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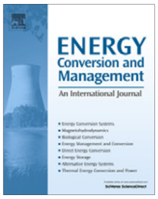

A wind turbine evaluation model under a multi-criteria decision making environment

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ABSTRACT

Due to the impacts of fossil and nuclear energy on the security, economics, and environment in the world, the demand of alternative energy resources is expanding consistently and tremendously in recent years. Wind energy production, with its safe and environmental characteristics, has become the fastest growing renewable energy source in the world. The construction of new wind farms and the installation of new wind turbines are important processes in order to provide a long-term energy production. In this research, a comprehensive evaluation model, which incorporates interpretive structural modeling (ISM) and fuzzy analytic network process (FANP), is constructed to select suitable turbines when developing a wind farm. A case study is carried out in Taiwan in evaluating the expected performance of several potential types of wind turbines, and experts in a wind farm are invited to contribute their expertise in determining the importance of the factors of the wind turbine evaluation and in rating the performance of the turbines with respect to each factor. The most suitable turbines for installation can finally be generated after the calculations. The results can be references for decision makers in selecting the most appropriate wind turbines.

1. Introduction

Global warming and climate change have increased the consciousness of human beings in preserving the world and have shifted the focus of industrial development towards low-carbon renewable energy. Commercial wind farms currently operate in around 80 countries, and there are many benefits for both developed and developing countries to build wind farms. These benefits include increased energy security, stable power prices, economic development to attract investment and to create jobs, reduced dependence on imported fuels, improved air quality, and CO_2 emissions reductions [1]. To generate electricity, a wind farm incurs three major types of costs: capital costs, running costs and financing cost. The capital costs include all the costs of building the power plant and connecting it to the grid; the running costs include the operation and maintenance of the wind farm; and the financing cost is the cost of acquiring the necessary funds for constructing and running a wind farm. The capital cost is very high, between 75% and 90% of the total for onshore projects, and wind turbines amount to 64% of total capital cost for a typical 5 MW onshore project [2]. Fortunately, the capital cost of producing wind turbines has fallen steadily over the past two decades because of advanced manufacturing techniques and mass production and automation [3]. Nevertheless, the selection of appropriate wind turbines is of extremely high importance as the costs of the wind turbines make up the majority of the total cost for a wind farm project. In addition, the suitability of the wind turbines for a particular location may affect the capacity factor of the wind turbines.

The evaluation and selection of renewable energy alternatives is a multi-criteria decision making (MCDM) problem because multiple criteria, some may even be in conflict, must be taken into consideration at the same time. MCDM methods, such as analytical hierarchy process (AHP), analytic network process (ANP), preference ranking organization method for enrichment of evaluations (PROMETHEE), multi-attribute utility theory (MAUT), technique for order preference by similarity to the ideal solution (TOPSIS), multi-objective decision making (MODM), VlšeKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) and ELimination Et Choix Traduisant la REalité (ELECTRE), have been used in the evaluation of renewable energy projects [4,5]. Past applications of MCDM on renewable energy include renewable energy project planning, wind farm projects, solar energy projects, geothermal projects and hydro-site selection, etc. [5]. Wang et al. [6] did a very comprehensive review on multi-criteria decision analysis aid in sustainable energy decision-making. Methods in different stages of MCDM for sustainable energy were reviewed, including criteria selection, criteria weighting, evaluation and final aggregation.

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Kahraman et al. [4] and San Cristóbal [5] also reviewed some works.

Some recent studies of decision-making in energy are reviewed here. Pilavachi et al. [7] proposed a MCDM method with an agglomeration function based on the statistical evaluation of weight factors to calculate sustainability indices for several combined heat and power (CHP) systems. Patlitzianas et al. [8] presented an integrated MCDM approach, based on ordered weighted average, to integrate qualitative judgments on many opportunities and threats factors for assessing the environment of renewable energy producers in EU accession member states. Afgan et al. [9] applied ASPID to calculate the priority ratings amongst selected alternative options of gas transport systems in Southeast and Central Europe. Önüt et al. [10] adopted the ANP to evaluate the most suitable energy resources for the manufacturing industry in Turkey. Nobre et al. [11] used a geo-spatial multi-criteria analysis methodology, based on geographic information systems (GIS) technology, to identify the best location for deploying a wave energy farm. Lee et al. [12] presented a MCDM method, with the incorporation of AHP and the benefits, opportunities, costs and risks (BOCR) concept, to help select a suitable wind farm project. Kolios et al. [13] provided a systematic methodology based on the TOPSIS for classification and evaluation of different available offshore wind turbine support structures. Lee [14] evaluated and ranked the energy performance of buildings from the perspective of multiple objective outputs by applying fuzzy measure and fuzzy integral, a multiple attribute decision-making approach. San Cristóbal [5] applied the AHP to obtain the relative importance weights of attributes and used the VIKOR method to select the most suitable renewable energy project in Spain.

Due to vagueness, ambiguity and subjectivity of human judgment in many decision making problems, the fuzzy set theory can be adopted to express the linguistic terms using membership functions [4,15]. Kahraman et al. [4] applied two MCDM methodologies for selecting the best renewable energy alternative in Turkey: fuzzy analytic hierarchy process (FAHP) and fuzzy axiomatic design (FAD). A comparative analysis of the case found that both methodologies led to the same outcome. Chen et al. [16] devised a FAHP approach associated with the BOCR concept to evaluate solar-wind power generation projects. Kaya and Kahraman [15] constructed an integrated VIKOR-AHP methodology with the application of the fuzzy logic, to the selection of the best renewable energy policy first and to the selection of the energy production site next. Lee et al. [17] developed a conceptual model for product strategy in the solar cell power industry, and interpretive structural modeling (ISM), FANP and the BOCR concept are integrated to analyze suitable strategic products.

The topic of renewable energy evaluation is getting more attention these days; however, the uses of MCDM methodologies with the consideration of imprecise and fuzzy information to tackle the complex problem are rather limited. Since the construction of wind farm is a complicated task and the selection of the most appropriate wind turbines is essential for the future operation of the wind farm, a systematic MCDM model for evaluating different wind turbine systems is necessary for making the correct selection decision. In the authors' understanding, this paper is the first one that examines the interrelationship of the criteria in the decision making process by adopting interpretive structural modeling (ISM) and fuzzy analytic network process (FANP) to evaluate different wind turbine systems. Based on the evaluation results, the firm can select the most appropriate wind turbine system to be constructed in its new wind farm.

The rest of this paper is organized as follows. Section 2 briefly introduces the research methods. In Section 3, an integrated MCDM model is constructed. In Section 4, the model is applied to a case study to evaluate wind turbine systems. Some concluding remarks are made in the last section.

2. Research methods

2.1. Interpretive structural modeling (ISM)

Interpretive structural modeling (ISM) was proposed by Warfield in 1974 to be applied in analyzing complex situations and putting together a course of action for solving a problem [18–20]. A question such as "Does criterion x_i affect criterion x_j?" is asked, and $\pi_{ij} = 1$ if the answer is yes, $\pi_{ij} = 0$ otherwise. A binary matrix, called relation matrix, can then be prepared [21]. A reachability matrix is calculated next to consider transitivity. By applying the operators of the Boolean multiplication and addition, a final reachability matrix, which can reflect the convergence of the relationship among the elements, is obtained, and a map of the complex relationships among elements can be depicted.

Since its introduction, the ISM has been applied in various fields. For example, Feng et al. [22] integrated factor analysis, ISM, Markov chain, fuzzy integral and the simple additive weighted method, and constructed a hybrid fuzzy integral decision-making model for selecting locations of high-tech manufacturing centers. Lee et al. [23] examined the interrelationship among the critical factors for technology transfer of new equipment in high technology industry using the ISM and applied the FANP to evaluate the technology transfer performance of equipment suppliers. Chen et al. [24] developed a decision-support system framework for adjudicating construction industry occupational accidents using case-based reasoning (CBR) with a nearest-neighbor retrieval (NNR) search mechanism. ISM was then used to build a three-layer hierarchy structure and to classify problem attributes into four aspect subsets. Lin et al. [25] proposed a hybrid method to cope with the problem of different dimensions' interdependence and feedback in vendor selection problem. The interrelationships amongst dimensions are distinguished by applying the ISM, and the weightings of each dimension are derived using the ANP. Chen and Wu [26] presented a systematic procedure to evaluate an automobile manufacturer-distributor partnership with two phases. In the first phase, ISM is used to sort system variables into groups of various characteristics and to develop a hierarchic/network model of the partnership. In the second phase, AHP/ANP is applied to evaluate partnerships. Lee et al. [27] developed a three-stage user interface design approach. Quality function deployment (QFD) was used to confirm the user's design demand; ISM was employed to construct a clear hierarchical structure; and the impact matrix cross-reference multiplication applied to a classification (MICMAC) was adopted to analyze the effect and dependence among the overall design components.

