Comparison of Energy Storage Alternatives Using Fuzzy TOSIS Method

Ronay Ak, Canan Ağlan

Abstract— The aim of global energy sustainability implies the replacement of all fossil fuels (oil, coal, natural gas) by renewable energy sources. Renewable energy is the energy coming from natural resources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (naturally replenished). Renewable energy sources should be first converted to electricity and then can be transferred to the place of use. However, the problem of matching the supply to meet the demand requires the efficient storage of energy. This calls for the development and the application of the energy storage devices / technologies. Since comparison of energy storage options is a multi-criteria decision making problem, we have attempted to compare of energy storage options by using Fuzzy TOPSIS method in this study.

Index Terms— Energy storage alternatives, fuzzy TOPSIS, multi-criteria.

I. Introduction

ENERGY storage is required to supply customers at times when need is greatest, which is during peak load. The problem of matching the supply to meet the demand requires the efficient storage of energy. The storing of energy is also particularly useful for enhancing the use of renewable generation plants (e.g., wind farms and solar plants). Thus, storing renewable energy allows renewable plants to be dispatched during the day when the demand (and price) is the highest and allow customers to get more value from such environmentally attractive power resources [9].

Energy storage has critical roles to play in securing our energy future including [14]:

- Stabilizing electricity market
- Stabilizing the transmission and distribution grid
- Enabling more efficient use of existing generation assets
- Making renewable energy economically viable
- Serving as an "electricity reserve" much like the national Petroleum Reserve

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There are several factors affecting the selection of the appropriate energy storage technology / device such as Efficiency, Plant Capital Cost (cost for power output, $/kW), cost per hour of operation at full output power (storage capital cost,$/kWhop), Maximum power, Modular, Cycle-life, Charge Time, Siting Ease, Lead Time, Environmental Impact, Risk, Thermal Requirement, Maturity. Therefore, an energy storage selection problem can be formulated as multiple criteria decision making problem in which alternatives are the storage alternatives to be selected and the criteria are the attributes under consideration.

Many efficient methods have been presented for the fuzzy multi-criteria decision-making problems with the decision-makers' preference information completely known and completely unknown, such as, TOPSIS method, AHP, average weighted comprehensive method, fuzzy optimum seeking method, minimum membership degree method, average weighted programming method, fuzzy neural networks comprehensive decision-making method, fuzzy iteration method, target decision by entropy weight and fuzzy [13]. Among many famous MCDM methods, Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) was first developed by Hwan and Yoon. It bases upon the concept that the chosen alternative should have the shortest distance from the positive ideal solution and the farthest from the negative ideal solution.

Moreover, selection of the best energy storage option requires the consideration of both quantitative and qualitative evaluation criteria. Therefore, Fuzzy Logic is appropriate method in order to consider both types of criteria.

The comparisons of energy storage options has been studied in literature before; however, to the best of the authors' knowledge, a study include fuzzy decision making approach has not been performed before. Therefore, the authors consider that the work introduced in this paper will pave the road for more studies in this field.

The primary aim of this paper is to compare and to select the best bulk energy storage alternative for industrial facilities under both qualitative and quantitative criteria.

This paper is organized as follows: First, energy storage options and evaluation criteria are defined in Section 1. Then the previous works related to energy storage options are described. In Section 4, the main principles of the fuzzy TOPSIS method used in this study are introduced. In Section 5, selected energy storage options are compared by

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using Fuzzy TOPSIS method. Finally, overall conclusions and recommendations for further research are presented in Section 6.

II. Energy storage alternatives and evaluation criteria

There are several energy storage alternatives. These may be classified according to the form in which the energy is stored, namely[5]:

- thermal energy: storage heaters, molten salts
- potential energy: pumped hydroelectric, compressed air
- kinetic energy: flywheels
- electromagnetic energy: superconducting coils
- electrostatic energy: capacitors, super capacitors
- chemical energy: batteries, methanol, hydrogen.

The characteristics of those systems are suitable for medium to large scale storage of energy. However, in this study only large scale storage will be covered. The large scale storage alternatives can be listed as below:

Pumped Storage: It is widely used around the world. The aboveground and underground storage is possible. In 2007, there was a net capacity of 38.306 GW of pumped storage installed in the EU-27, or 5 percent of total net installed generation capacity [8]. However underground storage is high compared to above ground. Pumped Storage requires 200-300 seasonal storage capacity which is not economical due to storage costs.

Battery Storage: Storage of solar energy in batteries requires high temperature applications [3]. Solar furnaces and solar towers are utilized in electricity production. These systems are being used in multiple applications some of them; Peak-shaving, Frequency control, Load leveling, Utility stabilization etc [5].

Superconducting Magnets: Superconducting magnetic energy storage (SMES). Large scale superconducting magnets for energy storage are still under development [1]. Those systems' storage capital cost makes these economically impractical. The solenoids magnetic field's in those systems can be counted as a problem.

