https://doi.org/10.1016/j.renene.2018.01.087

Sustainability Prioritization of Energy Storage Technologies for Promoting the Development of Renewable Energy: A Novel Intuitionistic Fuzzy Combinative Distance-based Assessment Approach

Jingzheng Ren[1]

[1] Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong SAR，China

Email renjingzheng123321@163.com; jire@polyu.edu.hk (J. Ren)

Correspondence at: Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong SAR，China

Abstract: Energy storage technology plays an important role for promoting the development of renewable energy sources due to their highly erratic and intermittent characteristics. However, it is usually difficult for the decision-makers/stakeholders to select the most sustainable scenario among multiple energy storage technologies. This study aims at developing a novel multi-criteria decision making method by combining the interval analytic hierarchy process (IAHP) and the intuitionistic fuzzy combinative distance-based assessment method for prioritizing the alternative energy storage technologies. Four alternative energy storage technologies including pumped hydro, compressed air, lithium-ion, and flywheel were studied by the proposed method, the sustainability sequence of the four energy storage technologies from the most sustainable to the least is pumped hydro, flywheel, lithium-ion, and compressed air. Sensitivity analysis was also carried out to investigate the effects of the weights of the metrics on the sustainability ranking of the four alternative energy storage technologies, and the results reveal that altering the preferences/willingness of the decision-makers/stakeholders and the relative importance of the metrics will change the sustainability ranking of the four energy storage technologies.

Keywords: Energy storage technologies; sustainability; intuitionistic fuzzy set; Combinative Distance-based Assessment Method

1. Introduction

The development of the power based on renewable energy sources (i.e. wind power, solar energy, and tidal energy, etc.) has been recognized as a promising way for energy security improvement and emissions mitigation all over the world (Ren and Sovacool, 2015). However, the integration of renewable energy sources into grid is often faced with reluctance by the utility operators due to the intermittent and stochastic features of renewable energy sources (Hall and Bain, 2008; Kuravi *et al.*, 2013). With the increase of the share of intermittent renewable energy sources in the power industry in many countries, energy storage technology for creating smart grid with a better utilization of fluctuating renewable energy sources becomes more and more important.

As discussed above, energy storage technology for facilitating the large-scale integration of variable renewable electricity sources, plays an important role in promoting the integration of renewable energy sources into grid through capturing immediate resources and keeping until they are required as renewable energy sources are usually highly erratic and intermittent (Satkin *et al.*, 2014). However, it is usually difficult for the decision-makers/stakeholders to select the most sustainable or the most suitable energy storage technology, because the decision-makers usually face multiple alternative choices for energy storage, i.e. mechanical (pumped hydro, compressed air and flywheel), electrochemical, thermochemical, thermal, chemical, and electrical energy storage technologies (Luo *et al.*, 2015). Meanwhile, the decision-making process also involves multiple conflict criteria when selecting the most suitable/sustainable scenario among multiple energy storage technologies.

According to literature reviews (Hadjipaschalis *et al.*, 2009; Divyaand Østergaard, 2009; Koohi-Kamali *et al.*, 2013), it is apparent that different energy storage technologies have different performances on economic, environmental and social aspects. For instance, the capital costs of pumped hydro energy storage and lithium-ion energy storage are different; they also have different environmental impacts and technological characteristics; in addition, the social impacts of these two technologies are also different because of their different performances on economic, environmental and technological aspects. Therefore, the decision-making on energy storage technology selection is of vital importance for the decision-makers/stakeholders to select the best scenario among multiple alternatives.

There are many studies focusing on multi-criteria decision making on the selection of energy storage technologies. For instance, Vo *et al.* (2017) employed cost, position flexibility, storage capacity/discharge time, efficiency, environmental issues, and energy carrier vector to compare three energy storage technologies, i.e. power to gas (methane), pumped hydroelectric storage and compressed air energy storage. Barin *et al*. (2009) combined Analytic Hierarchy Process (AHP) and fuzzy logic to evaluate the energy storage systems. Lee and Ho (2016) developed a technology evaluation technique to analyze the promising electricity storage technologies by considering multiple criteria (i.e. operation cost, safety, and deep-cycle life, etc.). All these studies are beneficial for the decision-makers/stakeholders to select the best energy storage technologies; however, there are still two research gaps:

(1) The lack of the methods for multi-criteria decision making under uncertainties, most of the previously published works have to know the exact data of the alternative energy storage technologies with respect to the metrics, while it is usually difficult to obtained all the data, and the methods for decision-making under uncertainties are of vital importance;

(2) The lack of the methods for accurately determining the weights of the metrics which represent the preferences/willingness of the decision-makers/stakeholders; AHP is the most widely used method for weights determination in the multi-criteria decision making on the selection of the alternative energy storage technologies, while this method replies on the scales from 1 to 9 and their reciprocals to establish the comparison matrix, it is usually

difficult for the users to use a crisp number to depict the relative perference of one metric over another.

The objective of this study is to overcome the above-mentioned two research gaps and develop a generic sustainability assessment method for prioritizing the alternative energy storage technologies comprehensively with the considerations of multiple sustainability criteria under uncertainties according to the actual conditions and the preferences of the decision-makers/stakeholders for the integration of renewable energy sources into grid, and to achieve scientific and democracy decisions for adapting the increased renewable energy penetration. The results obtained by the proposed method highlight the development roadmap of energy storage technology forpromoting the development of renewable energy.

2. Methods

There are three parts in this section. The criteria for sustainability assessment of energy storage technology were firstly presented in section 2.1; fuzzy set and intuitionistic fuzzy set were subsequently introduced in section 2.2; The intuitionistic fuzzy Multi-criteria decision making method was then developed by combining the Interval Analytic Hierarchy Process (IAHP) and the developed the Intuitionistic Fuzzy Combinative Distance-based Assessment Method (IFCODAS) in section 2.3.

2.1 Criteria for sustainability assessment of energy storage technology

Sustainability or sustainable development refers to achieve economy booming, environmental protection and social responsibility simultaneously (Ren et al., 2016). Thus, economic, environmental, and social issues are the three pillars of sustainability, and the criteria/metrics in these three aspects are widely used for sustainability assessment. A total of nine metrics in four aspects including economic, environmental, technological, and social aspects are summarized for sustainability assessment of energy storage technology, and they are capital cost (EC_1), life (EC_2), and operating cost (EC_3) in economic aspect (EC), CO_2 density (EN_1) and integrated environmental impact (EN_2) in environmental aspect (EN), energy efficiency (T_1), energy density (T_2), and technology maturity (T_3) in technological aspect (T) , and social acceptability (S_1) in social aspect (S) based on literature review (Ren and Ren, 2017) and focus group meetings.

2.2 Fuzzy set and intuitionistic fuzzy set

Definition 1. Fuzzy sets (FS) (Zadeh, 1965)

The set X is an universe of discourse composed by x, and a fuzz set $\tilde{a}$ can be characterized by a membership function $\mu_{\tilde{a}}(x)$ which can measure the degree of x belonging to α. $\mu_{\tilde{a}}(x)$ represents the membership of x in $\tilde{a}$

$$\alpha = \left\{ (x, \mu_{a}(x)) \mid x \in X \right\} \tag{1}$$

Definition 2. Intuitionistic fuzzy set (IFS)

Assuming that X is an object collection of x and $\beta \in X$ is a fixed set, the intuitionistic fuzzy set β on X can be defined as (Atanassov, 1986):

$$\beta = \left\{ (x, \mu_{\beta}(x), \upsilon_{\beta}(x)) \mid x \in X \right\} \tag{2}$$

where $\mu_{\beta}(x): X \to [0,1], x \in X \to \mu_{\beta}(x) \in [0,1]$ represents the degree of membership of the element $x \in X$ to the set β, and $\upsilon_{\beta}(x): X \to [0,1], x \in X \to \upsilon_{\beta}(x) \in [0,1]$ is the degree of non-membership of the element $x \in X$ to the set β.

μ_{β} and $\upsilon_{\beta}(x)$ usually satisfies $0 \le \mu_{\beta}(x) + \upsilon_{\beta}(x) \le 1$ for all $x \in X$ .Besides the degree of membership and non-membership, an indeterminacy degree, so-called “hesitancy degree” of x to the set β which is different from the numbers $\mu_{\beta}(x)$ and $\upsilon_{\beta}(x)$ representing the degree of membership and the degree of non-membership of the element $x \in X$ to the set β, can measure the degree of indeterminacy of $x \in X$ to the set β is defined as:

$$\pi_\beta(x) = 1 - \mu_\beta(x) - \upsilon_\beta(x), x \in X \tag{3}$$

Accordingly, an intuitionistic fuzzy number β can usually be represented by $\beta = \left(\mu_\beta, \upsilon_\beta, \pi_\beta\right)$ which included the degree of membership, non-membership, and indeterminacy degree.

