Integrated Fuzzy Logic and AHP-TOPSIS for Suitable Turbine Set Selection of Pumped Hydro Storage Powerplant: A Case Study from Thailand

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Abstract. *The purpose of this study is selecting the suitable turbine set for operating the 1,200 MW hydro powerplant at Chulabhorn Dam in Thailand to balance the system. This paper uses Multicriteria Decision Analysis (MCDA) technology by combining fuzzy Analytic Hierarchy Process method (AHP) for weighting criteria and fuzzy Technique for Order Preference by Similarity to an Ideal Solution method (TOPSIS) for prioritizing decision. Six criteria are involved: efficiency and flexibility generation mode, efficiency and flexibility pumped mode, cost, and installation space. There are ten alternatives integrated between three turbines including fixed speed turbine (fi), variable speed turbine by Doubly fed induction machines (df), and variable speed turbine by Full Size Frequency Converter (fs) to power the 1,200 MW generator. As a result, the suitable turbine set in the plant is three of variable speed turbines by Full Size Frequency Converter (fs3) because of its greatest distance from FNIS. Furthermore, this study shows the capability form mixing variety turbine in plant more effective than using the only type of turbine in a plant.*

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1. Introduction

In recent years, the most popular renewable energy source (RES) is used to generate electricity to reduce global warming and strategic energy security. However, due to weather and seasonal fluctuations, it cannot perform as a stand-alone power plant [1]. The important issues for operating the system are storage and balance. The hydro powerplant is selected as the first alternative for reserving excess energy and compensating the mentioned fluctuation to stabilize electricity in the system [2]–[4]. The turbine is the major equipment for transforming kinetic energy into mechanical energy in this powerplant. Nowadays, there are several technologies for selecting the optimal suitability for each requirement. There are two categories of typical turbine, i.e., the fixed speed turbine and the variable speed turbine; each of which has different advantages and disadvantages [5]–[7]. In reality, each project has taken into consideration of many criteria, including efficiency, flexibility, power, maintenance, and investment which lead to difficult decision making [8],[9].

Multi-criteria decision analysis (MCDA) technology is used to find a suitable result for a problem [10]. It can deal with big complex data by using systematic decision making. In the literature, there are many algorithms to determine the scores of criteria or ranking the best alternative. In terms of criteria evaluation, psychologists state that scoring by pairwise comparison from Analytic Hierarchy Process (AHP) is more convenient and more accurate than comparing all criteria simultaneously from the rate-directing process because pairwise comparison involves only two alternatives [11]. Therefore, AHP is being extensively used. Moreover, an algorithm for ranking alternatives offers many solutions for aggregating information, including simple addition weighting (SAW), weighted geometric mean (WGM), AHP and technique for order preference by similarity to an ideal solution (TOPSIS). However, there are many criteria and many alternatives for some problems leading to big complex data. Therefore, the TOPSIS method is preferred as the most straightforward method. In addition, the fuzzy logic is chosen to calculate the best results because the logic can estimate uncertainty in human decisions by means of computation from fuzzy number [12].

In this paper, two MCDM methods, fuzzy AHP and fuzzy TOPSIS are investigated for selection of optimal turbine set to solve the effects of fluctuations from RES at Chulabhorn Dam in Thailand. Thus, the result can be the most suitable option for this problem. Finally, this case study brings about a prototype to choose a turbine set with the decision process.

The rest of the article is organized as follows: Section 2 describes literature review and method; the results and discussion are presented in Section 3. Finally, the conclusions are drawn in Section 4.

2. Literature Review

2.1 Multi-Criteria Decision Analysis (MCDA)

MCDA means finding suitable decision from many criteria and alternatives based on evaluation, prioritization and selection process. There are 4 steps in the process [13].

2.1.1 Problem structuring

This step necessitates specifying details of problem about objective, stakeholders, criteria, and alternative for clearly adjusting the boundaries. There are two types of criteria: quantitative criteria measured by mathematical data, and qualitative criteria, which requires subjective judgments [9]. For some criterion, an ambiguous definition must be explained by sub-criteria, making easy and obvious scoring. In selecting a suitable turbine for each plant, the general criteria to take into account are head and flow of water. For example, the decision making on turbine types and capacities for run-of-river hydroelectric power plants - a case study on eglence-1 HEPP with four criteria including head, flow rate, cost, and cavitation [14].

The selection of low head pico hydro turbine is based on six criteria: efficiency, power, portability, civil work, modularity, maintenance, and serviceability [9]. The turbine selection principles are: head variable, hydro turbine efficiency, runner turbine, load variable, and size equipment [15].

However, the suitable criteria for selection turbine depend on the user's and stockholder's needs. The objective for this paper is the selection of suitable turbine set for operation at Chulabhorn Dam in Thailand, based on six criteria: efficiency generation mode, efficiency pumped mode, flexibility generation mode, flexibility pumped mode, cost, and installation space. There are ten alternatives integrated between three turbines, including fixed speed turbine (fi), variable speed turbine by Doubly Fed induction machines (df), and variable speed turbine by Full Size Frequency Converter (fs) with 400 MW generating capacity of each unit mix to 1,200 MW plant. The scoring criteria in this paper rely on rating by specialists from Electricity Generating Authority of Thailand.

2.1.2 Weighting the criteria

This step discusses the importance of and prioritization of the criteria by specialists with many algorithms. The advantage and disadvantage of each method [16] is shown in Table 1.

