Normalized relative weight
Parameter importance	0.5	0.5	0.5	0.4	0.5	0.25	–	–
Trough	0.44	0.18	0.70	0.42	0.30	1.00	0.454	0.788
Tower	0.55	0.21	0.80	0.31	0.52	0.74	0.512	0.889
Chimney	0.53	0.15	0.10	0.90	0.52	0.00	0.402	0.698
Dish	1.00	0.50	0.10	0.30	0.52	0.60	0.487	0.845
Pond	0.29	0.18	1.00	1.00	0.20	0.00	0.432	0.750
PV	0.84	1.00	0.10	0.36	1.00	0.00	0.576	1.000
CLFR	0.35	0.11	0.30	0.20	0.10	0.30	0.247	0.429

Normalized relative weight = relative weight/maximum relative weight

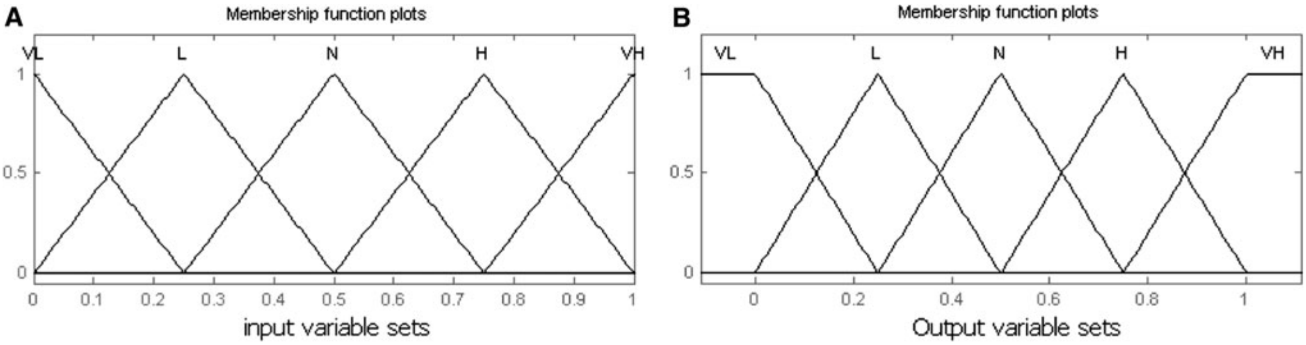


Fig. 10 Fuzzy sets. **a** input sets. **b** output sets

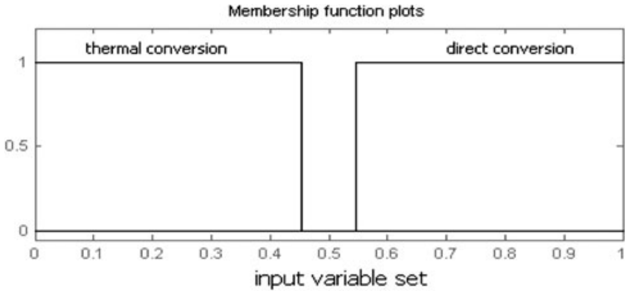
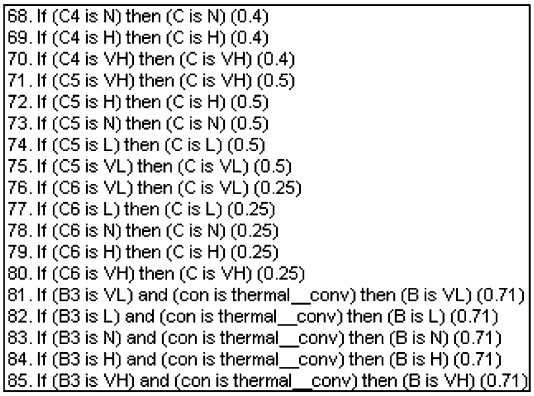


Fig. 11 Binary fuzzy sets

ratio” and to enable an accurate decision making as shown in Fig. 11.

Constructing fuzzy rules

The sets that have been used in the fuzzy implementation are activated in terms of the fuzzy rules which take the general form: IF condition1 and condition2… and THEN decision(s). The “and” operator uses the “min” (minimum) function, while “or” operator uses “max” (maximum) function. 85 rules were used for predicting the most preferable option(s) out of the seven solar technologies; they are in a statement format as shown in Fig. 12.