Flywheels: Flywheels have long been used to store energy in rotating machinery and larger flywheels using advanced materials are under development. Its storage capital cost is high so that using fly wheels in bulk electricity storage is impractical. [1]

Regenerative Fuel Cells: To charge this system electrical energy is converted into chemical energy in two electrolytic solutions in fuel cell and pumped into storage tanks; during discharge the process is reversed. Overall system efficiency is 65%. This is a new technology. System life time is estimated to be 15 years. Siting ease of this system will be improved with technological developments by reducing cell plant. Its thermal requirement is chemical energy.

Compressed Air: Compressed Air Energy Storage (CAES) In this system air is first compressed at constant entropy in the compressor then heated at constant pressure in the combustor. The storage energy is wind in this system. The extracted energy is used both to drive a generator to produce electricity. Power generation is based on gas turbines which are simple, reliable and inexpensive.

When a renewable energy storage alternative is evaluated several criteria has to be taken into account. Some of those criteria are qualitative rather than quantitative. Hence when someone wants to compare these alternatives, a proper evaluation technique which is far from subjective judgment must be made In Table I, comparison of renewable energy storage systems with respect to criteria is illustrated. The criteria and alternatives obtained by combining [1],[5] studies.

III. Literature Review

In recent years, there is an increase in the number of the researches related to energy storage systems / options. Some studies have focused on a specific energy storage option and discussed it under a couple of criteria. Reference [7], considered a battery test facility started in 1881 in Berlin. The device under test was a newly developed lead-acid battery. According to the authors regarding the chemical storage systems, the lead-acid battery leaves behind its competitors (Ni/Cd, Zn/Cl, Zn/Br, Redox, Na/S, Li/FeS) in being cheap and safe and available.

Reference [9] compared energy storage technology solutions on the basis of benefit / cost ratio. The technologies compared in their study are superconducting magnetic energy storage (SMES), batteries, flywheels, capacitors, compressed air energy storage (CAES), compressed air in vessels (CAS), and pumped hydro storage.

Reference [3] examined candidate storage technologies and interpreted their roles in providing energy security / global energy sustainability and environmental protection.
Reference [12] applied the central unit commitment and economic dispatch (UC-ED) optimization model, PowrSym3 (a multi-area, multi-fuel, chronological production cost simulation model), for the determination of the benefits of energy storage for the large-scale integration of wind power in the Dutch power system. In their work, three large-scale energy storage technologies are modeled: surface PAC, underground PAC (UPAC) and CAES.

IV. Fuzzy TOPSIS

In fuzzy TOPSIS, the decision makers may use linguistic variables or fuzzy numbers to evaluate the ratings of alternatives with respect to criteria. Assume that a decision group has K persons, and then the importance of the criteria and the rating of alternatives with respect to each criterion can be calculated as [2];

$$\tilde{x}_{ij} = \frac{1}{K\left[\tilde{x}_{ij}^{1}(+)\tilde{x}_{ij}^{2}(+)\tilde{x}_{ij}^{2}(+)...(+)\tilde{x}_{ij}^{K}\right]} \quad (1)$$

$$\tilde{w}_{j} = \frac{1}{K\left[\tilde{w}_{j}^{1}(+)\tilde{w}_{j}^{2}(+)...(+)\tilde{w}_{j}^{K}\right]} \quad (2)$$

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where, $\tilde{x}_{ij}^{K}$ is the rating of the K[th] decision maker for ith alternative with respect to jth criterion and $\tilde{w}_{j}^{K}$ is the importance weight of the Kth decision maker with respect to jth criterion. After obtaining weights of the criteria and fuzzy ratings of alternatives with respect to each criterion, the fuzzy multi-criteria decision-making problem can be given in matrix format as,

$$\tilde{D}=\begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & . & . & \tilde{x}_{1n} \\ \tilde{x}_{21} & . & . & . & \tilde{x}_{2n} \\ . & . & . & . & . \\ . & . & . & . & . \\ \tilde{x}_{ml} & \tilde{x}_{m2} & . & . & \tilde{x}_{mn} \end{bmatrix}$$

$$W=[w_1, w_2, ..., w_n], j=1,2,...,n \quad (3)$$

where $\tilde{x}_{ij}$ is the rating of the alternative A_i with respect to criterion j and w_j denotes the importance weight of C_j.

These linguistic variables can be described by triangular fuzzy numbers: $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$
In sum, we can explain the algorithm of the multi-person multi-criteria decision making with fuzzy set approach which is used here as follow:

Step 1: Decision makers choose the appropriate linguistic variables for the importance weight of the criteria and the linguistic ratings for alternatives with respect to criteria.

Step 2: We obtained the aggregated fuzzy weight $\tilde{w}_j$ of criterion C_j and pooled the decision makers' opinions to get the aggregated fuzzy rating $\tilde{x}_{ij}$ of alternative A_i under criterion C_j. Equations (1) and (2) are used in this step.