Method	Advantage	Disadvantage
Direct Rating (DR)	-simple and straightforward. - not use complex weighting methods.	- difficult for comparing simultaneously
Analytic Hierarchy Process (AHP)	- able to deal with qualitative and multi-dimension criteria. - suitable to judgments in linguistic terms. - recheck consistency.	- not flexibility for add or delete criteria.

Table 1 Comparison of weighting methods

2.1.3 Assessing each alternative of each criterion

A project criterion always has a unit for measurement. Therefore, it is necessary to use the data normalization to make all criteria comparable by proportional transformation, with the best value converted to 1, and the other less than 1.

2.1.4 Aggregating information and making decision based on the arrogated result criterion

This step computes combination between the alternative and criteria for ranking ability of each alternative to show the most suitable alternative for each problem. Several methods for ranking are compared in terms of advantages and disadvantages [16], as shown in Table 2.

Method	Advantage	Disadvantage
SAW	- simple. - ease of implementation.	- some case can be compensated between very low of one criterion and high score for another criteria.
AHP	- (same Table 1)	- (same Table 1)
TOPSIS	- the most straightforward method - suitable for large scale problem - judgement is based on user	- inability to deal with qualitative criteria - not flexible for uncertain score and add or removal alternatives

Table 2 Comparison of aggregating information for decision

2.2 Fuzzy logic

Fuzzy set is used to identify ambiguous data, including uncertain systems in industry, nature and humanity [12], with the degree of membership between 0-1, and the member level from minimum to maximum. The membership can be calculated from the mathematics concept borrowed from [17], [18].

A fuzzy number $\tilde{A}$ on R is a triangular fuzzy number (TFN) if its membership function $\mu_{\tilde{A}}(x) : R \rightarrow [0,1]$ is equal to the following Eq. (1).

$$\mu_A(x) = \begin{cases} (x-l)/(m-l), & l \leq x \leq m \\ (u-x)/(u-m), & l \leq x \leq m \\ 0, & otherwise \end{cases} \quad (1)$$

From Eq. (1), l and u mean the lower and upper boundary of the fuzzy number $\tilde{A}$, respectively, and m is a modal value for $\tilde{A}$ (as shown in Fig. 1), which can be denoted by $\tilde{A} = (l,m,u)$. This associates with linguistic variables with five levels: equal, not bad, good, very good, and perfect [19]. The details of fuzzy number of each level are illustrated in Table 3. For example from Table 3, the scale of fuzzy number (1,3,5) of the fuzzy number 3 which mean not bad can be explained by 1 is lower boundary (l) of modal number 3 (m) and 5 is upper boundary (u) of modal number 3 (m) respectively from Eq. (1). The operational laws of TFN $\tilde{A}_1 = (l_1, m_1, u_1)$ and $\tilde{A}_2 = (l_2, m_2, u_2)$ are illustrated in Table 4.

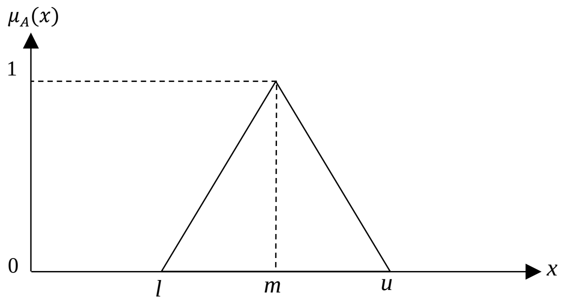

Fig 1.: The membership of the triangular fuzzy number [20]

Fuzzy number	**1**	**3**	**5**	**7**	**9**
Linguistic	Equal	Not bad	Good	Very good	Perfect
Scale of fuzzy number	(1,1,1)	(1,3,5)	(3,5,7)	(5,7,9)	(7,9,10)

Table 3 Linguistic scales of fuzzy number

Operational laws	Rule	Condition
Addition	$\tilde{A}_1 \oplus \tilde{A}_2 = (l_1 + l_2, m_1 + m_2, u_1 + u_2)$	-
Subtraction	$\tilde{A}_1 \ominus \tilde{A}_2 = (l_1 - l_2, m_1 - m_2, u_1 - u_2)$	-
Multiplication	$\tilde{A}_1 \otimes \tilde{A}_2 = (l_1 l_2, m_1 m_2, u_1 u_2)$	-
Division	$\tilde{A}_1 \oslash \tilde{A}_2 = (l_1/l_2, m_1/m_2, u_1/u_2)$	$\begin{cases} for\ l_1, l_2 > 0; \\ m_1, m_2 > 0; \\ u_1, u_2 > 0 \end{cases}$
Reciprocal	$\tilde{A}_1^{-1} = \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right)$	

Table 4 The operational laws of TFN

2.3 The Fuzzy AHP Method

Many complex decision problems use AHP method for hierarchy level of criteria by using pairwise comparison for rating each criterion [12]. The conceptual framework to assist weighting score depends on the data from customer needs/stakeholder requirements. In engineering, an application uses AHP to solve the problems in evaluating renewable energy alternatives in Turkey [21] and to select suitable power of wind turbine at Qassim, Saudi Arabia [22]. The result indicates that AHP is adequate for rearranging choices. However, if the user wants to use the score for calculating identity by value, fuzzy AHP can give different outcome of the results [23]. Thus, the method that combines fuzzy and AHP yields the value of result that covers the uncertainty from an environment of problems such as human decisions [24]. The triangular fuzzy numbers theory used in this process and the concept of fuzzy AHP calculation are discussed in the following sections.