68. If (C4 is N) then (C is N) (0.4)
69. If (C4 is H) then (C is H) (0.4)
70. If (C4 is VH) then (C is VH) (0.4)
71. If (C5 is VH) then (C is VH) (0.5)
72. If (C5 is H) then (C is H) (0.5)
73. If (C5 is N) then (C is N) (0.5)
74. If (C5 is L) then (C is L) (0.5)
75. If (C5 is VL) then (C is VL) (0.5)
76. If (C6 is VL) then (C is VL) (0.25)
77. If (C6 is L) then (C is L) (0.25)
78. If (C6 is N) then (C is N) (0.25)
79. If (C6 is H) then (C is H) (0.25)
80. If (C6 is VH) then (C is VH) (0.25)
81. If (B3 is VL) and (con is thermal__conv) then (B is VL) (0.71)
82. If (B3 is L) and (con is thermal__conv) then (B is L) (0.71)
83. If (B3 is N) and (con is thermal__conv) then (B is N) (0.71)
84. If (B3 is H) and (con is thermal__conv) then (B is H) (0.71)
85. If (B3 is VH) and (con is thermal__conv) then (B is VH) (0.71)

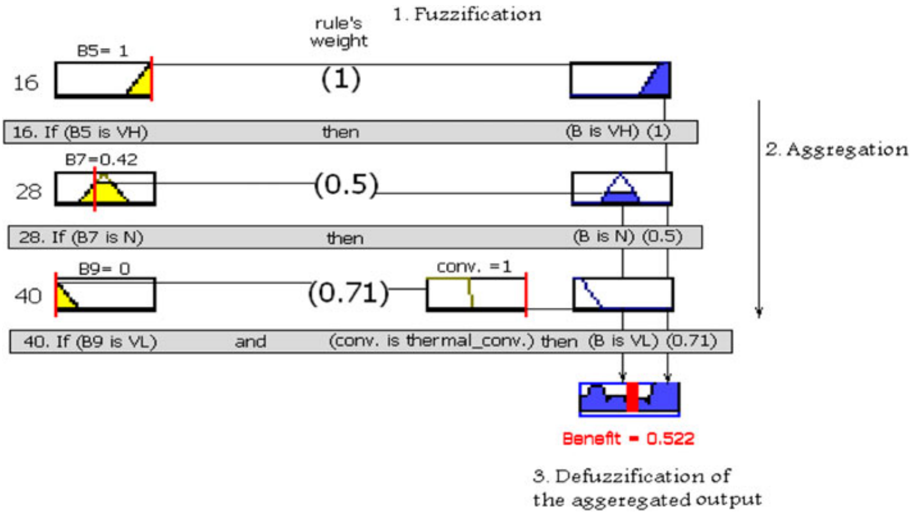
Fig. 12 Fuzzy rules

Performing fuzzy inference into the system

Systems fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic, and then the mapping provides a basis from which decisions can be made. The process of fuzzy inference involves membership functions, fuzzy logic operators, and IF–THEN rules (Negnevitsky 2005).

This procedure is used to compute the mapping from the input values to the output values, and it consists of three

Fig. 13 Fuzzy implementation sequence



sub-processes, fuzzification, aggregation, and defuzzification as shown in Fig. 13.

Fuzzification turns crisp numeric values into linguistic descriptions (VL, L, N, H, and VH). This process is accomplished by evaluating the membership functions (MFs) with respect to the input value to establish the degree of activation of each output MF.

At the end of this process, a list of activations is obtained, which can be carried forward to the next stage (aggregation sub-process). In the aggregation sub-process, the effects of each rule on the possible output conditions are accumulated. Defuzzification carries out the estimation of the crisp outcomes of the inference process. Each output variable is analyzed separately as shown in Fig. 13.