Definition 3. Arithmetic operations (Xu and Yager, 2006)

Let $\gamma = \left(\mu_\gamma, \upsilon_\gamma, \pi_\gamma\right)$ and $\beta = \left(\mu_\beta, \upsilon_\beta, \pi_\beta\right)$ be two intuitionistic fuzzy numbers, and the arithmetic operations between these two intuitionistic fuzzy numbers were presented as follows:

Addition

$$\gamma \oplus \beta = \left(\mu_\gamma, \upsilon_\gamma, \pi_\gamma\right) \oplus \left(\mu_\beta, \upsilon_\beta, \pi_\beta\right) = \left(\mu_\gamma + \mu_\beta - \mu_\gamma\mu_\beta, \upsilon_\gamma\upsilon_\beta, 1 + \mu_\gamma\mu_\beta - \mu_\gamma - \mu_\beta - \upsilon_\gamma\upsilon_\beta\right) \tag{4}$$

$$\overset{n}{\underset{j=1}{\oplus}} \gamma_j = \overset{n}{\underset{j=1}{\oplus}} \left(\mu_{\gamma_j}, \upsilon_{\gamma_j}, \pi_{\gamma_j}\right) = \left(1 - \prod_{j=1}^{n}\left(1 - \mu_{\gamma_j}\right), \prod_{j=1}^{n} \upsilon_{\gamma_j}, \prod_{j=1}^{n}\left(1 - \mu_{\gamma_j}\right) - \prod_{j=1}^{n} \upsilon_{\gamma_j}\right) \tag{5}$$

Multiplication

$$\gamma \otimes \beta = \left(\mu_\gamma, \upsilon_\gamma, \pi_\gamma\right) \otimes \left(\mu_\beta, \upsilon_\beta, \pi_\beta\right) = \left(\mu_\gamma\mu_\beta, \upsilon_\gamma + \upsilon_\beta - \upsilon_\gamma\upsilon_\beta, 1 + \upsilon_\gamma\upsilon_\beta - \mu_\gamma\mu_\beta - \upsilon_\gamma - \upsilon_\beta\right) \tag{6}$$

$$\overset{n}{\underset{j=1}{\otimes}} \gamma_j = \overset{n}{\underset{j=1}{\otimes}} \left(\mu_{\gamma_j}, \upsilon_{\gamma_j}, \pi_{\gamma_j}\right) = \left(\prod_{j=1}^{n} \mu_{\gamma_j}, \prod_{j=1}^{n}\left(1 - \upsilon_{\gamma_j}\right), 1 - \prod_{j=1}^{n} \mu_{\gamma_j} - \prod_{j=1}^{n}\left(1 - \upsilon_{\gamma_j}\right)\right) \tag{7}$$

Scale multiplication

$$\lambda\gamma = \left(1 - \left(1 - \mu_\gamma\right)^\lambda, \left(\upsilon_\gamma\right)^\lambda, \left(1 - \mu_\gamma\right)^\lambda - \left(\upsilon_\gamma\right)^\lambda\right) \tag{8}$$

where λ is a crisp number.

Definition 4. Geometric distance (Szmidt and Kacprzyk, 2000).

The distance between two intuitionistic fuzzy sets $\gamma = \left(\mu_\gamma, \upsilon_\gamma, \pi_\gamma\right)$ and $\beta = \left(\mu_\beta, \upsilon_\beta, \pi_\beta\right)$ can be determined by Eqs.9-10.

The Hamming distance:

$$d(\gamma,\beta)=\frac{1}{2}\sum_{j=1}^{n}\left(\left|\mu_\gamma(x_j)-\mu_\beta(x_j)\right|+\left|\upsilon_\gamma(x_j)-\upsilon_\beta(x_j)\right|+\left|\pi_\gamma(x_j)-\pi_\beta(x_j)\right|\right) \tag{9}$$

The Euclidean distance:

$$d(\gamma,\beta)=\sqrt{\frac{1}{2}\sum_{j=1}^{n}\left[\left(\mu_\gamma(x_j)-\mu_\beta(x_j)\right)^2+\left(\upsilon_\gamma(x_j)-\upsilon_\beta(x_j)\right)^2+\left(\pi_\gamma(x_j)-\pi_\beta(x_j)\right)^2\right]} \tag{10}$$

Definition 5. Score and accuracy degree of an intuitionistic fuzzy set (Hong and Choi, 2000). The score and the accuracy degree of the intuitionistic fuzzy set $\gamma=\left(\mu_\gamma,\upsilon_\gamma,\pi_\gamma\right)$ can be determined by Eq.11 and Eq.12, respectively.

$$S_\gamma=\mu_\gamma-\upsilon_\gamma \tag{11}$$

$$H_\gamma=\mu_\gamma+\upsilon_\gamma \tag{12}$$

where S_γ and H_γ are the score and the accuracy degree of the intuitionistic fuzzy set $\gamma=\left(\mu_\gamma,\upsilon_\gamma,\pi_\gamma\right)$.

2.3 Intuitionistic fuzzy Multi-criteria decision making method

A novel multi-criteria decision making (MCDM) method was developed for sustainability ranking of the alternative energy storage technologies by combining the IAHP and IFCODAS, the framework of the developed MCDM method was proposed in Figure 1. The IAHP which allows the decision-makers to use interval numbers rather than the crisp numbers to determine the comparison matrix was employed to determine the weights of the criteria for sustainability assessment of energy storage technologies. The IFCODAS method by combining the Intuitionistic Fuzzy Set (IFS) theory and the Combinative Distance-based Assessment Method (CODAS) method which allows the decision-makers/stakeholders using intuitionistic fuzzy numbers to rate the alternative energy storage technologies with respect to each criterion was used to prioritize the alternative energy storage technologies.

2.3.1 Interval Analytic Hierarchy Process

The interval Analytic Hierarchy Process (IAHP) consists of four steps (Xu and Da,2003):

Step 1: Determining the interval pair-wise comparison matrix.

Assuming that there a total of n metrics $\left(M_1, M_2, \cdots, M_n\right)$ which need the decision-makers to determine the relative weights, the decision-makers were asked to use the nine-scale system developed by Saaty (2008) to establish the pair-wise comparison matrix (see Table 1). The traditional AHP method usually used the numbers from 1 to 9 and their reciprocals for comparing each pair of factors for establishing the pair-wise comparison matrix; however, a single number sometime cannot depict the relative weight/priority of each pair metrics accurately. For example, there is not any single number can depict the relative weight/priority of a metric over another when the decision-makers held the view that the relative importance of a metric over another is between 'equal importance' (corresponding to number a) and 'moderate importance' (corresponding to number 3). Accordingly, the interval number [1, 3] can be used to depict this situation. In this way, the interval comparison matrix for the n metrics can be determined:

$$Q^{\pm} = \begin{array}{ccccc} & M_1 & M_2 & \cdots & M_n \\ M_1 & 1 & [q_{12}^L, q_{12}^U] & \cdots & [q_{1n}^L, q_{1n}^U] \\ M_2 & [q_{21}^L, q_{21}^U] & 1 & \cdots & [q_{2n}^L, q_{2n}^U] \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ M_n & [q_{n1}^L, q_{n1}^U] & [q_{n2}^L, q_{n2}^U] & \cdots & 1 \end{array} \tag{13}$$

where $Q^{\pm}$ represents the interval pair-wise matrix, $[q_{ij}^L, q_{ij}^U]$ is an interval number and denotes the relative importance of the i-th metric over the j-th metric, and a_{ij}^L and a_{ij}^U are the lower and upper boundary of the interval number $[q_{ij}^L, q_{ij}^U]$.

The relative importance of the j-th metric comparing to i-th metric can be determiend by Eq.14.

$$\frac{1}{[q_{ij}^L, q_{ij}^U]} = [\frac{1}{q_{ij}^U}, \frac{1}{q_{ij}^L}], i, j = 1, 2, \cdots, n \tag{14}$$

Step 2: Decomposing the interval pair-wise comparison matrix into two crisp nonnegative matrices.

The interval pair-wise comparison matrix in Eq. 14 can be decomposed into two crisp nonnegative matrices, as presented in Eqs. 15-16.

$$Q_L = \begin{vmatrix} 1 & q_{12}^L & \cdots & q_{1n}^L \\ 1/q_{21}^U & 1 & \cdots & q_{2n}^L \\ \vdots & \vdots & \ddots & \vdots \\ 1/q_{n1}^U & 1/q_{n2}^U & \cdots & 1 \end{vmatrix} \tag{15}$$

$$Q_U = \begin{vmatrix} 1 & q_{12}^U & \cdots & q_{1n}^U \\ 1/q_{21}^L & 1 & \cdots & q_{2n}^U \\ \vdots & \vdots & \ddots & \vdots \\ 1/q_{n1}^L & 1/q_{n2}^L & \cdots & 1 \end{vmatrix} \tag{16}$$

The geometric mean method (Ren *et al.*, 2017) can be used to determine the weights according to the matrices presented in Eqs.15-16, and the weight vectors determined by these two matrices were presented in Eq.17 and Eq.18, respectively.

$$W_L = \begin{bmatrix} \omega_1^L & \omega_2^L & \cdots & \omega_n^L \end{bmatrix} \tag{17}$$

$$W_U = \begin{bmatrix} \omega_1^U & \omega_2^U & \cdots & \omega_n^U \end{bmatrix} \tag{18}$$

where W_L and W_U represent the weight vectors determined by the matrices presented in Eq.15 and Eq.16, respectively. ω_j^L and ω_j^U are the weights of the j-th metric in W_L and W_U, respectively.