Step 1: Building matrix $\tilde{\boldsymbol{A}}$ from data of pairwise comparison of each criteria

$$\tilde{\boldsymbol{A}} = \begin{bmatrix} 1 & \tilde{a}_{12} & \ldots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \tilde{a}_{12} & \ldots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{2n} & \cdots & 1 \end{bmatrix} \quad (2)$$

Step 2: Defining the fuzzy geometric mean and fuzzy weights of each criterion by geometric mean technique from [25].

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \cdots \otimes \tilde{a}_{ij} \otimes \cdots \otimes \tilde{a}_{in})^{1/n},$$
$$\widetilde{w}_i = \tilde{r}_i \otimes [\tilde{r}_1 \otimes \cdots \otimes \tilde{r}_i \otimes \cdots \otimes \tilde{r}_n]^{-1} \quad (3)$$

Where $\tilde{r}_i$ from eq.(3) is a geometric mean of fuzzy comparison value of criterion i to each criterion, the weight of the ith criteria is defined $\widetilde{w}_i$ as lower, middle, and upper value of the fuzzy weight of the ith dimension stand for $lw_i, mw_i,\ and\ uw_i$ and can be indicated by a TFN, $\widetilde{w}_i = (lw_i, mw_i, uw_i)$.

2.4 The Fuzzy TOPSIS Method

This method is used for ranking the best alternative suitable for the problem by calculating data from scores of criteria and alternatives. In principle, the alternative selected should demonstrate the shortest distance from the positive ideal solution (PIS) or the longest distance from the negative ideal solution (NIS) [25]. The fuzzy TOPSIS is adaptable for use with several problems because the method can deal with uncertainty that arises from human decision [24]. It is able to solve many problems such as real-time for selection non-traditional machining processes [26], evaluation of the notebook computer ODM companies by hierarchical level of criteria from a specialist [18], selecting the most effective gas turbine component from the occurring failures [27], evaluation and selection of thermal power plant location [28]. There are five steps for prioritizing the alternatives [29], [30]:

Step 1: Use weighting of evaluation criteria by fuzzy AHP. Construct the fuzzy decision matrix as follows:

$$\tilde{\boldsymbol{D}} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \end{array} \quad (4)$$

$$\tilde{x}_{ij} = \frac{1}{K}\,(\tilde{x}_{ij}^1 \oplus \cdots \oplus \tilde{x}_{ij}^k \oplus \cdots \oplus \tilde{x}_{ij}^K)$$

$$i = 1, 2, \ldots, m \,;\, j = 1, 2, .., n$$

where $\tilde{x}_{ij}^k$ is the performance rating of alternative A_i with respect to criterion C_j evaluated by k^th expert, and $\tilde{x}_{ij}^k = (l_{ij}^k, m_{ij}^k, u_{ij}^k)$.

Step 2: Normalize the fuzzy-decision matrix denoted by $\tilde{\boldsymbol{R}}$ as in the following formula:

$$\tilde{\boldsymbol{R}} = [\tilde{r}_{ij}]_{m\times n}, i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n \quad (5)$$

Then the normalization process is performed by the following formula:

$$\tilde{r}_{ij} = \left(\frac{l_{ij}}{u_j^+}, \frac{m_{ij}}{u_j^+}, \frac{u_{ij}}{u_j^+}\right),\ u_j^+ = max_i\{u_{ij} | i = 1, 2, \ldots, n\}.$$

The weighted fuzzy normalized decision matrix is shown in the following matrix $\tilde{\boldsymbol{V}}$:

$$\tilde{\boldsymbol{V}} = [\tilde{v}_{ij}]_{m\times n}, i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n \quad (6)$$

where $\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \tilde{w}_j$.

Step 3: Determine the fuzzy positive-ideal solution (FPIS) and negative-ideal solution (FNIS). The aspiration and the worst level can defined by FPIS A+ and FNIS A-, respectively, as in the following formula:

$$A^+ = (\tilde{v}_1^*, \ldots, \tilde{v}_j^*, \ldots, \tilde{v}_n^*), \tilde{v}_j^* = (1,1,1);\ j = 1, 2, \ldots, n \quad (7)$$

$$A^- = (\tilde{v}_1^-, \ldots, \tilde{v}_j^-, \ldots, \tilde{v}_n^-), \tilde{v}_j^- = (0,0,0);\ j = 1, 2, \ldots, n \quad (8)$$

Step 4: Calculate the distance of each alternative ($\tilde{d}_i^+$ and $\tilde{d}_i^-$) from FPIS and FNIS.

$$\tilde{d}_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*), \tilde{d}_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-),$$

$$i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n \quad (9)$$

Step 5: Calculate the $\widetilde{CC}_i$ to define the fuzzy gaps-degree based on fuzzy closeness coefficients for improving the alternative, calculated by this formula:

$$\widetilde{CC}_i = \frac{\tilde{d}_i^-}{\tilde{d}_i^+ + \tilde{d}_i^-} = 1 - \frac{\tilde{d}_i^+}{\tilde{d}_i^+ + \tilde{d}_i^-}, i = 1, 2, \ldots, m \quad (10)$$

where $\frac{\tilde{d}_i^-}{\tilde{d}_i^+ + \tilde{d}_i^-}$ is defined as fuzzy satisfaction degree in *i*th alternative and $\frac{\tilde{d}_i^+}{\tilde{d}_i^+ + \tilde{d}_i^-}$ as fuzzy gap degree in *i*th alternative.