2.2. Analytic network process (ANP)

Analytic network process (ANP), introduced by Saaty, is a generalization of analytic hierarchy process (AHP). It is a multi-criteria decision support methodology to decompose a complex problem into a network when the relationships among clusters (elements) are not easily represented as higher or lower, dominated or being dominated, directly or indirectly [17,28,29]. After evaluating the importance of the clusters (elements) and inter-relationship among them, a "supermatrix" is formed. A weighted supermatrix is generated next to ensure column stochastic; that is, the sum of the elements in each column is equal to one [28]. Finally, a limit supermatrix is calculated for convergence and to obtain final solutions. ANP has been applied successfully in various fields in recent years. A good decision-marking model needs to tolerate vagueness or ambiguity; thus, fuzzy set theory can be incorporated with the conventional ANP, termed FANP.

Some recent works of FANP are reviewed here. Onut et al. [30] designed a FANP-based approach for selecting container port from production firms' perspective for sea transportation. Liou et al. [31] combined fuzzy preference programming and the ANP to form a model for selecting strategic alliance partners in the airline industry. Sevkli et al. [32] developed a FANP-based strengths, weaknesses, opportunities and threats (SWOT) analysis to evaluate alternative strategies for the airline industry. Özgen and Tanyas [33] formulated a FANP-based decision-making model for joint selection of customs broker agencies and international road transportation firms. Yucel et al. [34] developed a predictive risk assessment model for a hospital information system (HIS) by applying ANP, reality-design gap evaluation and fuzzy inference system. Büyüközkan and Çifçi [35] developed a supplier selection approach based on sustainability principles using FANP under a multi-person decision-making schema with incomplete preference relations. Vinodh et al. [36] applied FANP for the supplier selection process in a manufacturing organization for sustaining in the global markets. Kang et al. [37] proposed a FANP model to evaluate various aspects of suppliers with the consideration of multiple decision makers, and a sensitivity analysis was conducted to examine the robustness of the outcomes. Kang [38] proposed a MCDM approach, by incorporating FANP, fuzzy Delphi method (FDM), constraint programming (CP) and BOCR, for capacity allocation problem in semiconductor fabrication. Lee and Lin [39] constructed an integrated fuzzy QFD framework for new product development, with FDM to select the critical factors, fuzzy ISM to determine the relationships among the critical factors, and QFD and FANP to calculate the priorities of the critical factors.

3. Proposed model for evaluating wind turbines

A systematic ISM-FANP model is proposed here to help evaluate the expected performance of various types of wind turbines. The proposed steps are as follows:

Stage I: Construct a wind turbine evaluation network.

Step 1. Form a committee of experts in a wind farm company to define the wind turbine evaluation problem.

Step 2. Decompose the wind turbine evaluation problem into a network. A sample network is as depicted in Fig. 1.

Stage II: Determine the relationships among sub-criteria by ISM.

Step 3. Construct adjacency matrix (i.e., relation matrix) for the sub-criteria under each criterion. For each criterion C_i, establish relation matrix $\mathbf{D}_i$, using the sub-criteria identified in Step 2, to show the contextual relationship among the sub-criteria. Experts, through a questionnaire or the Delphi method, are invited to identify the contextual relationship between any two sub-criteria, and the associated direction of the relation. The relation matrix $\mathbf{D}_i$ is presented as follows:

$$\mathbf{D}_i = \begin{array}{c} \\ SC_{i1} \\ SC_{i2} \\ \vdots \\ SC_{ip} \\ \vdots \\ SC_{iq} \\ \vdots \\ SC_{im} \end{array} \begin{array}{c} \begin{array}{cccccccc} SC_{i1} & SC_{i2} & \cdots & SC_{ip} & \cdots & SC_{iq} & \cdots & SC_{im} \end{array} \\ \left[\begin{array}{cccccccc} 0 & \pi_{i12} & \cdots & \cdots & & \cdots & \cdots & \pi_{i1m} \\ \pi_{i21} & 0 & & & & & & \pi_{i2m} \\ \vdots & & \ddots & & & & & \vdots \\ \vdots & & \ddots & & \pi_{ipq} & \vdots & & \\ & & & & & & & \\ \vdots & & & \pi_{iqp} & & \ddots & & \vdots \\ \vdots & & & & & & 0 & \vdots \\ \pi_{im1} & \pi_{im2} & \cdots & \cdots & & \cdots & \cdots & 0 \end{array}\right] \end{array}, \quad p=1,2,\ldots,m;\ q=1,2,\ldots,m \tag{1}$$

where π_{ipq} denotes the relation between sub-criteria SC_{ip} and SC_{iq} under criterion i, and $\pi_{ipq} = 1$ if SC_{iq} is reachable from SC_{ip}; otherwise, $\pi_{ipq} = 0$.

Step 4. Develop initial reachability matrix for each criterion and check for transitivity. The initial reachability matrix $\mathbf{R}_i$ is calculated by adding $\mathbf{D}_i$ with the unit matrix $\mathbf{I}$:

$$\mathbf{R}_i = \mathbf{D}_i + \mathbf{I} \tag{2}$$

Step 5. Develop final reachability matrix $\mathbf{R}_i^*$ for each criterion i. Under the operators of the Boolean multiplication and addition, a convergence can be met:

$$\mathbf{R}_i^* = \mathbf{R}_i^l = \mathbf{R}_i^{l+1}, \quad l > 1 \tag{3}$$

$$\mathbf{R}_i^* = \begin{array}{c} \\ SC_{i1} \\ SC_{i2} \\ \vdots \\ SC_{ip} \\ \vdots \\ SC_{iq} \\ \vdots \\ SC_{im} \end{array} \begin{array}{c} \begin{array}{cccccccc} SC_{i1} & SC_{i2} & \cdots & SC_{ip} & \cdots & SC_{iq} & \cdots & SC_{im} \end{array} \\ \left[\begin{array}{cccccccc} \pi_{i11}^* & \pi_{i12}^* & \cdots & \cdots & & \cdots & \cdots & \pi_{i1m}^* \\ \pi_{i21}^* & \pi_{i22}^* & & & & & & \pi_{i2m}^* \\ \vdots & & \ddots & & & & & \vdots \\ \vdots & & & \ddots & & \pi_{iqp}^* & & \vdots \\ & & & & & & & \\ \vdots & & & \pi_{iqp}^* & & \ddots & & \vdots \\ \vdots & & & & & & \ddots & \vdots \\ \pi_{im1}^* & \pi_{im2}^* & \cdots & \cdots & & \cdots & \cdots & \pi_{imm}^* \end{array}\right] \end{array}, \quad p=1,2,\ldots,m;\ q=1,2,\ldots,m \tag{4}$$

where π_{ipq}^* denotes the impact of sub-criterion SC_p to sub-criterion SC_q under criterion i.

Step 6. Construct a sub-network for each criterion based on the final reachability matrix for the criterion.

Stage III: Calculate the priorities of wind turbine systems using FANP.

Step 7. Prepare a questionnaire to collect experts' opinions based on the network. Experts are asked to pairwise compare the importance of the criteria, the importance of the sub-criteria with respect to the same upper-level criterion, and the interdependence among the sub-criteria under the same upper-level criterion, using seven different linguistic terms, as listed in Table 1. The linguistic variables of pairwise comparison of each part of the questionnaire from each expert are transformed into trapezoid fuzzy numbers. Experts are also asked to determine the performance of each alternative with respect to each sub-criterion by a seven-step scale, as shown in Table 2.