Step 3: Determining the interval weights. The interval weights of each metric can be determined by Eqs.19-21.

$$k = \sqrt{\sum_{j=1}^{n} \frac{1}{\sum_{i=1}^{n} q_{ij}^{+}}} \tag{19}$$

$$m = \sqrt{\sum_{j=1}^{n} \frac{1}{\sum_{i=1}^{n} q_{ij}^{-}}} \tag{20}$$

It is worth pointing out that if k and m satisfy $0 < k \le 1 \le m$, then, the users can use Eq.21 to determine the interval weight of the *j*-th metric, or the users should modify the interval pair-wise comparison matrix to make k and m satisfy this condition.

$$\omega_j^{\pm} = \left[k\omega_j^{L} \quad m\omega_j^{U} \right] \tag{21}$$

where $\omega_j^{\pm}$ represents the interval weight of the *j*-th metric.

Step 4: Determining the crisp weights of the metrics. The possibility of $\omega_j^{\pm}$ be greater than $\omega_r^{\pm}$ can be determined by Eq.22 according to Xu and Da (2003).

$$p_{jr} = p\left(\omega_j^{\pm} \ge \omega_r^{\pm}\right) = \max\left\{1 - \max\left[\frac{m\omega_r^{U} - k\omega_j^{L}}{m\omega_r^{U} - k\omega_r^{L} + m\omega_j^{U} - k\omega_j^{L}}\right], 0\right\} \tag{22}$$

where $p_{jr} = P\left(\omega_j^{\pm} \ge \omega_r^{\pm}\right)$ represents the possibility of $\omega_j^{\pm}$ be greater than $\omega_r^{\pm}$.

After comparing each pair of weights, the possibility matrix can be determined by Eq.23.

$$P = \begin{vmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{vmatrix} \tag{23}$$

Then, the crisp of each metric can be determined by Eq.24.

$$\omega_j = \frac{\sum_{r=1}^{n} p_{jr} + \frac{n}{2} - 1}{n(n-1)} \tag{24}$$

where ω_j represents the crisp weight of the *j*-th metric.

2.3.2 Intuitionistic Fuzzy Combinative Distance-based Assessment Method

The Combinative Distance-based Assessment Method (CODAS) developed by Keshavarz Ghorabaee et al. (2016) which can measure the overall performances of the alternatives by the Euclidean and Taxicab distance from the native-ideal solutions. However, the traditional CODAS method cannot address the vagueness and ambiguity existing human judgements. Accordingly, the IFCODAS was developed by combining the intuitionistic fuzzy set theory and CODAS method. The IFCODAS developed in this study was specified as follows:

Step 1: Determining the intuitionistic fuzzy decision-making matrix. Assuming that there are m alternatives $\left(A_1, A_2, \cdots, A_m\right)$ to be evaluated by n metrics $\left(M_1, M_2, \cdots, M_n\right)$, the decision-makers were firstly asked to rate the alternatives with respect to each metric by using the linguistic variables including extreme good (EG), very good (VG), good (G), medium good (MG), fair (F), medium poor (MP), poor (P), very poor (VP), and extreme poor (EP). In other words, these linguistic terms were used to describe the relative performances of the m alternatives with respect to each of the m metrics. Subsequently, these linguistic variables can be transformed into intuitionistic fuzzy numbers according to Table 2. Then, the intuitionistic fuzzy decision-making matrix can be determined, as presented in Eq.13.

$$D = \begin{array}{c|cccc} & M_1 & M_2 & & M_n \\ A_1 & (\mu_{11}^x, \upsilon_{11}^x, \pi_{11}^x) & (\mu_{12}^x, \upsilon_{12}^x, \pi_{12}^x) & \cdots & (\mu_{1n}^x, \upsilon_{1n}^x, \pi_{1n}^x) \\ A_2 & (\mu_{21}^x, \upsilon_{21}^x, \pi_{21}^x) & (\mu_{22}^x, \upsilon_{22}^x, \pi_{22}^x) & \cdots & (\mu_{2n}^x, \upsilon_{2n}^x, \pi_{2n}^x) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & (\mu_{m1}^x, \upsilon_{m1}^x, \pi_{m1}^x) & (\mu_{m2}^x, \upsilon_{m2}^x, \pi_{m2}^x) & \cdots & (\mu_{mn}^x, \upsilon_{mn}^x, \pi_{mn}^x) \end{array} \qquad (13)$$

where D is the decision-making matrix, and $(\mu_{ij}^x, \upsilon_{ij}^x, \pi_{ij}^x)$ represents the relative performance of the *i*-th alternative with respect to the *j*-th metric.

Step 2: Determining the weighted intuitionistic fuzzy decision-making matrix. The weighted intuitionistic fuzzy decision-making matrix can be determined by Eqs.14-15. Note that the weights of the metrics in this study will be obtained by the IAHP method.

$$WD = \begin{array}{cccccc} & M_1 & M_2 & & M_n \\ A_1 & \omega_1(\mu_{11}^x,\upsilon_{11}^x,\pi_{11}^x) & \omega_2(\mu_{12}^x,\upsilon_{12}^x,\pi_{12}^x) & \cdots & \omega_n(\mu_{1n}^x,\upsilon_{1n}^x,\pi_{1n}^x) \\ A_2 & \omega_1(\mu_{21}^x,\upsilon_{21}^x,\pi_{21}^x) & \omega_2(\mu_{22}^x,\upsilon_{22}^x,\pi_{22}^x) & \cdots & \omega_n(\mu_{2n}^x,\upsilon_{2n}^x,\pi_{2n}^x) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & \omega_1(\mu_{m1}^x,\upsilon_{m1}^x,\pi_{m1}^x) & \omega_2(\mu_{m2}^x,\upsilon_{m2}^x,\pi_{m2}^x) & \cdots & \omega_n(\mu_{mn}^x,\upsilon_{mn}^x,\pi_{mn}^x) \end{array}$$

$$= \begin{array}{cccccc} & M_1 & M_2 & & M_n \\ A_1 & (\mu_{11},\upsilon_{11},\pi_{11}) & (\mu_{12},\upsilon_{12},\pi_{12}) & \cdots & (\mu_{1n},\upsilon_{1n},\pi_{1n}) \\ A_2 & (\mu_{21},\upsilon_{21},\pi_{21}) & (\mu_{22},\upsilon_{22},\pi_{22}) & \cdots & (\mu_{2n}^x,\upsilon_{2n}^x,\pi_{2n}^x) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & (\mu_{m1},\upsilon_{m1},\pi_{m1}) & (\mu_{m2},\upsilon_{m2},\pi_{m2}) & \cdots & (\mu_{mn},\upsilon_{mn},\pi_{mn}) \end{array} \tag{14}$$

$$wd_{ij} = (\mu_{ij},\upsilon_{ij},\pi_{ij}) = \omega_j(\mu_{ij}^x,\upsilon_{ij}^x,\pi_{ij}^x) = (1-\left(1-\mu_{ij}^x\right)^{\omega_j},\left(\upsilon_{ij}^x\right)^{\omega_j},\left(1-\mu_{ij}^x\right)^{\omega_j}-\left(\upsilon_{ij}^x\right)^{\omega_j}) \tag{15}$$

where WD represents the weighted intuitionistic fuzzy decision-making matrix, ω_j represents the weight of the j-th criterion, and $wd_{ij} = (\mu_{ij},\upsilon_{ij},\pi_{ij})$ is the element of cell (i, j) in the weighted intuitionistic fuzzy decision-making matrix.

Step 3: Determining the negative-ideal solutions (NIS). The negative-ideal solutions can be determined by Eqs.16-20.

$$NIS_j = (\mu_j,\upsilon_j,\pi_j), j = 1,2,\cdots,n \tag{16}$$

$$t = \arg\min_i(\mu_{ij}) \tag{17}$$

$$\mu_j = \mu_{tj} \tag{18}$$

$$\upsilon_j = \upsilon_{tj} \tag{19}$$

$$\pi_j = 1-\mu_{tj}-\upsilon_{tj} \tag{20}$$

Step 4: Determining the Euclidean distance and the Hamming distances of the alternatives to the negative-ideal solutions.