3. Results and Discussion

MCDA was applied by using fuzzy AHP and fuzzy TOPSIS for evaluating the suitable turbine set at Chulabhorn Dam in Thailand. The purpose was to choose a turbine set that responds to RES fluctuation. There are six criteria for selection of the set: 1. efficiency generation mode, 2. efficiency pumped mode, 3. flexibility generation mode, 4. flexibility pumped mode, 5. cost, and 6. installation space. Moreover, there are sub-criteria in the flexibility generation criteria: generating equal load, more than load, and less than load. The powerplant must be 1,200 MW operating by using three turbines, each of which consists of three types of turbines, i.e., fi, df, and fs. The steps for calculating priority criteria and for the best decision are listed below:

Step 1: Use gathering data from interview specialists (shown in Appendix A 5.1) to synthesize pairwise comparison matrix by fuzzy geometric mean method from Eq. (2) by [31], for example:

$$\begin{aligned} \tilde{a}_{21} &= (1,1,1) \otimes (0.20,0.33,1.00) \otimes \cdots \otimes (1,1,1)^{1/9} \\ &= (1 \times 0.20 \times \ldots \times 1)^{1/9}, (1 \times 0.33 \times \ldots \times 1)^{1/9}, \\ &\quad (1 \times 1 \times \ldots \times 1)^{1/9} \\ &= (0.52,0.71,1.05) \end{aligned}$$

The synthetic pairwise comparison matrix will be constructed as follows:

$$
\text{Matrix} = \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \end{array}
\begin{array}{cccccc} A_1 & A_2 & A_3 & A_4 & A_5 & A_6 \end{array}
\begin{bmatrix}
(1.00,1.00,1.00) & (0.96,1.40,1.92) & (0.88,1.03,1.20) & (0.99,1.36,1.97) & (0.39,0.65,0.97) & (1.20,2.06,2.81) \\
(0.52,0.71,1.05) & (1.00,1.00,1.00) & (0.67,0.92,1.36) & (0.89,1.23,1.97) & (0.36,0.55,0.89) & (1.35,2.47,3.49) \\
(0.71,0.97,1.26) & (0.73,1.09,1.50) & (1.00,1.00,1.00) & (1.53,1.95,2.51) & (0.84,1.34,2.31) & (0.79,1.38,2.29) \\
(0.51,0.73,1.01) & (0.51,0.81,1.12) & (0.40,0.51,0.66) & (1.00,1.00,1.00) & (0.48,0.75,1.10) & (0.88,1.35,1.91) \\
(1.03,1.54,2.54) & (1.13,1.83,2.79) & (0.43,0.75,1.20) & (0.91,1.34,2.09) & (1.00,1.00,1.00) & (0.53,0.78,1.33) \\
(0.36,0.48,0.84) & (0.29,0.41,0.74) & (0.44,0.73,1.27) & (0.52,0.74,1.14) & (0.75,1.28,1.90) & (1.00,1.00,1.00)
\end{bmatrix}
$$

Step 2: Calculate the fuzzy geometric mean, the weights of each criterion from Eq. (3) and BNP value of the fuzzy weights of each dimension seen in the following parts:

fuzzy geometric mean

$$
\begin{aligned}
\tilde{r}_1 &= (1 \times \ldots \times 1.20)^{1/6}, (1 \times \ldots \times 2.06)^{1/6}, \\
&\quad (1 \times \ldots \times 2.81)^{1/6} \\
&= (0.86,1.18,1.52)
\end{aligned}
$$

weights

$$
\begin{aligned}
\widetilde{w}_1 &= (0.86,1.18,1.52) \otimes (1/(0.86 + \cdots + 0.51), \\
&\quad 1/(1.18 + \cdots + 0.72), 1/(1.52 + \cdots + 1.09)) \\
&= (0.10,0.19,0.35)
\end{aligned}
$$

BNP value of the fuzzy weights of each dimension, the calculation process is as follows.

$$
\begin{aligned}
BNP_{w_1} &= \left[(U_{w_1} - L_{w_1}) + (M_{w_1} - L_{w_1})\right]/3 + L_{w_1} \\
&= [(0.35 - 0.10) + (0.19 - 0.10)]/3 + 0.10 \\
&= 0.21
\end{aligned}
$$

Similarly, we can obtain the remaining $\tilde{r}_i$, $\widetilde{w}_i$, and BNP_i shown in Table 5.

In this case, there are three turbines including fixed speed turbine (fi), variable speed turbine by Doubly fed induction machines (df), and variable speed turbine by Full Size Frequency Converter (fs). Therefore, there are ten alternatives from integrated the turbines Show in Table 6.