Step 8. Employ geometric average approach to aggregate experts' responses and calculate synthetic trapezoid fuzzy numbers. For instance, the synthetic trapezoid fuzzy number for the relative importance between criterion i and criterion j is calculated as follows:

$$\tilde{r}_{ij} = (\tilde{a}_{ij1} \otimes \tilde{a}_{ij2} \otimes \ldots\ldots \otimes \tilde{a}_{ijk})^{1/k} \tag{5}$$

where $\tilde{a}_{ijk}$ is the pairwise comparison value between criterion i and j determined by expert k.

Step 9. Calculate aggregated crisp pairwise comparison matrices. Defuzzify each fuzzy number into a crisp number using Yager [40] ranking method. For example, fuzzy number $\tilde{r}_{ij}$ is deffuzified into a crisp number r_{ij} as follows:

$$r_{ij} = \int_0^1 \frac{1}{2}\left((\tilde{r}_{ij})_\alpha^L + (\tilde{r}_{ij})_\alpha^U\right) d\alpha \tag{6}$$

The α-cuts of the fuzzy numbers are shown in Table 3. The aggregated pairwise comparison matrix for the criteria is:

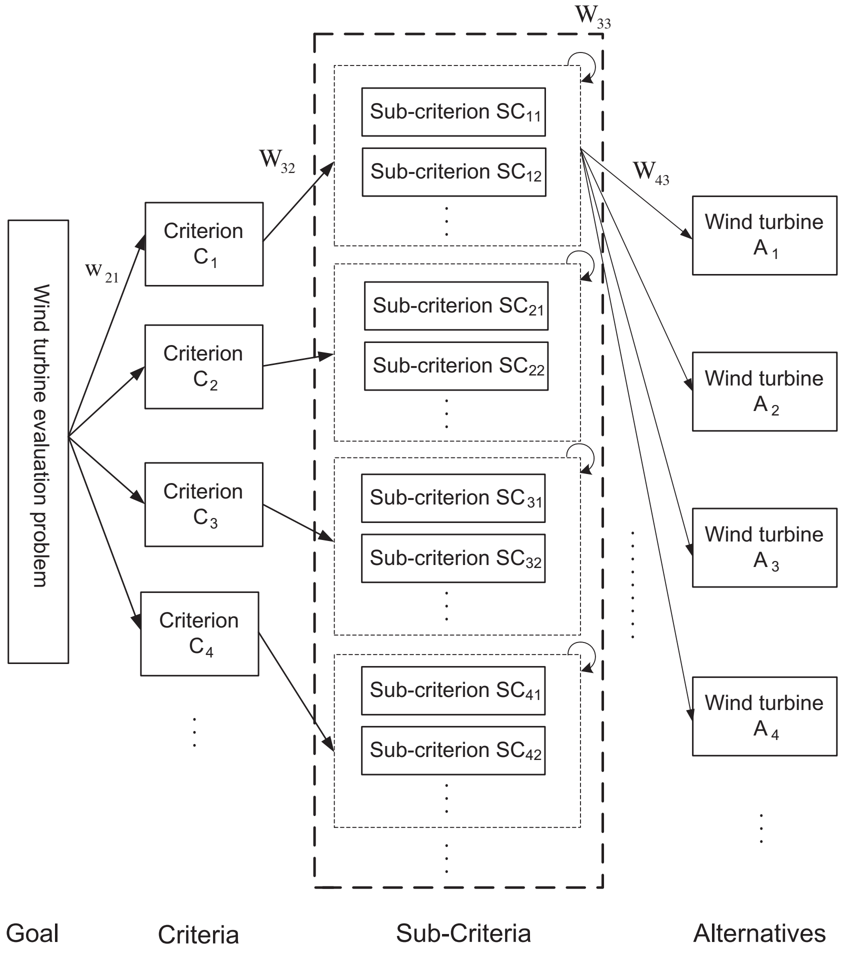


Fig. 1. The network.

Table 1
Membership function of fuzzy numbers for relative importance.

Linguistic variable	Positive trapezoidal fuzzy numbers	Positive reciprocal trapezoidal fuzzy numbers
Extremely high (EH)	(7.5, 8.5, 9, 9)	$(9^{-1}, 9^{-1}, 8.5^{-1}, 7.5^{-1})$
Very high (VH)	(6.5, 7.5, 7.5, 8.5)	$(8.5^{-1}, 7.5^{-1}, 7.5^{-1}, 6.5^{-1})$
High (H)	(5, 5.75, 6.75, 7.5)	$(7.5^{-1}, 6.75^{-1}, 5.75^{-1}, 5.5^{-1})$
Medium high (M)	(4, 5, 5, 6)	$(6^{-1}, 5^{-1}, 5^{-1}, 4^{-1})$
Moderately high (MH)	(2.5, 3.25, 4.25, 5)	$(5^{-1}, 4.25^{-1}, 3.25^{-1}, 2.5^{-1})$
Little high (LH)	(1.5, 2.5, 2.5, 3.5)	$(3.5^{-1}, 2.5^{-1}, 2.5^{-1}, 1.5^{-1})$
Equal (E)	(1, 1, 1.5, 2.5)	$(2.5^{-1}, 1.5^{-1}, 1, 1)$

$$\mathbf{W}_{21} = \begin{bmatrix} 1 & r_{12} & \cdots & \cdots & \cdots & \cdots & r_{1j} \\ 1/r_{12} & 1 & \cdots & \cdots & \cdots & \cdots & r_{2j} \\ \vdots & \vdots & 1 & \cdots & \cdots & \cdots & \cdots \\ \vdots & \vdots & \vdots & 1 & r_{ij} & \cdots & \cdots \\ \vdots & \vdots & \vdots & 1/r_{ij} & 1 & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & 1 & \cdots \\ 1/r_{1j} & 1/r_{2j} & \cdots & \cdots & \cdots & \cdots & 1 \end{bmatrix} \tag{7}$$

The aggregated pairwise comparison matrices for the sub-criteria with respect to the same upper-level criterion and for the interdependence among the sub-criteria under the same upper-level criterion are obtained in the same way.

Step 10. Determine the priorities of the criteria, sub-criteria, and interdependence among sub-criteria. For instance, the priority vector for the aggregated comparison matrix for the criteria is derived as follows:

$$\mathbf{W}_{21} \times w_{21} = \lambda_{\max} \times w_{21} \tag{8}$$

where $\mathbf{W}_{21}$ is the aggregated comparison matrix for the criteria, w_{21} is the eigenvector, and $\lambda_{\max}$ is the largest eigenvalue of $\mathbf{W}_{21}$.

Step 11. Examine the consistency property of the aggregated comparison matrices. The consistency index (CI) and consistency ratio (CR) are defined as [28,41]:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{9}$$

$$CR = \frac{CI}{\mathrm{RI}} \tag{10}$$

where n is the number of items being compared in the matrix, and RI is random index. As suggested by Saaty [41], RI is 0.00 for a 2 × 2 matrix, 0.58 for a 3 × 3 matrix, 0.90 for a 4 × 4 matrix, 1.12 for a 5 × 5 matrix, and 1.24 for a 6 × 6 matrix, etc. When a calculated CR value exceeds the threshold, it is an indication of inconsistent judgment. The experts are asked to revise the part of the questionnaire, and the calculations in Steps 7–10 are done again.

Table 2
Membership function of fuzzy numbers for ranking.