The Euclidean distance:

$$E\left(wd_{ij},NIS_j\right)=\sqrt{\frac{1}{2}\sum_{j=1}^{n}\left[\left(\mu_{ij}-\mu_j\right)^2+\left(\upsilon_{ij}-\upsilon_j\right)^2+\left(\pi_{ij}-\pi_j\right)^2\right]} \tag{21}$$

The Hamming distance:

$$H\left(wd_{ij},NIS_j\right)=\frac{1}{2}\sum_{j=1}^{n}\left(\left|\mu_{ij}-\mu_j\right|+\left|\upsilon_{ij}-\upsilon_j\right|+\left|\pi_{ij}-\pi_j\right|\right) \tag{22}$$

Step 5: Establishing the relative assessment matrix. The relative assessment matrix can be determined by Eqs.23-24.

$$R=\left\{r_{ik}\right\}_{m\times m} \tag{23}$$

$$r_{ik}=\left[E\left(wd_{ij},NIS_j\right)-E\left(wd_{kj},NIS_j\right)\right]+\Phi\left[E\left(wd_{ij},NIS_j\right)-E\left(wd_{kj},NIS_j\right)\right]\times\left[H\left(wd_{ij},NIS_j\right)-H\left(wd_{kj},NIS_j\right)\right]$$

(22)

$$\Phi\left[E\left(wd_{ij},NIS_j\right)-E\left(wd_{kj},NIS_j\right)\right]=\begin{cases}1 & if \quad -\tau\le E\left(wd_{ij},NIS_j\right)-E\left(wd_{kj},NIS_j\right)\le\tau\\ 0 & if \quad others\end{cases} \tag{24}$$

where Φ represents the threshold function to recognize the equality of the Euclidean distance of two alternatives, τ is the threshold value set by the users according to their judgments, and r_{ik} represent the priority difference of the *i*-th alternative to the *k*-th alternative.

Step 6: Determining the final assessment score of each alternative and ranking the alternatives. The final score of each alternative can be determined by Eq.25.

$$F_i=\sum_{k=1}^{m}r_{ik} \tag{25}$$

where F_i represent the final assessment score of the i-th alternative.

After determining the final assessment score of each alternative, the alternatives can be ranked according to the rule that the greater the value of the final assessment score, the more superior the alternative will be.

3. Case study

Four energy storage technologies including pumped hydro storage (A_1), compressed air energy storage (A_2), Lithium-ion battery (A_3), and flywheel energy storage system (A_4) were studied by the proposed intuitionistic fuzzy multi-criteria decision making method. These four energy storage technologies have been specified as follows:

Pumped hydro: pumped hydro storage is a kind of large scale system for energy storage by controlling the gravitational potential energy of water. The water will be pumped from a lower reservoir to an upper reservoir when the power demand is low, and it will flow from the upper reservoir to the lower reservoir to activate the turbines to generate electricity during the periods of higher energy demand (Díaz-González *et al.*, 2012);

Compressed air: compressed air energy storage system is based on the conventional gas turbine technology in which the energy is stored in form of compressed air in an underground storage cavern. The energy in the form of compressed air will be transformed into rotational kinetic energy through a set of high and low pressure turbines(Díaz-González *et al.*, 2012);

Lithium-ion: Li-ion batteries is one of the battery energy storage systems, which can store the energy in the form of electrochemical energy, and Li-ion batteries is based on the electrochemical reactions between positive lithium ions (Li+) with anolytic and catholytic active materials (Wakihara, 2011).

Flywheel: The flywheel energy storage system is an electromechanical system that stores energy in form of kinetic energy. Energy is transferred to the flywheel through the flywheel accelerates, and the system is discharged when the electric machine regenerates through the drive (slowing the flywheel) (Díaz-González *et al*., 2012).

A total of nine criteria in four categories (economic, environmental, technological and social aspects) have been employed for sustainability assessment , and there are capital cost (EC_1), life (EC_2), and operating cost (EC_3) in economic aspect (EC), CO_2 density (EN_1) and integrated environmental impact (EN_2) in environmental aspect (EN), energy efficiency (T_1), energy density (T_2), and technology maturity (T_3) in technological aspect (T) , and social acceptability (S_1) in social aspect (S). The IAHP was firstly used to determine the weights of the four categories and the weights of the criteria in each aspect. Taking the calculation of the weights of the four categories as an example, the four steps of IAHP were specified as follows:

Step 1: The interval pair-wise comparison matrix (see Table 3) can be firstly determined for determining the weights of the four categories.

Step 2: The two crisp nonnegative matrices can be then determined according to Table 1, and the results were presented in Eq.26 and Eq.27, respectively.

$$Q_L = \begin{vmatrix} 1 & 1 & 1/3 & 5 \\ 1/2 & 1 & 1/5 & 3 \\ 1 & 3 & 1 & 7 \\ 1/7 & 1/5 & 1/9 & 1 \end{vmatrix} = \begin{vmatrix} q_{11}^- & q_{12}^- & q_{13}^- & q_{14}^- \\ q_{21}^- & q_{22}^- & q_{23}^- & q_{24}^- \\ q_{31}^- & q_{32}^- & q_{33}^- & q_{34}^- \\ q_{41}^- & q_{42}^- & q_{43}^- & q_{44}^- \end{vmatrix} \tag{26}$$

$$Q_U = \begin{vmatrix} 1 & 2 & 1 & 7 \\ 1 & 1 & 1/3 & 5 \\ 3 & 5 & 1 & 9 \\ 1/5 & 1/3 & 1/7 & 1 \end{vmatrix} = \begin{vmatrix} q_{11}^+ & q_{12}^+ & q_{13}^+ & q_{14}^+ \\ q_{21}^+ & q_{22}^+ & q_{23}^+ & q_{24}^+ \\ q_{31}^+ & q_{32}^+ & q_{33}^+ & q_{34}^+ \\ q_{41}^+ & q_{42}^+ & q_{43}^+ & q_{44}^+ \end{vmatrix} \tag{27}$$

Then, W_L and W_U can be determined by the geometric-method, and the result were presented in Eq.28 and Eq.29, respectively.

$$W_L = \begin{bmatrix} 0.2671 & 0.1740 & 0.5032 & 0.0558 \end{bmatrix} \tag{28}$$

$$W_U = \begin{bmatrix} 0.2848 & 0.1673 & 0.5019 & 0.0460 \end{bmatrix} \tag{29}$$

Step 3: The parameters k and m can be determined by Eq.30 and Eq.31, respectively.

$$k = \sqrt{\sum_{j=1}^{4} \frac{1}{\sum_{i=1}^{4} q_{ij}^{+}}} = 0.8727 \tag{30}$$

$$m = \sqrt{\sum_{j=1}^{4} \frac{1}{\sum_{i=1}^{4} q_{ij}^{-}}} = 1.1141 \tag{31}$$

According to Eq.21, the interval weights of the four categories for sustainability assessment of energy storage technologies can be determined, and the results were presented in Eqs.32-35.

$$\omega_{EC}^{\pm} = \begin{bmatrix} 0.8727 \times 0.2671 & 1.1141 \times 0.2848 \end{bmatrix} = \begin{bmatrix} 0.2331 & 0.3173 \end{bmatrix} \tag{32}$$

$$\omega_{EN}^{\pm} = \begin{bmatrix} 0.8727 \times 0.1740 & 1.1141 \times 0.1673 \end{bmatrix} = \begin{bmatrix} 0.1518 & 0.1864 \end{bmatrix} \tag{33}$$

$$\omega_{T}^{\pm} = \begin{bmatrix} 0.8727 \times 0.5032 & 1.1141 \times 0.5019 \end{bmatrix} = \begin{bmatrix} 0.4391 & 0.5592 \end{bmatrix} \tag{34}$$

$$\omega_{S}^{\pm} = \begin{bmatrix} 0.8727 \times 0.0558 & 1.1141 \times 0.0.0460 \end{bmatrix} = \begin{bmatrix} 0.0487 & 0.0512 \end{bmatrix} \tag{35}$$

Step 4: The elements in the possibility matrix can be determined by comparing the weights of each pair of categories according to Eq.22. Taking the possibility of $\omega_{EC}^{\pm}$ be greater than $\omega_{EN}^{\pm}$ as an example:

$$\begin{aligned} P\left(\omega_{EC}^{\pm} \geq \omega_{EN}^{\pm}\right) &= \max\left\{1 - \max\left[\frac{\omega_{EN}^{U} - \omega_{EC}^{L}}{\omega_{EN}^{U} - \omega_{EN}^{L} + \omega_{EC}^{U} - \omega_{EC}^{L}}, 0\right], 0\right\} \\ &= \max\left\{1 - \max\left[\frac{0.1864 - 0.2331}{0.1864 - 0.1518 + 0.3173 - 0.2331}, 0\right], 0\right\} \\ &= 1.0000 \end{aligned} \tag{36}$$

In a similar way, all the elements in the possibility matrix can be determined, and the results were presented in Eq.37.