Table 3 Benefit to cost ratio

Solar technology	Normalized benefits relative weight	Normalized costs relative weight	B/C	Normalized B/C
Trough	1.000	0.788	1.269	0.682
Tower	0.952	0.889	1.071	0.575
Chimney	0.583	0.698	0.835	0.449
Dish	0.825	0.845	0.976	0.524
Pond	0.556	0.750	0.741	0.398
PV	0.763	1.000	0.763	0.410
CLFR	0.798	0.429	1.860	1.000

The final results are shown in Fig. 14

Results and discussion

The fuzzy sets enabled us to utilize large amount of data, collected for comparison between the different solar technologies systems, by compressing them into a smaller set of variable rules (see Tables 1, 2).

The benefit -to-cost ratio is shown in Table 3:

As can be noted from Table 3 and Fig. 14, and from the fuzzy sets' analysis, CLFR technology has the highest benefit-to-cost ratio, and thus, it is the best option for power generation plants. It is even expected to be competitive relative to the fossil within the next 5 years (Wibberley et al. 2006) because of its simple structure, high availability, and low maintenance cost. The second- and third-best choices are parabolic trough technology and central receiver, respectively. Parabolic trough is a proven technology in the utility scale since mid-1980s. It has the higher popularity and the higher power capacity than other solar technologies, and only the parabolic trough power plants have managed to reach beyond the R&D stage. Their overall production is about 1,000 MW_e annually since 1989 (Carl-Jochen 1991).

Figure 14 shows that PV and solar pond technologies have the least benefit-to-cost ratio. PV has never been used in base load generation mode; moreover, it is not expected to contribute in base load generation over the next 25 years because of its very high cost (Wibberley et al. 2006). Solar pond power plants have been installed in a relatively small power capacity; Their capacities reached only up to a few Megawatts (Zumerchik 2001). However, it can be utilized in other applications like distillation.

Conclusion

The foreseeable energy shortage due to the increased population and the industrial activities in the world, and the already unreliable and distinctly expensive fossil resources in the present times are forcing us to opt for a

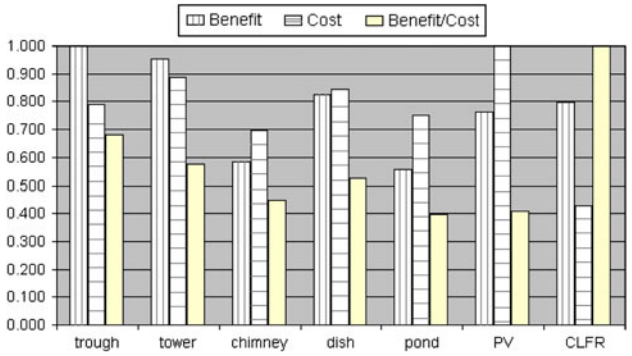


Fig. 14 Comparison between benefits, costs, and normalized benefit-to-cost ratios

diversification of energy sources and driving the demand toward solar technologies in the near future.

Presumably, the depletion of the fossil energy resources will not be the major reason, which will force a change in the use of energy; in fact, it will be the limited capacity of the environment to absorb the waste-products of energy consumption, which demands resolute actions toward a more economically sustainable energy.

Fuzzy logic methodology for evaluating the solar thermal power technology enables us to compress huge amount of data into smaller sets; it has the ability to decide for the selection of the best among different solar technologies on the basis of their benefits and costs. Based on fuzzy logic results, the CLFR proved to be the best choice because of its high power generation capabilities, high power-to-land area ratio, high availability, simple structure, and low components' cost. Its low-cost feature could allow CLFR to become competitive compared with fossil fuel within the next few years.

The next best option is parabolic trough; only the parabolic trough power plants have managed to reach beyond the R&D stage. Its overall production is about 1,000 MW_e annually since 1989, but it still needs further cost reduction to generate electricity at an affordable cost. The third choice is the central receiver technology, although the central receiver plants are considered to be still farther away from commercialization compared to parabolic trough systems. Solar towers have good longer-term prospects for high conversion efficiencies. Meanwhile, more scaled-up demonstration projects are needed. The last two choices are PV and solar ponds, respectively. PV has never been used in base load generation mode; moreover, it is not expected to contribute in base load generation over the next 25 years because of its very high cost. Solar pond power plants have been installed in a relatively small power capacity, which reaches only up to a few Megawatts. However, it can be utilized in other applications such as distillation.

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