Linguistic variable	Positive trapezoidal fuzzy numbers
Very good (VG)	(0.75, 0.9, 0.9, 0.9)
Good (G)	(0.65, 0.7, 0.8, 0.85)
Medium good (MG)	(0.45, 0.6, 0.6, 0.75)
Fair (F)	(0.35, 0.4, 0.5, 0.55)
Medium poor (MP)	(0.15, 0.3, 0.3, 0.45)
Poor (P)	(0.05, 0.1, 0.2, 0.25)
Very poor (VP)	(0, 0, 0, 0.15)

Step 12. Determine the priorities of the alternatives with respect to each sub-criterion. Based on the collected experts' opinions, the membership function of fuzzy numbers for ranking on Table 2, the synthetic trapezoid fuzzy number for the expected performance of an alternative is calculated as follows:

$$\tilde{g}_{i_p v} = (\tilde{f}_{i_p v1} \otimes \tilde{f}_{i_p v2} \otimes \ldots\ldots \otimes \tilde{f}_{i_p vk})^{1/k} \tag{11}$$

where $\tilde{f}_{i_p vk}$ is the expected performance of alternative v under sub-criterion p of criterion i determined by expert k. Defuzzify each fuzzy number into a crisp number using Yager [40] ranking method, and normalize the priorities of alternatives with respect to each sub-criterion. Quantitative performance indicators can also be used for evaluating the alternatives. Quantitative data is transformed into values between zero and one by membership functions, where "1" represents the best outcome and "0" represents the worst outcome. For a sub-criterion that is better with a bigger value, its membership function is as follows:

$$g_{i_p v} = \begin{cases} \left(f_{i_p v} - f_{i_p}^{-}\right) / \left(f_{i_p}^{+} - f_{i_p}^{-}\right), & f_{i_p}^{-} \leqslant f_{i_p v} \leqslant f_{i_p}^{+} \\ 1, & f_{i_p v} \geqslant f_{i_p}^{+} \end{cases} \tag{12}$$

For a sub-criterion that is better with a smaller value, its membership function is as follows:

$$g_{i_p v} = \begin{cases} \left(f_{i_p}^{+} - f_{i_p v}\right) / \left(f_{i_p}^{+} - f_{i_p}^{-}\right), & f_{i_p}^{-} \leqslant f_{i_p v} \leqslant f_{i_p}^{+} \\ 1, & f_{i_p v} \leqslant f_{i_p}^{-} \end{cases} \tag{13}$$

where $f_{i_p}^{+}$ is the largest possible value of sub-criterion p of criterion i, $f_{i_p}^{-}$ is the smallest possible value of a sub-criterion p of criterion i, $f_{i_p v}$ is the value of alternative v under sub-criterion p of criterion i.

Step 13. Form an unweighted supermatrix. Based on the priorities obtained from Steps 11 and 12, an unweighted supermatrix is formed, as depicted in Fig. 2.

Step 14. Calculate a weighted supermatrix. To ensure column stochastic, the unweighted supermatrix must be transformed into a weighted supermatrix [28,42].

Step 15. Calculate the limit supermatrix and obtain the final priorities of the alternatives. By taking the weighted supermatrix to powers, the supermatrix can converge into a stable supermatrix, called the limit supermatrix. The final priorities of the alternatives are shown in the alternative-to-goal column of the limit supermatrix.

Table 3
α-cuts of fuzzy numbers.

$\tilde{a}$	$(\tilde{a})_{\alpha}^{L}$	$(\tilde{a})_{\alpha}^{U}$
$\tilde{a}_{EH} = (7.5, 8.5, 9, 9)_{\text{L-R}}$	$(\tilde{a}_{EH})_{\alpha}^{L} = 7.5 + \alpha$	$(\tilde{a}_{EH})_{\alpha}^{U} = 9$
$\tilde{a}_{VH} = (6.5, 7.5, 7.5, 8.5)_{\text{L-R}}$	$(\tilde{a}_{VH})_{\alpha}^{L} = 6.5 + \alpha$	$(\tilde{a}_{VH})_{\alpha}^{U} = 8.5 - \alpha$
$\tilde{a}_{H} = (5, 5.75, 6.75, 7.5)_{\text{L-R}}$	$(\tilde{a}_{H})_{\alpha}^{L} = 5 + 0.75\alpha$	$(\tilde{a}_{H})_{\alpha}^{U} = 7.5 - 0.75\alpha$
$\tilde{a}_{M} = (4, 5, 5, 6)_{\text{L-R}}$	$(\tilde{a}_{M})_{\alpha}^{L} = 4 + \alpha$	$(\tilde{a}_{M})_{\alpha}^{U} = 6 - \alpha$
$\tilde{a}_{MH} = (2.5, 3.25, 4.25, 5)_{\text{L-R}}$	$(\tilde{a}_{MH})_{\alpha}^{L} = 2.5 + 0.75\alpha$	$(\tilde{a}_{MH})_{\alpha}^{U} = 5 - 0.75\alpha$
$\tilde{a}_{LH} = (1.5, 2.5, 2.5, 3.5)_{\text{L-R}}$	$(\tilde{a}_{LH})_{\alpha}^{L} = 1.5 + \alpha$	$(\tilde{a}_{LH})_{\alpha}^{U} = 3.5 - \alpha$
$\tilde{a}_{E} = (1, 1, 1.5, 2.5)_{\text{L-R}}$	$(\tilde{a}_{E})_{\alpha}^{L} = 1$	$(\tilde{a}_{E})_{\alpha}^{U} = 2.5 - \alpha$

4. Case study

Taiwan depends heavily on imported fossil fuels, with an import of 98% of its fuel requirements. Facing the problems caused by increasing energy consumption and scarcer global fuel energy, Taiwan is encountering energy shortages, escalating fuel price, pollution emission and environmental issues. The government had introduced a feed-in tariff in 2009 and set a target for renewable energy to meet 10% of the electricity supply by 2010 [1]. Because of its unique geographic characteristics, Taiwan can develop wind farms in various places, especially on its western coast and offshore in the island. During 2010, Taiwan installed 83 MW of new wind power, and its capacity has increased to a total of 519 MW, expecting to meet 80% of renewable energy production [43]. However, the development of wind power needs to consider important aspects such as political issues, technologies, costs and societal environments, and the guaranteed purchase price must be high enough to encourage investment. In addition, the construction of wind farm can be a complicated task, and the selection of the most appropriate wind turbines is essential for the future operation of the wind farm. To be precise, wind turbine evaluation problem is a MCDM problem which involves the assessments of different factors under an uncertain environment. Thus, the proposed model is used to help a wind farm evaluate the expected performance of different types of wind turbines.

Stage I: Construct a wind turbine evaluation network. With literature review and interview with the management in the anonymous firm, the network is constructed, as shown in Fig. 3. There are four criteria, namely, machine characteristics, economic aspects, environmental issues and technical levels. Under each criterion, there are sub-criteria. The criteria and sub-criteria are defined in Table 4. To keep anonymousness, the four wind turbines under evaluation are identified as A$_1$, A$_2$, A$_3$ and A$_4$, and their specifications are listed in Table 5.

Stage II: Determine the relationships among sub-criteria by ISM. A committee of five experts in the firm was formed. These experts included one senior manager and two managers from the operations department, and one senior manager and one manger from the engineering department. The experts were asked to determine whether there are interrelationships among the

$$\begin{array}{c|c|c|c|c} & \text{Goal} & \text{Criteria} & \text{Sub-criteria} & \text{Alternatives} \\ \hline \text{Goal} & \mathbf{I} & & & \\ \hline \text{Criteria} & w_{21} & & & \\ \hline \text{Sub-criteria} & & \mathbf{W}_{32} & \mathbf{W}_{33} & \\ \hline \text{Alternatives} & & & \mathbf{W}_{43} & \mathbf{I} \end{array}$$

Fig. 2. Unweighted supermatrix [23].

sub-criteria in a meeting so that a consensus could be met. For example, an adjacency matrix (relation matrix) for the sub-criteria under criterion *machine characteristics* was formed after discussion, as follows:

$$\mathbf{D}_1 = \begin{array}{c|cccc|} & SC_{11} & SC_{12} & SC_{13} & SC_{14} \\ SC_{11} & 0 & 0 & 1 & 1 \\ SC_{12} & 0 & 0 & 0 & 0 \\ SC_{13} & 1 & 0 & 0 & 1 \\ SC_{14} & 1 & 0 & 1 & 0 \end{array}$$

The initial reachability matrix $\mathbf{R}_1$ for the sub-criteria under criterion *machine characteristics* is calculated:

$$\mathbf{R}_1 = \mathbf{D}_1 + \mathbf{I} = \begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 \end{bmatrix}$$

The final reachability matrix $\mathbf{R}_1^*$ for the sub-criteria under criterion *machine characteristics* is:

$$\mathbf{R}_1^* = \mathbf{R}_1^2 = \mathbf{R}_1^3 = \begin{bmatrix} 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 \end{bmatrix}$$

Based on $\mathbf{R}_1^*$, the interrelationship among the four sub-criteria can be depicted as in Fig. 4(1). According to the experts' opinions through ISM analysis, SC_{11}, SC_{13}, SC_{14} are mutually interrelated. This can be seen from the double-sided arrows among these three criteria. For example, while *system conversion rate* (SC_{11}) had an effect on *utilization rate* (SC_{13}) and *construction reliability* (SC_{14}), the sub-criterion was also affected by these two sub-criteria. In addition, SC_{12} is independent. The interrelationships among sub-criteria under the other three criteria are also shown in Fig. 4(2)–(4).