Name	fi3	fs3	df3	fi2fs	fi2df	fs2fi	df2fi	fs2df	df2fs	fifsdf
#fi	3	-	-	2	2	1	1	-	-	1
#df	-	-	3	-	1	-	2	1	2	1
#fs	-	3	-	1	-	2	-	2	1	1

Table 6 The alternatives of the problem

i	Criteria	$\tilde{r}_i$	$\widetilde{w}_i$	BNP_i	Rank
1	efficiency generation mode	(0.86,1.18,1.52)	(0.10,0.19,0.35)	0.21	3
2	efficiency pumped mode	(0.73,1.01,1.43)	(0.09,0.17,0.33)	0.19	4
3	flexibility generation mode	(0.90,1.25,1.71)	(0.11,0.20,0.39)	0.23	1
4	flexibility pumped mode	(0.59,0.82,1.08)	(0.07,0.13,0.25)	0.15	5
5	cost	(0.79,1.14,1.69)	(0.09,0.19,0.39)	0.22	2
6	installation space	(0.51,0.72,1.09)	(0.06,0.12,0.25)	0.14	6

Table 5 Value of $\tilde{r}_i$, $\widetilde{w}_i$, and BNP_i

Step 3: Process data of the alternatives shown in Appendix 5.2. Using Eq. (5) to normalize the fuzzy matrix as seen in Table 7 and Table 8.

Criteria	fi3	fs3	df3	fi2fs	fi2df
1	(0.77,0.97,1.00)	(1.00,1.00,1.00)	(0.79,0.99,1.00)	(0.78,0.98,1.00)	(0.78,0.98,1.00)
2	(1.00,1.00,1.00)	(0.79,0.99,1.00)	(1.00,1.00,1.00)	(0.80,1.00,1.00)	(1.00,1.00,1.00)
3	(0.02,0.22,0.42)	(1.00,1.00,1.00)	(0.23,0.43,0.63)	(0.08,0.28,0.48)	(0.09,0.29,0.49)
4	(0.10,0.17,0.37)	(1.00,1.00,1.00)	(0.07,0.27,0.47)	(0.39,0.59,0.79)	(0.05,0.25,0.45)
5	(1.00,1.00,1.00)	(0.39,0.59,0.79)	(0.57,0.77,0.97)	(0.61,0.81,1.00)	(0.71,0.91,1.00)
6	(1.00,1.00,1.00)	(0.51,0.71,0.91)	(0.60,0.80,1.00)	(0.68,0.88,1.00)	(0.72,0.92,1.00)

Table 7 Normalization of the fuzzy matrix

Criteria	fs2fi	df2fi	fs2df	df2fs	fifsdf
1	(0.79,0.99,1.00)	(0.79,0.99,1.00)	(0.80,1.00,1.00)	(0.80,1.00,1.00)	(0.79,0.99,1.00)
2	(0.79,0.99,1.00)	(1.00,1.00,1.00)	(0.79,0.99,1.00)	(0.80,1.00,1.00)	(0.80,1.00,1.00)
3	(0.22,0.42,0.62)	(0.17,0.37,0.57)	(0.42,0.62,0.82)	(0.30,0.50,0.70)	(0.20,0.40,0.60)
4	(0.66,0.86,1.00)	(0.05,0.25,0.45)	(0.68,0.88,1.00)	(0.43,0.63,0.83)	(0.42,0.62,0.82)
5	(0.48,0.68,0.88)	(0.63,0.83,1.00)	(0.44,0.64,0.84)	(0.50,0.70,0.90)	(0.55,0.75,0.95)
6	(0.59,0.79,0.99)	(0.66,0.86,1.00)	(0.54,0.74,0.94)	(0.57,0.77,0.97)	(0.62,0.82,1.00)

Table 8 Normalization of the fuzzy matrix

Step 4: Establish the weighted normalized fuzzy-decision matrix by using Eq. (6). The result is shown in Table 9 and Table 10.

Criteria	fi3	fs3	df3	fi2fs	fi2df
1	(0.08,0.19,0.35)	(0.13,0.19,0.35)	(0.08,0.19,0.35)	(0.08,0.19,0.35)	(0.08,0.19,0.35)
2	(0.09,0.17,0.33)	(0.07,0.16,0.33)	(0.09,0.17,0.33)	(0.07,0.17,0.33)	(0.09,0.17,0.33)
3	(0.00,0.04,0.16)	(0.11,0.20,0.39)	(0.02,0.09,0.25)	(0.01,0.06,0.19)	(0.01,0.06,0.19)
4	(0.01,0.02,0.09)	(0.07,0.13,0.25)	(0.00,0.04,0.12)	(0.03,0.08,0.19)	(0.00,0.03,0.11)
5	(0.09,0.19,0.39)	(0.04,0.11,0.30)	(0.05,0.14,0.37)	(0.06,0.15,0.39)	(0.07,0.17,0.39)
6	(0.06,0.12,0.25)	(0.03,0.08,0.23)	(0.04,0.09,0.25)	(0.04,0.10,0.25)	(0.04,0.11,0.25)

Table 9 The weighted normalized fuzzy-decision matrix

Criteria	fs2fi	df2fi	fs2df	df2fs	fifsdf
1	(0.08,0.19,0.35)	(0.08,0.19,0.35)	(0.08,0.19,0.35)	(0.08,0.19,0.35)	(0.08,0.19,0.35)
2	(0.07,0.16,0.33)	(0.09,0.17,0.33)	(0.07,0.16,0.33)	(0.07,0.17,0.33)	(0.07,0.17,0.33)
3	(0.02,0.90,0.24)	(0.02,0.08,0.22)	(0.04,0.13,0.32)	(0.03,0.10,0.27)	(0.02,0.08,0.23)
4	(0.05,0.12,0.25)	(0.00,0.03,0.11)	(0.05,0.12,0.25)	(0.03,0.09,0.21)	(0.03,0.08,0.20)
5	(0.04,0.13,0.34)	(0.06,0.16,0.39)	(0.04,0.12,0.32)	(0.05,0.13,0.35)	(0.05,0.14,0.37)
6	(0.04,0.09,0.25)	(0.04,0.10,0.25)	(0.03,0.09,0.23)	(0.03,0.09,0.24)	(0.04,0.10,0.25)

Table 10 The weighted normalized fuzzy-decision matrix

Step 5: Determine the FPIS and FNIS as: A^+ and A^- from Eq. (7)-(8). The result is shown in Table 11.