$$P = \begin{array}{ccccc} & EC & EN & T & S \\ EC & 0.5000 & 1.0000 & 0 & 1.0000 \\ EN & 0 & 0.5000 & 0 & 1.0000 \\ T & 1.0000 & 1.0000 & 0.5000 & 1.0000 \\ S & 0 & 0 & 0 & 0.5000 \end{array} \tag{37}$$

Then, the crisp weight of each metric can be determined according to Eq.38, and the results were presented in Eqs.38-41.

$$\omega_{EC} = \frac{\sum_{r=1}^{4} p_{1r} + \frac{4}{2} - 1}{4(4-1)} = \frac{0.5000 + 1.0000 + 0 + 1.0000 + \frac{4}{2} - 1}{4(4-1)} = 0.2917 \tag{38}$$

$$\omega_{EN} = \frac{\sum_{r=1}^{4} p_{2r} + \frac{4}{2} - 1}{4(4-1)} = \frac{0 + 0.5000 + 0 + 1.0000 + \frac{4}{2} - 1}{4(4-1)} = 0.2083 \tag{39}$$

$$\omega_{T} = \frac{\sum_{r=1}^{4} p_{3r} + \frac{4}{2} - 1}{4(4-1)} = \frac{1.0000 + 1.0000 + 0.5000 + 1.0000 + \frac{4}{2} - 1}{4(4-1)} = 0.3750 \tag{40}$$

$$\omega_{S} = \frac{\sum_{r=1}^{4} p_{4r} + \frac{4}{2} - 1}{4(4-1)} = \frac{0 + 0 + 0 + 0.5000 + \frac{4}{2} - 1}{4(4-1)} = 0.1250 \tag{41}$$

Therefore, the weights of the economic, environmental, technological and social categories are 0.2917, 0.2083, 0.3750, and 0.1250, respectively.

In a similar way, the weights of the criteria in each category for sustainability assessment of energy storage technologies can also be determined, and the results were presented in Tables 4-6.

After determining the weights of the four categories and that of the metrics in each category, and the global weights of the nine metrics can be determined, and the results were presented in Table 7.

Then, the linguistic variables were firstly used by the decision-makers to rate the four alternative energy storage technologies with respect to each of the metrics for sustainability assessment, and there are eight experts including two professor who focuses on energy storage technologies, three senior researchers of renewable energy, and two PhD students from Chinese universities who majored in power system engineering participating in rating the four energy storage technologies. The results were summarized in Table 8.

The linguistic variables can be transformed into intuitionistic fuzzy numbers according to Table 1. For instance, "VG" in Table 7 can be transformed into (0.85, 0.10, 0.05). In a similar way, all the elements in Table 1 can be transformed into intuitionistic fuzzy numbers, and the results were summarized in Table 9.

According to Eq.15, the element in the weighted intuitionistic fuzzy decision-making matrix can be determined. Taking the element "(0.65, 0.25, 0.10)" in cell (1,1) which represents the value of pumped hydro (A_1) with respect to capital cost (EC_1) as an example:

$$\begin{aligned} wd_{11} = (\mu_{11},\upsilon_{11},\pi_{11}) = \omega_1(\mu_{11}^x,\upsilon_{11}^x,\pi_{11}^x) = (1-\left(1-\mu_{11}^x\right)^{\omega_1},\left(\upsilon_{11}^x\right)^{\omega_1},\left(1-\mu_{11}^x\right)^{\omega_1}-\left(\upsilon_{11}^x\right)^{\omega_1}) \\ =(1-\left(1-0.65\right)^{0.0972},\left(0.25\right)^{0.0972},\left(1-0.65\right)^{0.0972}-\left(0.25\right)^{0.0972}) \\ =(0.0970,0.8739,0.0291) \end{aligned} \quad (42)$$

where wd_{11} represents the value of the element in cell (1,1) of the weighted intuitionistic fuzzy decision-making matrix.

In a similar way, all the elements in the weighted intuitionistic fuzzy decision-making matrix can be then determined, and the results were summarized in Table 10.

According to Eqs.16-20, the negative-ideal solutions can be determined. Taking the negative-ideal solution with respect to EC_1 as an example:

The relative performances of these four alternatives (A_1, A_2, A_3, and A_4) with respect to EC_1 are (0.0970, 0.8739, 0.0291), (0.1684, 0.7995, 0.0321), (0.0276, 0.9590, 0.0134), and (0.0410, 0.9435, 0.0154), respectively. According to Eq.16, it could be obtained that

$$t = \arg\min_{i=1,2,3,4}(0.0970,0.1684,0.0276,0.0410) = 3 \quad (43)$$

Then, the three elements in the negative-ideal solution with respect to EC_1 can be determined:

$$\mu_j = \mu_{3j} = 0.0276 \tag{44}$$

$$\upsilon_j = \upsilon_{3j} = 0.9590 \tag{45}$$

$$\pi_j = 1 - \mu_{3j} - \upsilon_{3j} = 1 - 0.0276 - 0.9590 = 0.0134 \tag{46}$$

In a similar way, all the negative-ideal solutions can be determined, and the results were presented in Table 11.

The Euclidean and Hamming distance from each energy storage technology to the negative-ideal solutions can be determined according to Eq.21 and Eq.22, respectively, and the results were presented in Table 12.

The threshold value set τ was set as 0.05, and the relative assessment matrix can be determined according to Eqs.23-24, and the results were presented in Eq.47.

$$R = \begin{array}{ccccc} & A_1 & A_2 & A_3 & A_4 \\ A_1 & 0 & 0.0973 & 0.0514 & 0 \\ A_2 & -0.0973 & 0 & -0.0459 & -0.0841 \\ A_3 & -0.0514 & 0.0459 & 0 & -0.0382 \\ A_4 & 0 & 0.0841 & 0.0382 & 0 \end{array} \tag{47}$$

Then, the final assessment score of each alternative energy storage technology can be determined by Eq.25. For instance, the final assessment score of the four alternative energy storage technologies can be determined by Eqs.48-51respectively.

$$F_1 = 0 + 0.0973 + 0.0514 + 0 = 0.1487 \tag{48}$$

$$F_2 = -0.0973 + 0 + (-0.0459) + (-0.0841) = -0.2272 \tag{49}$$

$$F_3 = -0.0514 + 0.0459 + 0 + (-0.0382) = -0.0437 \tag{50}$$

$$F_4 = 0 + 0.0841 + 0.0382 + 0 = 0.1223 \tag{51}$$

According to the final assessment scores of the four energy storage technologies, pumped hydro (A_1) was recognized as the most sustainable one, followed by flywheel (A_4), lithium-ion (A_3), and compressed air (A_2) from the most sustainable to the least. The result of recognizing pumped hydro as the most sustainable was reasonable, because this technology has the longest life, lowest CO_2 emission, relatively lower capital cost and higher technology maturity. However, it is worth pointing out that the sustainability order of the four energy storage technologies may change when the weights of the metrics change.

4. Discussions

The single-criterion analysis method was also employed to rank these four alternative energy storage technologies according to the relative performances on each of the nine metrics. The single-criterion analysis method was specified as follows:

Suppose $\gamma = \left(\mu_\gamma, \upsilon_\gamma, \pi_\gamma\right)$ and $\beta = \left(\mu_\beta, \upsilon_\beta, \pi_\beta\right)$ are two intuitionistic fuzzy numbers to describe the relative performances of two alternative energy storage technologies A and B on an evaluation criterion, respectively. The more superior energy storage technology between these two alternatives can be determined according to the following rules (Xu, 2007):

(1) If $S_\gamma = \mu_\gamma - \upsilon_\gamma < S_\beta = \mu_\beta - \upsilon_\beta$, then, $\gamma = \left(\mu_\gamma, \upsilon_\gamma, \pi_\gamma\right)$ is smaller than $\beta = \left(\mu_\beta, \upsilon_\beta, \pi_\beta\right)$, and A is inferior to B;

(2) If $S_\gamma = \mu_\gamma - \upsilon_\gamma < S_\beta = \mu_\beta - \upsilon_\beta$, then:

I. $H_\gamma = \mu_\gamma + \upsilon_\gamma = H_\beta = \mu_\beta + \upsilon_\beta$, then, $\gamma = \left(\mu_\gamma, \upsilon_\gamma, \pi_\gamma\right)$ is equal to $\beta = \left(\mu_\beta, \upsilon_\beta, \pi_\beta\right)$, and A is indifferent to B;

II. $H_\gamma = \mu_\gamma + \upsilon_\gamma < H_\beta = \mu_\beta + \upsilon_\beta$, then, $\gamma = \left(\mu_\gamma, \upsilon_\gamma, \pi_\gamma\right)$ is smaller than $\beta = \left(\mu_\beta, \upsilon_\beta, \pi_\beta\right)$, and A is inferior to B;

III. $H_\gamma = \mu_\gamma + \upsilon_\gamma > H_\beta = \mu_\beta + \upsilon_\beta$, then, $\gamma = \left(\mu_\gamma, \upsilon_\gamma, \pi_\gamma\right)$ is bigger than $\beta = \left(\mu_\beta, \upsilon_\beta, \pi_\beta\right)$, and A is superior to B;

where S_γ and S_β represent the scores of the intuitionistic fuzzy sets $\gamma = \left(\mu_\gamma, \upsilon_\gamma, \pi_\gamma\right)$ and $\beta = \left(\mu_\beta, \upsilon_\beta, \pi_\beta\right)$, respectively. H_γ and H_β are the accuracy degrees of the intuitionistic fuzzy sets $\gamma = \left(\mu_\gamma, \upsilon_\gamma, \pi_\gamma\right)$ and $\beta = \left(\mu_\beta, \upsilon_\beta, \pi_\beta\right)$, respectively.