Stage III: Calculate the priorities of wind turbine systems using FANP.

Based on the network in Fig. 3 and the interrelationship among sub-criteria under each criterion in Fig. 4, a questionnaire using seven different linguistic terms from Table 1 was prepared to pairwise compare the importance of the criteria, the importance of the sub-criteria with respect to the same upper-level criterion, and the interdependence among the sub-criteria under the same upper-level criterion. For the performance evaluation of the alternatives with respect to each sub-criterion, the seven different linguistic terms from Table 2 were used. The five experts in the committee were invited to fill out the questionnaire. Geometric average approach was used to aggregate experts' responses. For example, the pairwise comparison between *machine characteristics* (C_1) and *economic aspects* (C2) by the experts are (1,1,1.5,2.5), (3.5^{-1}, 2.5^{-1}, 2.5^{-1}, 1.5^{-1}), (1,1,1.5,2.5), (3.5^{-1}, 2.5^{-1}, 2.5^{-1}, 1.5^{-1}) and (1.5,2.5,2.5,3.5). The aggregated trapezoid fuzzy number is: $\tilde{r}_{12} = ((1 \times 3.5^{-1} \times 1 \times 3.5^{-1} \times 1.5)^{1/5}, (1 \times 2.5^{-1} \times 1 \times 2.5^{-1} \times 2.5)^{1/5}, (1.5 \times 2.5^{-1} \times 1.5 \times 2.5^{-1} \times 2.5)^{1/5}, (2.5 \times 1.5^{-1} \times 2.5 \times 1.5^{-1} \times 3.5)^{1/5}) = (0.657, 0.833, 0.979, 1.576)$.

The fuzzy aggregated pairwise comparison matrix for the criteria is:

$$\widetilde{\mathbf{W}}_{21} = \begin{array}{c|cccc|} & C_1 & C_2 & C_3 & C_4 \\ C_1 & (1,1,1,1) & (0.657, 0.833, 0.979, 1.576) & (1.084, 1.201, 1.661, 2.674) & (1.661, 2.635, 2.780, 3.759) \\ C_2 & (0.635, 1.021, 1.201, 1.522) & (1,1,1,1) & (1.904, 2.211, 2.895, 3.930) & (2.790, 3.089, 3.633, 4.859) \\ C_3 & (0.374, 0.602, 0.833, 0.922) & (0.254, 0.345, 0.452, 0.525) & (1,1,1,1) & (1.741, 1.904, 2.428, 3.548) \\ C_4 & (0.266, 0.360, 0.380, 0.602) & (0.206, 0.275, 0.324, 0.358) & (0.282, 0.412, 0.525, 0.574) & (1,1,1,1) \end{array}$$

The Yager ranking method is applied next to prepare a defuzzified comparison matrix. For example, with the synthetic trapezoid fuzzy number for the comparison between C_1 and C_2 of (0.657, 0.833, 0.979, 1.576), the defuzzified comparison between C_1 and C_2 is 1.011. The defuzzified aggregated pairwise comparison matrix is:

$$\mathbf{W}_{21} = \begin{array}{c|cccc|} & C_1 & C_2 & C_3 & C_4 \\ C_1 & 1 & 1.011 & 1.655 & 2.709 \\ C_2 & 0.989 & 1 & 2.735 & 3.593 \\ C_3 & 0.604 & 0.366 & 1 & 2.405 \\ C_4 & 0.369 & 0.278 & 0.416 & 1 \end{array}$$

The priority vector and $\lambda_{\max}$ of the defuzzified aggregated pairwise comparison matrix for the criteria are calculated:

$$w_{21} = \begin{array}{c|c|} C_1 & 0.3219 \\ C_2 & 0.3895 \\ C_3 & 0.1883 \\ C_4 & 0.1003 \end{array}, \quad \lambda_{\max} = 4.0542$$

The consistency test is performed by calculating *CI* and *CR*:

$$CI = \frac{\lambda_{\max} - n}{n - 1} = \frac{4.0542 - 4}{4 - 1} = 0.0181, \quad \text{and}$$
$$CR = \frac{CI}{\mathrm{RI}} = \frac{0.0181}{0.90} = 0.0201.$$

Since *CR* is less than 0.1, the experts' judgment is consistent. If the consistency test fails, the experts are asked to fill out the specific part of the questionnaire again.

Priority vectors for the importance of the sub-criteria with respect to the same upper-level criterion, and the interdependence

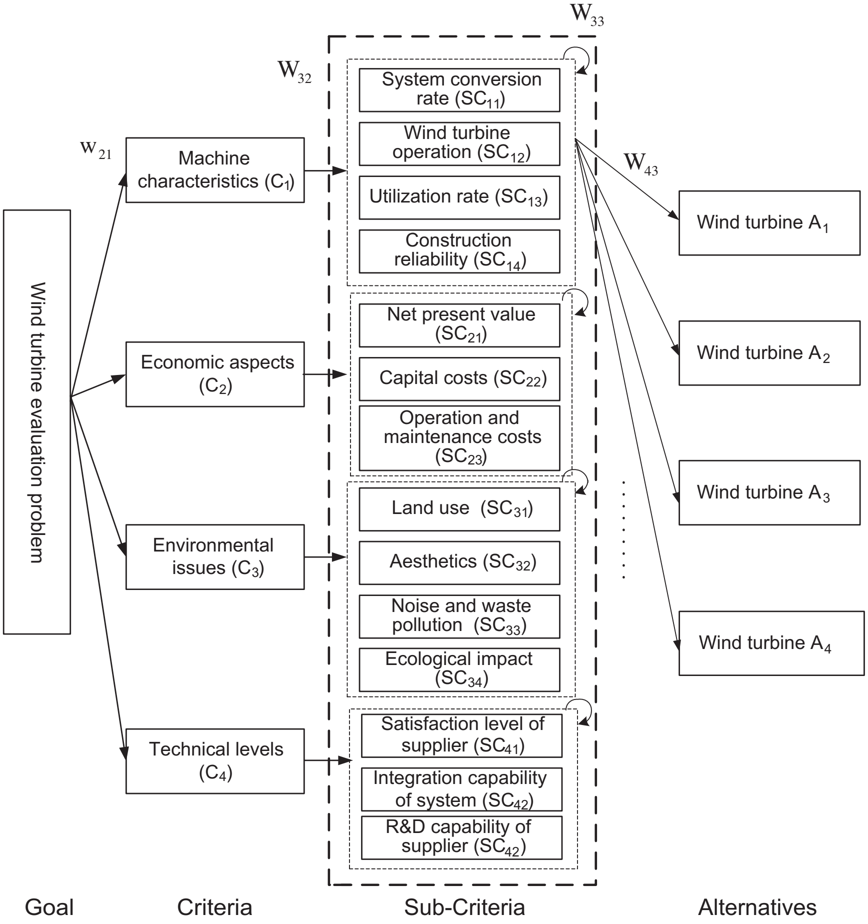


Fig. 3. The network for the case.

Table 4
Definitions of the criteria and sub-criteria.

Criteria	Sub-criteria	Definition
Machine characteristics (C_1)	System conversion rate (SC_{11})	The rate to convert wind's energy into electricity. A low start up wind speed and a maximum generating power are preferred
	Wind turbine operation (SC_{12})	Easiness in operating the wind turbines
	Utilization rate (SC_{13})	The normal utilization rate of the wind turbine system after deducting system breakdowns and equipment malfunctions, etc.
	Construction reliability (SC_{14})	The physical strength, safety and reliability of the wind turbine system
Economic aspects (C_2)	Net present value (NPV) (SC_{21})	The total present value of a time series of cash flows generated from the operation of wind turbines, considering the operation life of wind turbines, bank financing terms, buy-back price of electricity, etc.
	Capital costs (SC_{22})	The cost of wind turbines and connections in constructing the wind turbine system
	Operation and maintenance costs (SC_{23})	Day-to-day operation costs and maintenance costs incurred in operating the wind turbine system
Environmental issues (C_3)	Land use (SC_{31})	The geographic area and the size of land required for constructing wind turbines with different destructive impacts to the environment
	Aesthetics (SC_{32})	The aesthetics of the area being diminished
	Noise and waste pollution (SC_{33})	The noise, interference with radio and television signals, shadow flicker and waste from the operation of wind turbines, which have negative impacts on the people and may damage the environment
	Ecological impact (SC_{34})	The impact of wind turbines and buildings to the ecology, such as the collision of birds and bats and the harmful impacts on wildlife
Technical levels (C_4)	Satisfaction level of supplier (SC_{41})	Technology and parts support of supplier
	Integration capability of system (SC_{42})	The integration of hardware and software of the wind turbine system, including equipment, parts, personnel and supervisory control and data acquisition (SCADA) system, etc.
	R&D capability of supplier (SC_{43})	R&D level and improvements that can be achieved by the supplier, including incremental improvement and radical innovation

Table 5
Specifications of the four wind turbines.