Alternatives	fi3	fs3	df3	fi2fs	fi2df	fs2fi	df2fi	fs2df	df2fs	fifsdf
d_i^+	0.20	0.08	0.16	0.16	0.18	0.13	0.17	0.10	0.12	0.14
d_i^-	0.40	0.44	0.39	0.39	0.39	0.39	0.39	0.41	0.39	0.39
CC_i^+	0.33	0.15	0.29	0.30	0.32	0.25	0.30	0.19	0.24	0.26
CC_i^-	0.67	0.85	0.71	0.70	0.68	0.75	0.70	0.81	0.76	0.74

Table 11 The closeness coefficients and distances from FPIS, FNIS of each of the alternatives

From previous work [8] The data which study about efficiency and flexibility of each set turbine is show in Fig. 2.

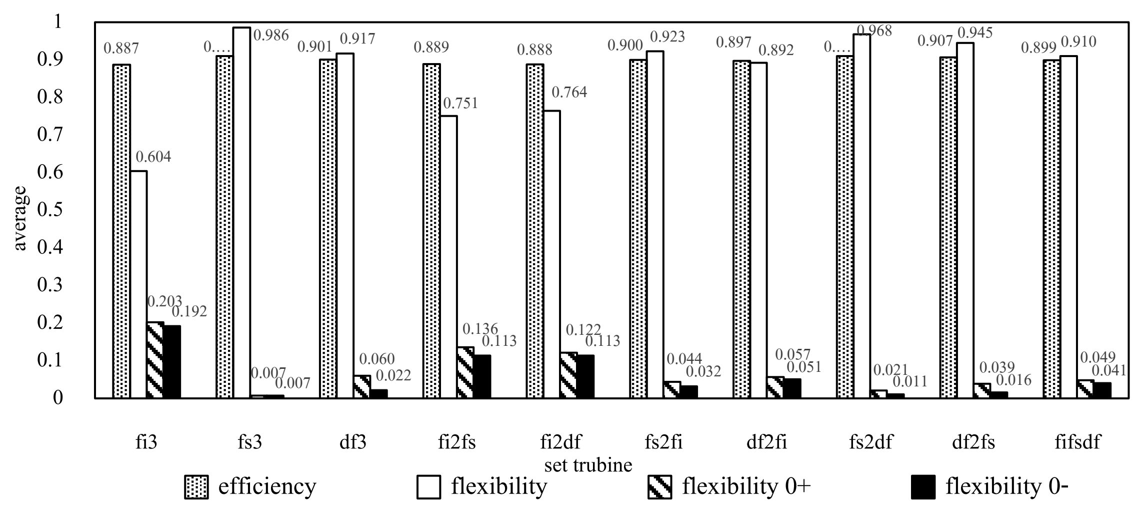

Fig. 2: Ability of set turbines [8]

The fuzzy TOPSIS is used to prioritize and rank the alternatives. The result indicates the satisfactory degree and gap degree of each turbine set. The gap degree value from negative ideal solution (CC_i^-) from Table. 9 of fi3, fs3, df3, fi2fs, fi2df, fs2fi, df2fi, fs2df, df2fs, and fifsdf are 0.67, 0.85, 0.71, 0.70, 0.68, 0.75, 0.70, 0.81, 0.76, and 0.74 levels, respectively. The top three alternatives have most distance from FNIS, i.e., are fs3, fs2df, and df2fs respectively. From the proposed fuzzy AHP and fuzzy TOPSIS, we found the top three criteria for selecting the turbine set: flexibility generation mode, cost, and efficiency generation mode. Moreover, the fs3, fs2df, and df2fs are the top three turbine sets obtained from ranking the alternatives. The distance value from negative ideal solution score can categorize 4 groups having similar scores. The first group shows the greatest distance value of CC_i^- around 0.85 and 0.81, or fs3 and fs2df, respectively. The fs3 has the advantage related to efficiency of operation (see in Fig 2) and common maintenance. On the other hand, the fs2df has a little advantage in investment cost. The second group including df2fs, fs2fi and fifsdf demonstrates the values of CC_i^- around 0.76, 0.75 and 0.74, respectively. In this group, maintenance of the fifsdf is complicated because an operator has to prepare the component of each diversity turbine type to repair it. Thus, we should select the df2fs or fs2fi instead of the fifsdf. However, we cannot identify the best set in this group because the investment cost of the two sets is similar. The values of CC_i^- of the third group, including df3, df2fi and fi2fs, are 0.71, 0.70 and 0.70, respectively. When considering the advantages in terms of efficiency (see in Fig 2), cost and maintenance of parts, the df 3 is the best alternative in this collection because it has maximum gap from negative ideal solution and the set using the same type of turbine. The last group including fi2df and fi3 shows the value of CC_i^- around 0.68 and 0.67. Comparison between investment cost and ability reveals that the fi3 is better than the fi2df because the set is of lower prices than the fi2df whereas the ability is similar.