The results of using the single-criterion analysis method to rank these four alternative energy storage technologies were presented in Table 13. It is apparent that the rankings of these four alternative energy storage technologies based on different criteria are different. Thus, the decision-makers/stakeholders need a unique sustainability order of these four alternative energy storage technologies by aggregating the performances of each alternative on the nine evaluation criteria into a generic index. The developed intuitionistic fuzzy multi-criteria decision making model facilitate the decision-makers/stakeholders to achieve this objective.

In order to analyze the influences of the threshold value τ on the final ranking, the value of τ has been altered to investigate the change of the sustainability ranking of the four alternative energy storage technologies, and the results were presented in Table 14.

The results reveal the results were robust to the threshold value in this case, but it is worth pointing out that the threshold value may have significant effects on the final priority ranking of the alternatives in some other cases.

In order to investigate the weights of the nine metrics for sustainability assessment of energy storage technologies (set $\tau = 0.05$), the following cases have been studied:

Case 0: the weights determined by the IAHP method;

Case 1: equal weights-all the nine metrics was assigned to be equal $\omega_{EC_1} = \omega_{EC_2} = \cdots = \omega_{S_1} = \frac{1}{9}$;

Case 2-10: a dominant weight 0.36 was assigned to each of the nine metrics (capital cost (EC_1), life (EC_2), and operating cost (EC_3), CO_2 density (EN_1) and integrated environmental impact (EN_2), energy efficiency (T_1), energy density (T_2), and technology maturity (T_3), and social acceptability (S_1) in social aspect (S)) one by one, and the other metrics were assigned an equal weight 0.08. For instance, 0.36 was assigned to capital cost (EC_1), and 0.08 was assigned to the other eight metrics.

The rankings of the four alternative energy storage technologies when changing the weights of the evaluation criteria were presented in Figure 2. It is apparent that the final assessment scores of the four energy storage technologies which represent their relative priorities vary with the change of the weights of the metrics for sustainability assessment. The energy storage technology-flywheel (A_4) was ranked as the most sustainable energy storage technology in most of the cases， pumped hydro (A_1) and lithium-ion (A_3) located in the middle, and compressed air (A_2) was recognized as the worst according to its sustainability. The results of sensitivity analysis reveal that the sustainability ranking is highly sensitive to the weights of the metrics for sustainability assessment of energy storage technologies. Therefore, the accurate determination of the weights of the metrics for sustainability assessment of energy storage technologies is critical for determining the sustainability order.

Moreover, it is worth pointing out that the final sustainability rankings of these four alternative energy storage technologies may change with the progress in technological aspects, because the factors in technological aspects usually have significant effects on the criteria in economic, environmental and social aspects (Ren *et al*., 2016a).

5. Conclusion

This objective of this study is to develop an intuitionistic fuzzy multi-criteria decision making model for sustainability assessment of energy storage technologies, an intuitionistic fuzzy multi-criteria decision making model was developed by combing the interval analytic hierarchy process method and the intuitionistic fuzzy combinative distance-based assessment method. The interval analytic hierarchy process which allows the decision-makers/stakeholders to use interval numbers which can address the vagueness and ambiguity in human judgments to establish the pair-wise comparison matrices for determining the weights of the metrics. The intuitionistic fuzzy combinative distance-based assessment method which allows the decision-makers/stakeholders to use the intuitionistic fuzzy numbers to rate the alternative energy storage technologies with respect to each metric for sustainability assessment was developed to determine the sustainability order of the alternative energy storage technologies. Four alternative energy storage technologies including pumped hydro, compressed air, lithium-ion, and flywheel were studied by the proposed method, the sustainability order of the four technologies from the most sustainable to the least is pumped hydro, flywheel, lithium-ion, and compressed air according to the weights determined by the decision-makers; however, the weights of the metrics have significant impacts on the final sustainability ranking of the alternative energy storage technologies according to the results of sensitivity analysis. All in all, the developed intuitionistic fuzzy multi-criteria decision making model for sustainability assessment of energy storage technologies has the following advantages:

(1) Interval numbers which are more suitable for the decision-makers/stakeholders to express the opinions on the relative importance of one metric over another were adopted to establish the pair-wise comparison matrices for determining the weights of the metrics;

(2) Linguistic terms corresponding to intuitionistic fuzzy numbers were used to rate the energy storage technologies, and the decision-makers/stakeholders do not need to know the exact data of the alternative energy storage technologies when selecting the most sustainable energy storage technology among multiple alternatives.

The developed intuitionistic fuzzy multi-criteria decision making method can not only be used for selecting the most sustainable energy storage technology, but also for determining the best or the most sustainable energy scenario among multiple alternatives in some other cases. In other words, the developed intuitionistic fuzzy multi-criteria decision making method can be popularized to some other cases in energy sector.

Besides the advantages of the proposed intuitionistic fuzzy multi-criteria decision making method, there is also a severe weak point-it cannot effectively use the known data even the data of some alternatives with respect to some evaluation criteria can be described with units quantitatively., and the performances of all the alternatives were described subjectively by using the intuitionistic fuzzy numbers in the proposed method. The future work of the authors is to develop a multi-criteria decision making method which can handle the decision-making matrix composed by the hybrid numbers (i.e. the mixture of intuitionistic fuzzy numbers, crisp numbers and interval numbers) to help the decision-makers/stakeholders to select the most sustainable energy storage technology.

References

Atanassov, K. T., 1986. IFSs. Fuzzy Sets and Systems 20(1),87-96.

Barin, A., Canha, L. N., da Rosa Abaide, A., Magnago, K. F. (2009, November). Selection of storage energy technologies in a power quality scenario—the AHP and the fuzzy logic. In Industrial Electronics, 2009. IECON'09. 35th Annual Conference of IEEE (pp. 3615-3620). IEEE.

Díaz-González, F., Sumper, A., Gomis-Bellmunt, O., Villafáfila-Robles, R. (2012). A review of energy storage technologies for wind power applications.Renewable and sustainable energy reviews, 16(4), 2154-2171.

Divya, K. C., Østergaard, J. (2009). Battery energy storage technology for power systems—An overview. Electric Power Systems Research, 79(4), 511-520.

Hall, P. J., Bain, E. J. (2008). Energy-storage technologies and electricity generation. Energy policy, 36(12), 4352-4355.

Hadjipaschalis, I., Poullikkas, A., Efthimiou, V. (2009). Overview of current and future energy storage technologies for electric power applications.Renewable and sustainable energy reviews, 13(6), 1513-1522.

Hong, D. H., Choi, C. H., 2000. Multicriteria fuzzy decision-making problems based on vague set theory. Fuzzy sets and systems 114(1), 103-113.

Keshavarz Ghorabaee, M., Zavadskas, E. K., Turskis, Z., Antucheviciene, J., 2016. A NEW COMBINATIVE DISTANCE-BASED ASSESSMENT (CODAS) METHOD FOR MULTI-CRITERIA DECISION-MAKING. Economic Computation & Economic Cybernetics Studies & Research, 50(3).

Koohi-Kamali, S., Tyagi, V. V., Rahim, N. A., Panwar, N. L., Mokhlis, H. (2013). Emergence of energy storage technologies as the solution for reliable operation of smart power systems: A review. Renewable and Sustainable Energy Reviews, 25, 135-165.

Kuravi, S., Trahan, J., Goswami, D. Y., Rahman, M. M., Stefanakos, E. K. (2013). Thermal energy storage technologies and systems for concentrating solar power plants. Progress in Energy and Combustion Science, 39(4), 285-319.

Lee, D., Ho, J. C. (2016, September). Evaluation of electricity storage technologies for renewable energy production: A proposed model. InManagement of Engineering and Technology (PICMET), 2016 Portland International Conference on (pp. 2837-2845). IEEE.

Luo, X., Wang, J., Dooner, M., Clarke, J. (2015). Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy, 137, 511-536.

Pramanik, S., Mukhopadhyaya, D., 2011. Grey relational analysis based intuitionistic fuzzy multi-criteria group decision-making approach for teacher selection in higher education. International Journal of Computer Applications,34(10), 21-29.