Wind turbine	A_1	A_2	A_3	A_4
Location of manufacturer	Netherlands	Denmark	Spain	Germany
Model	Z-72	V-80	G-80	E-70
Rated power (MW)	2.0	2.0	2.0	2.3
Generator	Direct-drive annular generator	Asynchronous generator	Asynchronous generator	Direct-drive annular generator
Rotor	–	Doubly-fed machine	Doubly-fed machine	–
Gearbox	Gearless	Parallel	Parallel	Gearless
Voltage (V)	690	690	690	400
Hub height (m)	65	67	67	65
Rotor diameter (m)	70.64	80	80	71
Swept area (m^2)	3696	5027	5026	3959
Rotational speed (rpm)	22.5	9–19	10.8–22.8	6–21.5
Cut-in wind speed (m/s)	3	4	4	2
Cut-out wind speed (m/s)	25	25	25	35
Nominal wind speed (m/s)	13	15	15	12
Maximum wind speed (m/s)	70	70	70	70
Design life time (years)	20	20	20	20

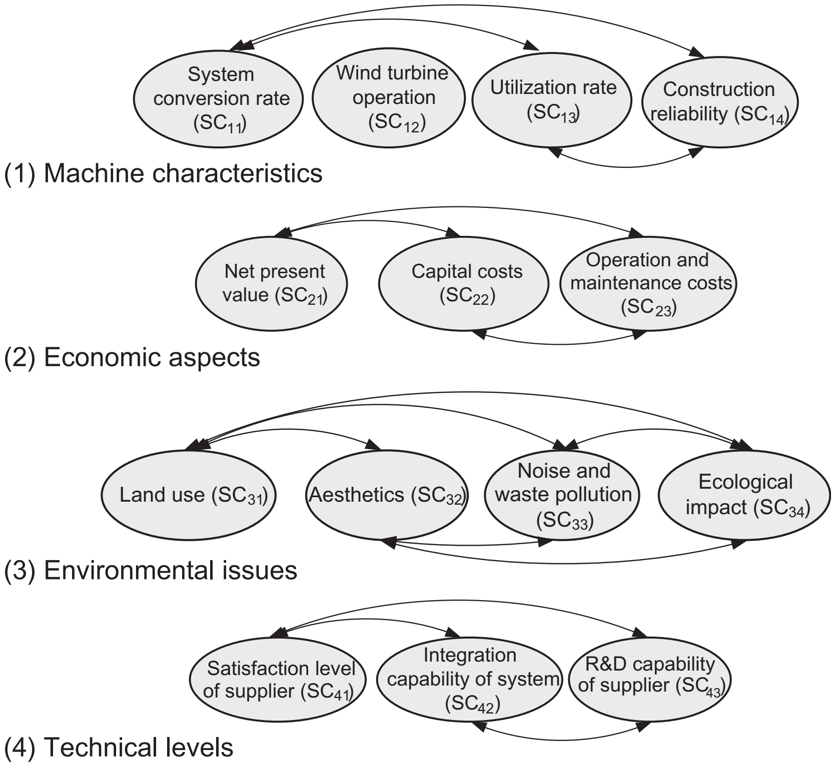
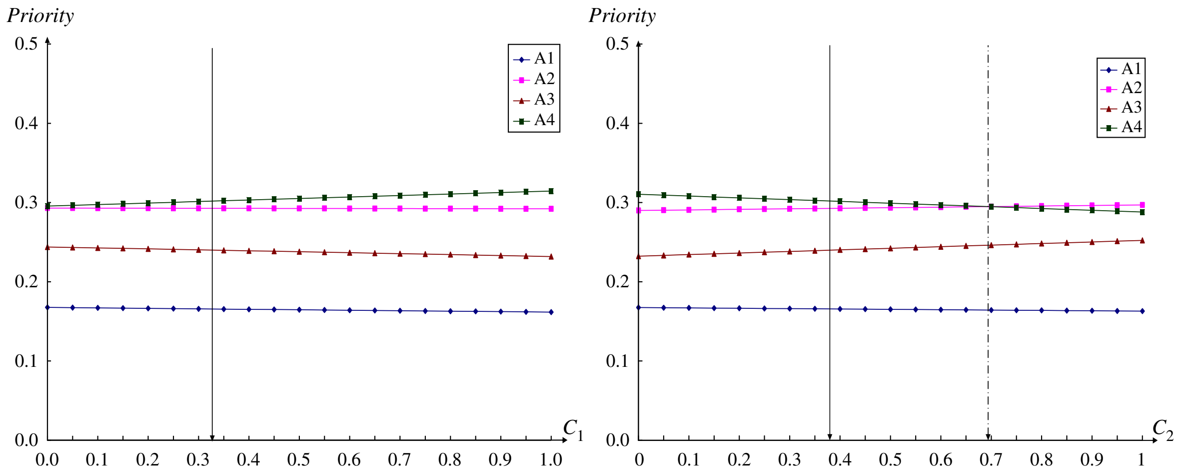


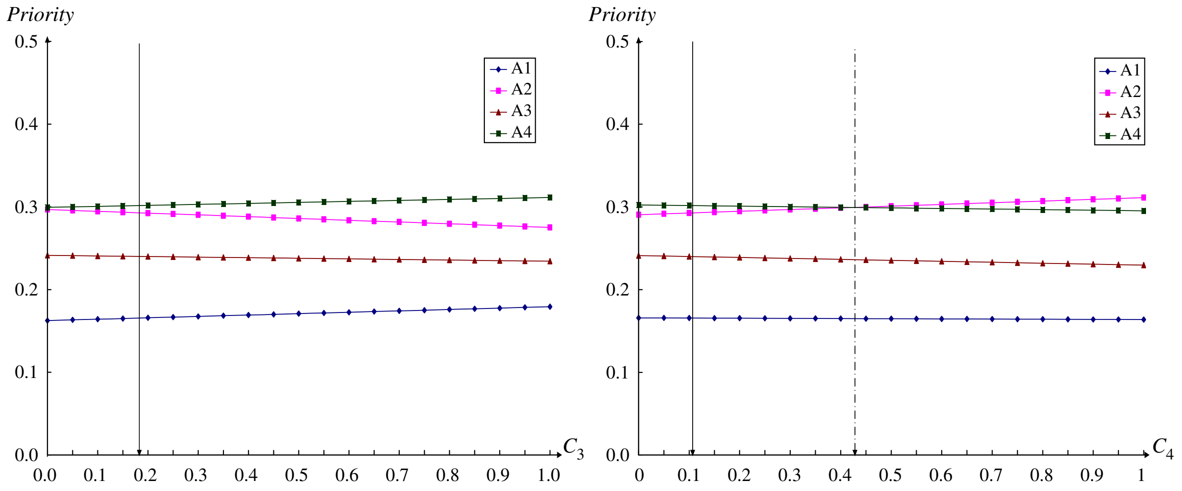
Fig. 4. The interrelationship among sub-criteria under each criterion.

among the sub-criteria under the same upper-level criterion are calculated in a similar way. For the performance of the alternatives, geometric average method is adopted to aggregate experts' opinions, Yager [40] ranking method is used to obtain crisp values, and normalization is applied to calculate the priorities of alternatives with respect to each sub-criterion. For instance, the expected performance of wind turbine A_1 under *system conversion rate* (SC_{11}) is evaluated by the five experts as: fair, medium poor, poor, medium poor and medium poor. The fuzzy numbers are (0.35,0.4,0.5, 0.55), (0.15,0.3,0.3,0.45), (0.05,0.1,0.2,0.25), (0.15,0.3,0.3,0.45) and (0.15,0.3,0.3,0.45). The aggregated trapezoid fuzzy number is $(0.143,0.255,0.306,0.416) = ((0.35 \times 0.15 \times 0.05 \times 0.15 \times 0.15)^{1/5}, (0.4 \times 0.3 \times 0.1 \times 0.3 \times 0.3)^{1/5}, (0.5 \times 0.3 \times 0.2 \times 0.3 \times 0.3)^{1/5}, (0.55 \times 0.45 \times 0.25 \times 0.45 \times 0.45)^{1/5})$. After defuzzification, the priority of wind turbine A_1 under *system conversion rate* (SC_{11}) is 0.2801. Similar calculations are performed to obtain the priorities of A_2, A_3 and A_4 under *system conversion rate* (SC_{11}), which are 0.5131, 0.4376 and 0.6002, respectively. After normalization, the priorities of A_1, A_2, A_3 and A_4 under *system conversion rate* (SC_1) are 0.1530, 0.2802, 0.2390 and 0.3278, respectively. The priorities of A_1, A_2, A_3 and A_4 under the other sub-criteria are calculated in the same way.