4. Conclusions

The integrated calculation method simplifies decision making and leads to better understanding of the complex evaluation process. From the scores obtained from weighting the criteria and ability of each alternative, the suitable turbine set in the plant is fs3 because of its greatest distance from FNIS and the least distance from FPIS. On the other hand, fi3 is the worst choice, since the set has minimum ability in the important criteria. The value of fi3 demonstrates the minimum distance from FNIS and the maximum distance from FPIS. It should be noted the result can be uncertain because it depends on the score criteria required by specialists or stakeholders. Furthermore, this study shows the capability form mixing variety turbine in plant more effective than using the only type of turbine in a plant. However, the decision selected under this study has undergone a systematic, effective and accurate method. Therefore, this method is appropriate to be adapted for the cases of complex problems for finding a suitable decision for each problem.

5. Appendices

5.1 Linguistic scale of each expert

$$\begin{array}{c|cccccc|} & D_1 & D_2 & D_3 & D_4 & D_5 & D_6 \\ \hline D_1 & 1 & \tilde{1} & \tilde{5} & \tilde{5} & \tilde{7}^{-1} & \tilde{3} \\ D_2 & \tilde{1} & 1 & \tilde{5} & \tilde{5} & \tilde{5}^{-1} & \tilde{3} \\ D_3 & \tilde{5}^{-1} & \tilde{5}^{-1} & 1 & \tilde{1} & \tilde{3}^{-1} & \tilde{3} \\ D_4 & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{1} & 1 & \tilde{7}^{-1} & \tilde{5}^{-1} \\ D_5 & \tilde{7} & \tilde{5} & \tilde{3} & \tilde{7} & 1 & \tilde{5} \\ D_6 & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{5} & \tilde{5}^{-1} & 1 \end{array}, \quad \begin{array}{c|cccccc|} & D_1 & D_2 & D_3 & D_4 & D_5 & D_6 \\ \hline D_1 & 1 & \tilde{3} & \tilde{7} & \tilde{7} & \tilde{3} & \tilde{5} \\ D_2 & \tilde{3}^{-1} & 1 & \tilde{7} & \tilde{7} & \tilde{3} & \tilde{5} \\ D_3 & \tilde{7}^{-1} & \tilde{7}^{-1} & 1 & \tilde{7} & \tilde{5} & \tilde{5} \\ D_4 & \tilde{7}^{-1} & \tilde{7}^{-1} & \tilde{7}^{-1} & 1 & \tilde{5} & \tilde{5} \\ D_5 & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{5}^{-1} & \tilde{5}^{-1} & 1 & \tilde{3}^{-1} \\ D_6 & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{3} & 1 \end{array}, \quad \begin{array}{c|cccccc|} & D_1 & D_2 & D_3 & D_4 & D_5 & D_6 \\ \hline D_1 & 1 & \tilde{7} & \tilde{5} & \tilde{7} & \tilde{5}^{-1} & \tilde{1} \\ D_2 & \tilde{7}^{-1} & 1 & \tilde{5}^{-1} & \tilde{1} & \tilde{5}^{-1} & \tilde{3} \\ D_3 & \tilde{5}^{-1} & \tilde{5} & 1 & \tilde{7} & \tilde{5}^{-1} & \tilde{3}^{-1} \\ D_4 & \tilde{7}^{-1} & \tilde{1} & \tilde{7}^{-1} & 1 & \tilde{7}^{-1} & \tilde{5}^{-1} \\ D_5 & \tilde{5} & \tilde{5} & \tilde{5} & \tilde{7} & 1 & \tilde{3}^{-1} \\ D_6 & \tilde{1} & \tilde{3}^{-1} & \tilde{3} & \tilde{5} & \tilde{3} & 1 \end{array}$$