Step 3: We constructed the fuzzy decision matrix and the normalized fuzzy decision matrix. Here we used Chen's approach to obtain normalized matrixes. According to Chen approach we can obtain the normalized fuzzy decision matrix denoted by $\tilde{R}$.

$$\tilde{R} = [\tilde{r}_{ij}]_{mxn} ,$$

where *B* and *C* are the set of benefit criteria and cost criteria, respectively, and

$$\tilde{r}ij=\left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), \quad j\in B \quad (4)$$

$$\tilde{r}_{ij}=\left(\frac{a_j^-}{c_{ij}}, \frac{b_j^-}{c_{ij}}, \frac{c_j^-}{c_{ij}}\right), \quad j\in C \quad (5)$$

$$r_j^* = \max c_{ij} \quad if. \quad j\in B \quad (6)$$

Step 4: We then constructed weighted normalized fuzzy decision matrix as

$$\tilde{V}=[\tilde{v}_{ij}]_{mxn} \; i= \; 1,2...,n, \quad (7)$$

where $\tilde{v}_{ij} = \tilde{r}_{ij}(.)\tilde{w}_j$. Here $\tilde{v}_{ij}, \forall i,j$ are normalized positive triangular fuzzy numbers and their ranges belong to the closed interval [0, 1].

Step 5: From here, we determined FPIS and FNIS as

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, ..., \tilde{v}_n^*), \quad (8)$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, ...\tilde{v}_n^-), \quad (9)$$

Where $\tilde{v}_j^* = (1,1,1)$ and $\tilde{v}_j^- = (0,0,0) \quad j=1,2,...n$

Step 6: We calculated the distance of each alternative from FPIS (fuzzy positive ideal solution) and FNIS (fuzzy negative ideal solution), respectively.

$$d_i^* = \sum_{j=1} [(d(\tilde{v}_{ij}), \tilde{v}_j^*] \quad i= \; 1,2,3...m, \quad (10)$$

$$d_i^- = \sum_{j=1} [(d(\tilde{v}_{ij}), \tilde{v}_j^-] \quad i= \; 1,2,3...m, \quad (11)$$

where $d(.,.)$ is the distance between two fuzzy numbers.

Step 7: We then calculated the closeness coefficient of each alternative as

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+} \quad i= \; 1,2,...m. \quad (12)$$

Step 8: Finally, we determined the ranking order of all alternatives according to the closeness coefficient.

V. COMPARISON OF ALTERNATIVES

Although there are several bulk energy storage alternatives and different criteria, we consider those which are illustrated in Table I. In this study the terms used; "Possibly", "Poor", "Moderate", "Small", "Large", "Good", "Benign" "~" "Mature" "Embryonic" "Available" will be evaluated according to the fuzzy numbers assigned to those terms. According to the three decision makers' judgments, fuzzy membership function and weights of each criterion are obtained.

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TABLE I
COMPARISON OF ENERGY STORAGE ALTERNATIVES

	Pumped hydro	CAES	Flywheels	SMES	Batteries
Efficiency	~75%	~70%	~90%	~95%	~85%
Maximum Energy	10 GWh	5 GWh	15 MWh	1,5 GWh	50 MWh
Maximum Power	3 GW	1 GW	10 MW	1 GW	100 MW
Modular	No	No	Yes	Possibly	Yes
Charge Time	Hours	Hours	Minutes-Hours	Minutes-Hours	Hours
Siting Ease	Poor	Poor	Good	Poor	Moderate
Lead Time	Years	Years	Weeks	Years	Months
Environmental Impact	Large	Large	Benign	Moderate	Moderate
Risk	Moderate	Moderate	Small	Moderate	Moderate
Total Capital Cost ($/KW)	2100	600-750	3695-4313	380-489	1850-2150

After all calculations distance measurements and Closeness Coefficients of alternatives are obtained as seen in Table II.

TABLE II
POSITIVE, NEGATIVE DISTANCES AND CLOSENESS COEFFICIENTS

	A^*	A^-	CC
Pumped Hydro	5.5	5.1	0.48
CAES	6.8	3.7	0.35
Flywheel	5.9	4.9	0.45
SMES	6.7	4	0.38
Batteries	6.6	4.1	0.38

VI. CONCLUSION AND FUTURE WORKS

Although capital costs and the presence of appropriate geography are critical decision factors, Pumped-hydro energy storage technique is currently the most cost-effective means of storing large amounts of electrical energy on an operating basis. Moreover, it is the most widespread energy storage system in use on power networks. Hence, it is not surprising that the result of the Fuzzy TOPSIS marked Pumped-Hydro as the best selection. For future research, with additional criteria, such as recyclability of the materials used to manufacture those storage devices and maturity feature, comparison can be re-performed.

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