To obtain global priorities in a system with interdependent influences, the local priority vectors were entered in the appropriate columns of the unweighted supermatrix [28]. For example, the priorities of the criteria (C_1–C_4) with respect to the goal are 0.3219, 0.3895, 0.1883, and 0.1003, respectively. They are entered into the (2,1) block of the unweighted supermatrix in Table A1 in Appendix A. The (3,2) block shows the priorities of sub-criteria with respect to the criteria when the interrelationship among sub-criteria was not considered. The interrelationships among sub-criteria are depicted in the (3,3) block. Each zero entry in the supermatrix



(1) Priority changes in *machine characteristics* (C_1) (2) Priority changes in *economic aspects* (C_2)



(3) Priority changes in *environmental issues* (C_3) (4) Priority changes in *technical levels* (C_4)

Fig. 5. Sensitivity analysis.

Table 6
Priorities of criteria and sub-criteria.

Criteria/sub-criteria	Criterion priorities	Sub-criterion priorities	Integrated priorities	Integrated ranking
Machine characteristics (C_1)	0.3219			
System conversion rate (SC_{11})		0.3937	0.1267	2
Wind turbine operation (SC_{12})		0.3622	0.1166	4
Utilization rate (SC_{13})		0.1438	0.0463	9
Construction reliability (SC_{14})		0.1003	0.0323	11
Economic aspects (C_2)	0.3895			
Net present value (NPV) (SC_{21})		0.5604	0.2183	1
Capital costs (SC_{22})		0.3104	0.1209	3
Operation and maintenance costs (SC_{23})		0.1291	0.0503	8
Environmental issues (C_3)	0.1883			
Land use (SC_{31})		0.3936	0.0741	5
Aesthetics (SC_{32})		0.2990	0.0563	7
Noise and waste pollution (SC_{33})		0.1671	0.0315	12
Ecological impact (SC_{34})		0.1404	0.0264	13
Technical levels (C_4)	0.1003			
Satisfaction level of supplier (SC_{41})		0.5376	0.0539	6
Integration capability of system (SC_{42})		0.3316	0.0333	10
R&D capability of supplier (SC_{43})		0.1308	0.0131	14

implies that there is no relationship between the two elements. The performance of wind turbines with respect to each sub-criterion is shown in the (4,3) block. For example, the priorities of the four types of wind turbines under *system conversion rate* (SC_{11}), that is, 0.1530, 0.2802, 0.2390 and 0.3278 respectively, can be found in the first column of the (4,3) block.

To make the matrix stochastic, a weighted supermatrix is formed, as shown in Table A2. Finally, by taking the weighted supermatrix to a large power, a limit supermatrix is obtained, as shown in Table A3. The priorities of the alternatives can be seen from the (4, 1) block of the limit supermatrix. That is, the priorities for wind turbines A_1, A_2, A_3 and A_4 are 0.1657, 0.2926, 0.2400 and 0.3016, respectively. Thus, A_4 performs the best with the highest priority, followed by A_2, A_3 and A_1.

The importance of criteria and sub-criteria in making the wind turbine selection decision should be understood by the management. Table 6 shows the relative priorities of criteria and sub-criteria. *Economic aspects* (C_2), with a priority of 0.3895, is the most important criterion, followed by *machine characteristics* (C_1), with a priority of 0.3219. The priorities of sub-criteria under the same upper-level criterion can be compared too. For example, under the *machine characteristics* (C_1) criterion, the most important sub-criterion, out of a total of four sub-criteria, is *system conversion rate*, with a priority of 0.3937. This means that the major machine characteristics concern for selecting wind turbines is the *system conversion rate* for the power generated. The second and third sub-criteria are *wind turbine operation* (0.3622) and *utilization rate* (0.1438). Table 6 also shows the integrated priorities of sub-criteria, and their respective rankings. Among all the factors, *net present value* (SC_{21}), with an integrated priority of 0.2183 in the network, is the most important concern in selecting the wind turbines. Other important factors include *system conversion rate* (SC_{11}), *capital costs* (SC_{22}), *wind turbine operation* (SC_{12}), and *land use* (SC_{31}).

To examine the robustness of the outcomes, a sensitivity analysis is carried out next by changing the priorities of the criteria, and the results are shown in Fig. 5. Fig. 5(1)–(4) show the sensitivity analysis graphs when the priority of *machine characteristics* (C_1), *economic aspects* (C_2), *environmental issues* (C_3) and *technical levels* (C_4) changes, respectively. Depending on the changes of the priorities of the criteria, the best wind turbine system may change as a result. As shown in Fig. 5(1) and (3), no matter how much the priority of C_1 or C_3 changes, the ranking of the four alternatives remains the same. While the original best alternative is wind turbine A_4, A_2 may become the best alternative when C_2 increases from 0.3895 to 0.695, as shown in Fig. 5(2). The same applies when C_4 increases from 0.1003 to 0.425. Nevertheless, the likelihood that C_2 or C_4 has such a big change is small. Therefore, the current solution is rather robust.

5. Conclusions and discussions

While energy is being one of the most important sources for economic development and fossil fuels keeps depleting exponentially, renewable energy has been recognized as the last resort for future economic development. Wind energy is expected to be the most promising renewable energy source, and the construction of wind farms is the elementary step for a long-term operation. This study is a continuation of Kang et al. [44], in which a comprehensive evaluation model was constructed to select a suitable location for developing a wind farm. In Kang et al. [44], the model incorporated ISM and FANP to evaluate the benefits, opportunities, costs and risks aspects of different wind farm locations. After the wind farm location is determined, the selection of the most suitable wind turbine system is a next important issue. It is also a MCDM problem that requires multiple decision makers being involved in the process. In this research, a decision analysis model in selecting the most suitable type of wind turbines is thus proposed. The factors for achieving the goal are listed first through literature review and interview with experts, and they are used to construct a network with four major criteria, namely, machine

Table A1
Unweighted supermatrix.