Ren, J., Sovacool, B. K. (2015). Prioritizing low-carbon energy sources to enhance China's energy security. Energy Conversion and Management, 92, 129-136.

Ren, J., Xu, D., Cao, H., Wei, S. A., Dong, L., Goodsite, M. E. (2016a). Sustainability decision support framework for industrial system prioritization. AIChE Journal, 62(1), 108-130.

Ren, J., Ren, X., Liang, H., Dong, L., Zhang, L., Luo, X., Yang, Y., Gao, Z. (2017). Multi-actor multi-criteria sustainability assessment framework for energy and industrial systems in life cycle perspective under uncertainties. Part 2: improved extension theory. The International Journal of Life Cycle Assessment, 22 (9), 1406-1417.

Ren, J., Ren, X. (2017). Sustainability Ranking of Energy Storage Technologies under Uncertainties. Journal of Cleaner Production. (in press).

Saaty, T. L. (2008). Decision making with the analytic hierarchy process.International journal of services sciences, 1(1), 83-98.

Satkin, M., Noorollahi, Y., Abbaspour, M., Yousefi, H. (2014). Multi criteria site selection model for wind-compressed air energy storage power plants in Iran. Renewable and Sustainable Energy Reviews, 32, 579-590.

Szmidt, E., Kacprzyk, J., 2000. Distance between intuitionistic fuzzy sets. Fuzzy Sets and Systems 114, 505-518.

Vo, T. T., Xia, A., Rogan, F., Wall, D. M., Murphy, J. D., 2017. Sustainability assessment of large-scale storage technologies for surplus electricity using group multi-criteria decision analysis. Clean Technologies and Environmental Policy, 19(3), 689-703.

Wakihara, M., 2001. Recent developments in lithium ion batteries. Materials Science and Engineering: R: Reports, 33(4), 109-134.

Xu, Z., 2007. Intuitionistic fuzzy aggregation operators. IEEE Transactions on fuzzy systems, 15(6), 1179-1187.

Xu, Z.S., Yager, R.R., 2006. Some geometric aggregation operators based on intuitionistic fuzzy sets. International Journal of General Systems 35, 417-433.

Xu, Z., Da, Q., 2003. A possibility-based method for priorities of interval judgment matrices. Chinese Journal of Management Science 11(1), 63-65. (in Chinese).

Zadeh , L. A., 1965. Fuzzy sets. Inf Control 8, 338-53.

Figure captions

Figure 1: The framework of the MCDM method based on the interval analytic hierarchy process and the CODAS method

Figure 2: The results of sensitivity analysis

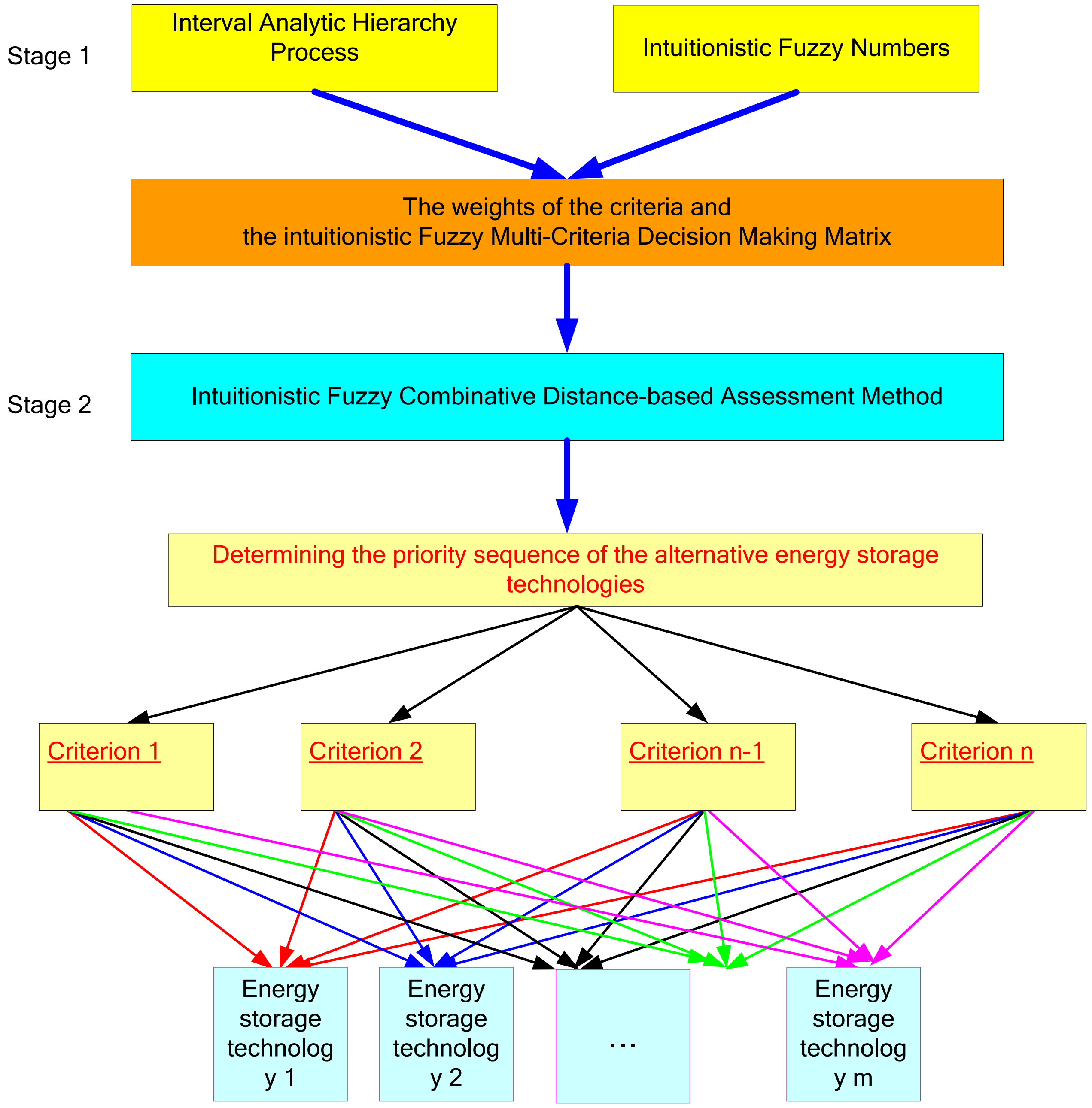

Figure 1: The framework of the MCDM method based on the interval analytic hierarchy process and the CODAS method

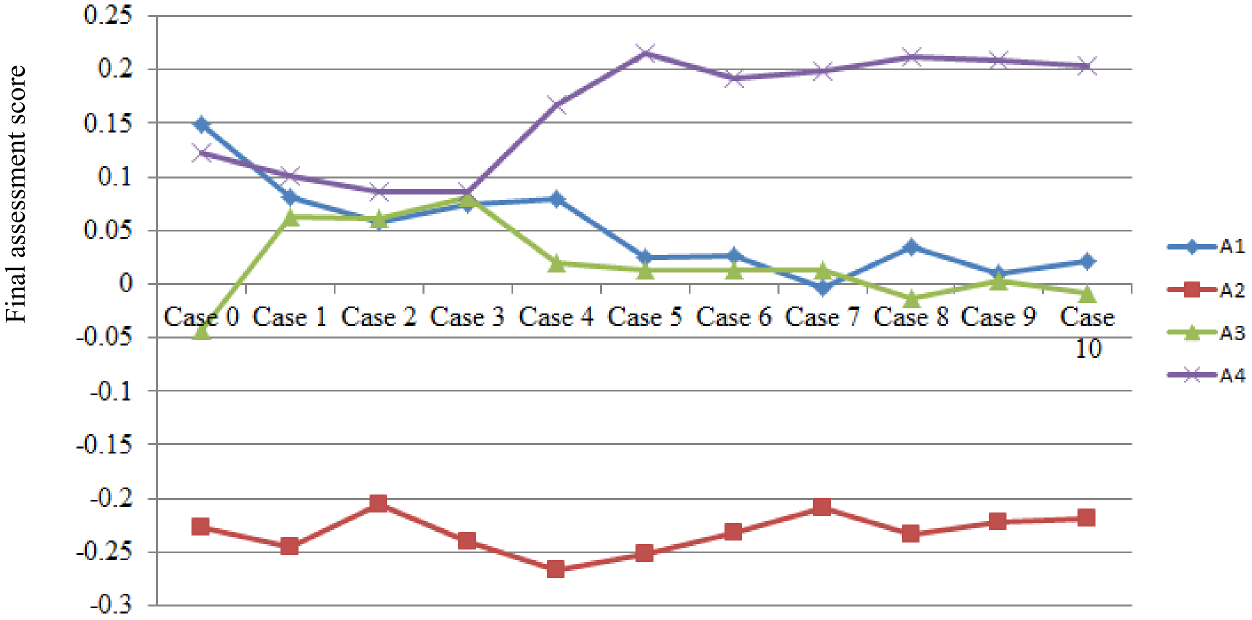

Figure 2: The rankings of the four alternative energy storage technologies when changing the weights of the evaluation criteria