$$\begin{array}{c|cccccc|} & D_1 & D_2 & D_3 & D_4 & D_5 & D_6 \\ \hline D_1 & 1 & \tilde{3}^{-1} & \tilde{1} & \tilde{1} & \tilde{9}^{-1} & \tilde{3} \\ D_2 & \tilde{3} & 1 & \tilde{5} & \tilde{3}^{-1} & \tilde{9}^{-1} & \tilde{5} \\ D_3 & \tilde{1} & \tilde{5}^{-1} & 1 & \tilde{3}^{-1} & \tilde{5}^{-1} & \tilde{3}^{-1} \\ D_4 & \tilde{1} & \tilde{3} & \tilde{3} & 1 & \tilde{5}^{-1} & \tilde{5} \\ D_5 & \tilde{9} & \tilde{9} & \tilde{5} & \tilde{5} & 1 & \tilde{5} \\ D_6 & \tilde{3}^{-1} & \tilde{5}^{-1} & \tilde{3} & \tilde{5}^{-1} & \tilde{5}^{-1} & 1 \end{array}, \quad \begin{array}{c|cccccc|} & D_1 & D_2 & D_3 & D_4 & D_5 & D_6 \\ \hline D_1 & 1 & \tilde{3} & \tilde{3}^{-1} & \tilde{5} & \tilde{5}^{-1} & \tilde{5} \\ D_2 & \tilde{3}^{-1} & 1 & \tilde{5}^{-1} & \tilde{5} & \tilde{5}^{-1} & \tilde{5} \\ D_3 & \tilde{3} & \tilde{5} & 1 & \tilde{5} & \tilde{5} & \tilde{5} \\ D_4' & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{5}^{-1} & 1 & \tilde{5} & \tilde{5} \\ D_5 & \tilde{5} & \tilde{5} & \tilde{5}^{-1} & \tilde{5}^{-1} & 1 & \tilde{5} \\ D_6 & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{5}^{-1} & 1 \end{array}, \quad \begin{array}{c|cccccc|} & D_1 & D_2 & D_3 & D_4 & D_5 & D_6 \\ \hline D_1 & 1 & \tilde{7}^{-1} & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{3} & \tilde{7} \\ D_2 & \tilde{7} & 1 & \tilde{5}^{-1} & \tilde{3}^{-1} & \tilde{7} & \tilde{7} \\ D_3 & \tilde{5} & \tilde{5} & 1 & \tilde{5} & \tilde{5} & \tilde{5} \\ D_4 & \tilde{5} & \tilde{3} & \tilde{5}^{-1} & 1 & \tilde{5} & \tilde{7} \\ D_5 & \tilde{3}^{-1} & \tilde{7}^{-1} & \tilde{5}^{-1} & \tilde{5}^{-1} & 1 & \tilde{5}^{-1} \\ D_6 & \tilde{7}^{-1} & \tilde{7}^{-1} & \tilde{5}^{-1} & \tilde{7}^{-1} & \tilde{5} & 1 \end{array}$$

$$\begin{array}{c|cccccc|} & D_1 & D_2 & D_3 & D_4 & D_5 & D_6 \\ \hline D_1 & 1 & \tilde{1} & \tilde{1} & \tilde{1} & \tilde{5} & \tilde{3} \\ D_2 & \tilde{1} & 1 & \tilde{1} & \tilde{1} & \tilde{5} & \tilde{3} \\ D_3 & \tilde{1} & \tilde{1} & 1 & \tilde{1} & \tilde{5} & \tilde{3} \\ D_4 & \tilde{1} & \tilde{1} & 1 & 1 & \tilde{3} & \tilde{3} \\ D_5 & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{5}^{-1} & \tilde{3}^{-1} & 1 & \tilde{5}^{-1} \\ D_6 & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{3}^{-1} & 5 & 1 \end{array}, \quad \begin{array}{c|cccccc|} & D_1 & D_2 & D_3 & D_4 & D_5 & D_6 \\ \hline D_1 & 1 & \tilde{7} & \tilde{9}^{-1} & \tilde{3}^{-1} & \tilde{5} & \tilde{1} \\ D_2 & \tilde{7}^{-1} & 1 & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{3}^{-1} & \tilde{1} \\ D_3 & \tilde{9} & \tilde{3} & 1 & \tilde{1} & \tilde{5} & \tilde{1} \\ D_4 & \tilde{3} & \tilde{3} & \tilde{1} & 1 & \tilde{3}^{-1} & \tilde{1} \\ D_5 & \tilde{5}^{-1} & \tilde{3} & \tilde{5}^{-1} & \tilde{3} & 1 & \tilde{1} \\ D_6 & \tilde{1} & \tilde{1} & \tilde{1} & \tilde{1} & \tilde{1} & 1 \end{array}, \quad \begin{array}{c|cccccc|} & D_1 & D_2 & D_3 & D_4 & D_5 & D_6 \\ \hline D_1 & 1 & \tilde{1} & \tilde{1} & \tilde{5}^{-1} & \tilde{7}^{-1} & \tilde{7}^{-1} \\ D_2 & \tilde{1} & 1 & \tilde{1} & \tilde{1} & \tilde{7}^{-1} & \tilde{7}^{-1} \\ D_3 & \tilde{1} & \tilde{1} & 1 & \tilde{1} & \tilde{3}^{-1} & \tilde{7}^{-1} \\ D_4 & \tilde{5} & \tilde{1} & \tilde{1} & 1 & \tilde{7}^{-1} & \tilde{7}^{-1} \\ D_5 & \tilde{7} & \tilde{7} & \tilde{3} & \tilde{7} & 1 & \tilde{5}^{-1} \\ D_6 & \tilde{7} & \tilde{7} & \tilde{7} & \tilde{7} & \tilde{5} & 1 \end{array}$$

5.2 Ability Scale of Each Alternative

Criteria	fi3	fs3	df3	fi2fs	fi2df	fs2fi	df2fi	fs2df	df2fs	fifsdf
1	9.74	10.00	9.90	9.77	9.76	9.89	9.86	9.99	9.96	9.87
2	10.00	9.92	10.00	9.97	10.00	9.95	10.00	9.95	9.97	9.97
3	2.20	10.00	4.30	2.81	2.90	5.84	3.87	7.07	5.18	4.34
4	1.68	10.00	0.66	4.45	2.00	7.23	2.33	7.55	5.10	4.78
5	10.00	5.58	7.69	8.11	9.09	6.82	8.33	6.38	6.98	7.50
6	10.00	7.14	8.00	8.82	9.23	7.89	8.57	7.41	7.69	8.22

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