	Goal	C_1	C_2	C_3	C_4	SC_{11}	SC_{12}	SC_{13}	SC_{14}	SC_{21}	SC_{22}	SC_{23}	SC_{31}	SC_{32}	SC_{33}	SC_{34}	SC_{41}	SC_{42}	SC_{43}	A_1	A_2	A_3	A_4
Goal	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_1	0.3219	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_2	0.3895	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_3	0.1883	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_4	0.1003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{11}	0	0.3937	0	0	0	0.5878	0	0.6837	0.6495	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{12}	0	0.3622	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{13}	0	0.1438	0	0	0	0.2522	0	0.1933	0.2122	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{14}	0	0.1003	0	0	0	0.1600	0	0.1231	0.1384	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{21}	0	0	0.5604	0	0	0	0	0	0	0.6146	0.5620	0.5949	0	0	0	0	0	0	0	0	0	0	0
SC_{22}	0	0	0.3104	0	0	0	0	0	0	0.2824	0.3381	0.2679	0	0	0	0	0	0	0	0	0	0	0
SC_{23}	0	0	0.1291	0	0	0	0	0	0	0.1030	0.0999	0.1373	0	0	0	0	0	0	0	0	0	0	0
SC_{31}	0	0	0	0.3936	0	0	0	0	0	0	0	0	0.4115	0.3332	0.4236	0.3437	0	0	0	0	0	0	0
SC_{32}	0	0	0	0.2990	0	0	0	0	0	0	0	0	0.2179	0.3622	0.2926	0.3402	0	0	0	0	0	0	0
SC_{33}	0	0	0	0.1671	0	0	0	0	0	0	0	0	0.2631	0.1703	0.1756	0.1817	0	0	0	0	0	0	0
SC_{34}	0	0	0	0.1404	0	0	0	0	0	0	0	0	0.1075	0.1344	0.1082	0.1343	0	0	0				
SC_{41}	0	0	0	0	0.5376	0	0	0	0	0	0	0	0	0	0	0	0.5904	0.6288	0.5542	0	0	0	0
SC_{42}	0	0	0	0	0.3316	0	0	0	0	0	0	0	0	0	0	0	0.3074	0.2832	0.3483	0	0	0	0
SC_{43}	0	0	0	0	0.1308	0	0	0	0	0	0	0	0	0	0	0	0.1023	0.0880	0.0975	0	0	0	0
A_1	0	0	0	0	0	0.1530	0.1709	0.1676	0.1540	0.1596	0.1603	0.1862	0.2059	0.1625	0.1670	0.1557	0.1786	0.1603	0.0999	1	0	0	0
A_2	0	0	0	0	0	0.2802	0.3293	0.2521	0.2601	0.2894	0.3246	0.2629	0.2696	0.2882	0.2744	0.2630	0.3357	0.2700	0.3046	0	1	0	0
A_3	0	0	0	0	0	0.2390	0.2024	0.2670	0.2601	0.2693	0.2263	0.2343	0.2475	0.1866	0.2509	0.2786	0.2236	0.2481	0.2084	0	0	1	0
A_4	0	0	0	0	0	0.3278	0.2974	0.3132	0.3258	0.2816	0.2888	0.3167	0.2770	0.3627	0.3077	0.3027	0.2622	0.3217	0.3871	0	0	0	1

Table A2
Weighted supermatrix.

	Goal	C_1	C_2	C_3	C_4	SC_{11}	SC_{12}	SC_{13}	SC_{14}	SC_{21}	SC_{22}	SC_{23}	SC_{31}	SC_{32}	SC_{33}	SC_{34}	SC_{41}	SC_{42}	SC_{43}	A_1	A_2	A_3	A_4
Goal	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_1	0.1609	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_2	0.1947	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_3	0.0942	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_4	0.0501	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{11}	0	0.3937	0	0	0	0.2939	0	0.3418	0.3248	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{12}	0	0.3622	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{13}	0	0.1438	0	0	0	0.1261	0	0.0966	0.1061	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{14}	0	0.1003	0	0	0	0.0800	0	0.0615	0.0692	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{21}	0	0	0.5604	0	0	0	0	0	0	0.3073	0.2810	0.2974	0	0	0	0	0	0	0	0	0	0	0
SC_{22}	0	0	0.3104	0	0	0	0	0	0	0.1412	0.1690	0.1339	0	0	0	0	0	0	0	0	0	0	0
SC_{23}	0	0	0.1291	0	0	0	0	0	0	0.0515	0.0500	0.0686	0	0	0	0	0	0	0	0	0	0	0
SC_{31}	0	0	0	0.3936	0	0	0	0	0	0	0	0	0.2058	0.1666	0.2118	0.1719	0	0	0	0	0	0	0
SC_{32}	0	0	0	0.2990	0	0	0	0	0	0	0	0	0.1090	0.1811	0.1463	0.1701	0	0	0	0	0	0	0
SC_{33}	0	0	0	0.1671	0	0	0	0	0	0	0	0	0.1315	0.0851	0.0878	0.0909	0	0	0	0	0	0	0
SC_{34}	0	0	0	0.1404	0	0	0	0	0	0	0	0	0.0537	0.0672	0.0541	0.0671	0	0	0	0	0	0	0
SC_{41}	0	0	0	0	0.5376	0	0	0	0	0	0	0	0	0	0	0	0.2952	0.3144	0.2771	0	0	0	0
SC_{42}	0	0	0	0	0.3316	0	0	0	0	0	0	0	0	0	0	0	0.1537	0.1416	0.1741	0	0	0	0
SC_{43}	0	0	0	0	0.1308	0	0	0	0	0	0	0	0	0	0	0	0.0511	0.0440	0.0488	0	0	0	0
A_1	0	0	0	0	0	0.0765	0.0854	0.0838	0.0770	0.0798	0.0801	0.0931	0.1030	0.0812	0.0835	0.0779	0.0893	0.0801	0.0500	1	0	0	0
A_2	0	0	0	0	0	0.1401	0.1647	0.1261	0.1300	0.1447	0.1623	0.1314	0.1348	0.1441	0.1372	0.1315	0.1678	0.1350	0.1523	0	1	0	0
A_3	0	0	0	0	0	0.1195	0.1012	0.1335	0.1300	0.1347	0.1132	0.1171	0.1238	0.0933	0.1254	0.1393	0.1118	0.1240	0.1042	0	0	1	0
A_4	0	0	0	0	0	0.1639	0.1487	0.1566	0.1629	0.1408	0.1444	0.1583	0.1385	0.1814	0.1539	0.1513	0.1311	0.1608	0.1935	0	0	0	1

Table A3
Limit supermatrix.

	Goal	C_1	C_2	C_3	C_4	SC_{11}	SC_{12}	SC_{13}	SC_{14}	SC_{21}	SC_{22}	SC_{23}	SC_{31}	SC_{32}	SC_{33}	SC_{34}	SC_{41}	SC_{42}	SC_{43}	A_1	A_2	A_3	A_4
Goal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C_4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{11}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{12}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{13}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{14}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{21}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{22}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{23}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{31}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{32}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{33}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{34}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{41}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{42}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SC_{43}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A_1	0.1657	0.1617	0.1629	0.1793	0.1638	0.1548	0.1708	0.1619	0.1552	0.1611	0.1614	0.1746	0.1931	0.1702	0.1736	0.167	0.1719	0.1631	0.1325	1	0	0	0
A_2	0.2926	0.2920	0.2969	0.2752	0.3112	0.2753	0.3294	0.2618	0.2656	0.2931	0.3112	0.2794	0.2721	0.282	0.2748	0.2693	0.3240	0.2917	0.3079	0	1	0	0
A_3	0.2400	0.2319	0.2522	0.2343	0.2296	0.2440	0.2024	0.2574	0.2541	0.2613	0.2392	0.2436	0.242	0.2093	0.2424	0.2557	0.2266	0.2387	0.2192	0	0	1	0
A_4	0.3016	0.3145	0.2879	0.3114	0.2953	0.3259	0.2974	0.3188	0.3251	0.2845	0.2881	0.3022	0.2929	0.3385	0.3093	0.308	0.2775	0.3064	0.3404	0	0	0	1

characteristics, economic aspects, environmental issues and technical levels, and various sub-criteria. By adopting interpretive structural modeling, the interrelationships among sub-criteria under each criterion are determined. After questionnaires are filled out by decision makers, fuzzy analytic network process is used to calculate the importance of the criteria and the sub-criteria and to evaluate the expected overall performance of the wind turbines. With the implementation of the model, the most suitable type of wind turbines can be selected for constructing the wind farm. The model can also be adjusted as required to help evaluate other renewable energy equipment.

In the case study, *economic aspects* (C_2) is the most important criterion, followed by *machine characteristics* (C_1). Under the *economic aspects* (C_2), *net present value* is the most important objective of the experts, followed by the reduction of *Capital costs*. This means that the financial return is the most important factor in selecting wind turbines. Such outcome is in accord with the fact why governments in many countries need to provide favorable support schemes, financial incentives, adequate grid infrastructure and access to financing to wind farm operators. Under the *machine characteristics* (C_1), *system conversion rate* is the highest concern, followed by the easiness in operating the wind turbines. The geographic area and the size of land are also important concerns in constructing wind turbines in order to prevent destructive impacts to the environment. Needless to say, technology and parts support provided by suppliers is important for running the wind farm smoothly, and the selection of a credible supplier for long-term cooperation is essential. Although the results may be case specific, the proposed model can be tailored and applied by other wind farms in different locations or countries as a reference when selecting the most appropriate wind turbines.

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Appendix A

Tables A1, A2, A3.

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