Tables

Table 1: Saaty scales for establishing the pair-wise comparison matrix

Scales	Definition	Explanation
1	Equal importance	Two elements perform equally
3	Moderate importance	Experience and judgement slightly favour one element over another
5	Essential importance	Experience and judgement strongly favour one element over another
7	Very Strong importance	An element is favoured very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one element over another is of the highest possible order of affirmation
2,4,6,8	Intermediate value	Intermediate value

Reference: Saaty (2008)

Table 2: Linguistic variables and their corresponding intuitionistic fuzzy numbers

Linguistic variables	Abbreviation	Intuitionistic fuzzy numbers
Extreme good	EG	(0.95, 0.05, 0)
Very good	VG	(0.85, 0.10, 0.05)
Good	G	(0.75, 0.15, 0.10)
Medium good	MG	(0.65, 0.25, 0.10)
Fair	F	(0.50, 0.40, 0.10)
Medium poor	MP	(0.35, 0.55, 0.10)
Poor	P	(0.25, 0.65, 0.10)
Very Poor	VP	(0.15, 0.80, 0.05)
Extreme poor	EP	(0.05, 0.95, 0)

Reference: Pramanik and Mukhopadhyaya, 2011

Table 3: The interval pair-wise comparison matrix for determining the weights of the four categories

	Economic	Environmental	Technological	Social
Economic (EC)	1	[1 2]	[1/3 1]	[5 7]
Environmental (EN)	[1/2 1]	1	[1/5 1/3]	[3 5]
Technological (T)	[1 3]	[3 5]	1	[7 9]
Social (S)	[1/7 1/5]	[1/5 1/3]	[1/9 1/7]	1

Table 4: The interval pair-wise comparison matrix for determining the weights of the three criteria in economic category

	Capital cost (EC_1)	Life (EC_2)	Operating cost (EC_3)
Capital cost (EC_1)	1	[1 3]	[1/2 1]
Life (EC_2)	[1/3 1]	1	[1/4 1/2]
Operating cost (EC_3)	[1 2]	[2 4]	1
Weights	0.3333	0.1667	0.5000

Table 5: The interval pair-wise comparison matrix for determining the weights of the three criteria in environmental category

	CO_2 density (EN_1)	Integrated environmental impact (EN_2)
CO_2 density (EN_1)	1	[1/4 1/2]
Integrated environmental impact (EN_2)	[2 4]	1
Weights	0.2500	0.7500

Table 6: The interval pair-wise comparison matrix for determining the weights of the three criteria in technological category

	Energy efficiency (T_1)	Energy density (T_2)	Technology maturity(T_3)
Energy efficiency (T_1)	1	[1/3 1]	[1/4 1/2]
Energy density (T_2)	[1 3]	1	[1/4 1]
Technology maturity (T_3)	[2 4]	[1 4]	1
Weights	0.1667	0.3333	0.5000

Table 7: The global weights of the nine metrics

Metrics	EC_1	EC_2	EC_3	EN_1	EN_2	T_1	T_2	T_3	S_1
Weights	0.0972	0.0486	0.1459	0.0521	0.1562	0.0625	0.1250	0.1875	0.1250

Table 8: The performances of the four energy storage technologies using linguistic variables

	A_1	A_2	A_3	A_4
EC_1	MG	VG	P	MP
EC_2	VG	G	VP	F
EC_3	P	F	MG	VP
EN_1	G	EG	F	EP
EN_2	VP	MP	F	G
T_1	MG	MP	G	VG
T_2	VP	F	VG	MP
T_3	MG	G	P	F
S_1	MP	G	VG	MG

Table 9: The performances of the four energy storage technologies using intuitionistic fuzzy numbers

	A_1	A_2	A_3	A_4
EC_1	(0.65, 0.25, 0.10)	(0.85, 0.10, 0.05)	(0.25, 0.65, 0.10)	(0.35, 0.55, 0.10)
EC_2	(0.85, 0.10, 0.05)	(0.75, 0.15, 0.10)	(0.15, 0.80, 0.05)	(0.50, 0.40, 0.10)
EC_3	(0.25, 0.65, 0.10)	(0.50, 0.40, 0.10)	(0.65, 0.25, 0.10)	(0.15, 0.80, 0.05)
EN_1	(0.75, 0.15, 0.10)	(0.95, 0.05, 0)	(0.50, 0.40, 0.10)	(0.05, 0.95, 0)
EN_2	(0.15, 0.80, 0.05)	(0.35, 0.55, 0.10)	(0.50, 0.40, 0.10)	(0.75, 0.15, 0.10)
T_1	(0.65, 0.25, 0.10)	(0.35, 0.55, 0.10)	(0.75, 0.15, 0.10)	(0.85, 0.10, 0.05)
T_2	(0.15, 0.80, 0.05)	(0.50, 0.40, 0.10)	(0.85, 0.10, 0.05)	(0.35, 0.55, 0.10)
T_3	(0.65, 0.25, 0.10)	(0.75, 0.15, 0.10)	(0.25, 0.65, 0.10)	(0.50, 0.40, 0.10)
S_1	(0.35, 0.55, 0.10)	(0.75, 0.15, 0.10)	(0.85, 0.10, 0.05)	(0.65, 0.25, 0.10)

Table 10: The weighted intuitionistic fuzzy decision-making matrix

	A_1	A_2	A_3	A_4
EC_1	(0.0970, 0.8739, 0.0291)	(0.1684, 0.7995, 0.0321)	(0.0276, 0.9590, 0.0134)	(0.0410, 0.9435, 0.0154)
EC_2	(0.0881, 0.8941, 0.0178)	(0.0652, 0.9119, 0.0229)	(0.0079, 0.9892, 0.0029)	(0.0331, 0.9564, 0.0104)
EC_3	(0.0411, 0.9391, 0.0198)	(0.0962, 0.8749, 0.0290)	(0.1420, 0.8169, 0.0411)	(0.0234, 0.9680, 0.0086)
EN_1	(0.0697, 0.9059, 0.0244)	(0.1445, 0.8555, 0)	(0.0355, 0.9534, 0.0111)	(0.0027, 0.9973, 0)
EN_2	(0.0251, 0.9657, 0.0092)	(0.0651, 0.9108, 0.0241)	(0.1026, 0.8666, 0.0307)	(0.1947, 0.7435, 0.0618)
T_1	(0.0635, 0.9170, 0.0195)	(0.0266, 0.9633, 0.0101)	(0.0830, 0.8882, 0.0288)	(0.1118, 0.8660, 0.0222)
T_2	(0.0201, 0.9725, 0.0074)	(0.0830, 0.8918, 0.0252)	(0.2111, 0.7499, 0.0390)	(0.0524, 0.9280, 0.0196)
T_3	(0.1787, 0.7711, 0.0502)	(0.2289, 0.7007, 0.0704)	(0.0525, 0.9224, 0.0251)	(0.1219, 0.8421, 0.0360)
S_1	(0.0524, 0.9280, 0.0196)	(0.1591, 0.7889, 0.0520)	(0.2111, 0.7499, 0.0390)	(0.1230, 0.8409, 0.0361)

Table 11: The negative-ideal solutions

Metrics	NIS
EC_1	(0.0276, 0.9590, 0.0134)
EC_2	(0.0079, 0.9892, 0.0029)
EC_3	(0.0234, 0.9680, 0.0086)
EN_1	(0.0027, 0.9973, 0)
EN_2	(0.0251, 0.9657, 0.0092)
T_1	(0.0266, 0.9633, 0.0101)
T_2	(0.0201, 0.9725, 0.0074)
T_3	(0.0525, 0.9224, 0.0251)
S_1	(0.0524, 0.9280, 0.0196)

Table 12: The Euclidean and Hamming distance from each energy storage technology to the negative-ideal solutions

	A_1	A_2	A_3	A_4
Euclidean distance	1.8787	1.7814	1.8273	1.8655
Hamming distance	4.2170	4.1632	4.2026	4.2099

Table 13: The ranking of the four energy storage technologies using the single-criterion analysis method

	A_1	A_2	A_3	A_4
EC_1	2	1	4	3
EC_2	1	2	4	3
EC_3	3	2	1	4
EN_1	2	1	3	4
EN_2	4	3	2	1
T_1	3	4	2	1
T_2	4	2	1	3
T_3	2	1	4	3
S_1	4	2	1	3

Table 14: The results of the analysis of the threshold value on the sustainability ranking of the four energy storage technologies

	A_1	A_2	A_3	A_4
Final assessment score ($\tau = 0.01, 0.02, 0.03, 0.04$)	0.1618	-0.2272	-0.0437	0.1091
Ranking	1	4	3	2