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Multi-Criteria Decision Making for the Prioritization of Energy Systems under Uncertainties after Life Cycle Sustainability Assessment

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Abstract: This study aims at developing a life cycle sustainability prioritization framework for ranking the energy systems under uncertainties. The fuzzy two-stage logarithmic goal programming method was firstly employed to determine the weights of the criteria for sustainability assessment, and the interval grey relational analysis method was subsequently used to determine the sustainability order of the alternative energy systems. Then, an illustrative case including four alternatives for electricity generation in UK, namely, coal-pulverised, combined cycle gas turbines, nuclear-pressurised water reactor, and offshore wind powder based electricity, was investigated, and pressurised water reactor was recognized as the most sustainable, followed by combined cycle gas turbines, offshore wind powder, and coal-pulverised in the descending order. Finally, the results were validated by the interval TOPSIS, and sensitivity analysis was also carried used to investigate the effects of the weights of the criteria for sustainability assessment on the final sustainability order of the alternative energy systems.

Keywords: sustainability assessment; energy system; life cycle sustainability assessment; multi-criteria decision making; uncertainties

1. Introduction

Energy as the food of industry plays a significant important role for promoting the development of the economy of the world (Ren and Sovacool, 2015). The consumptions of energy sources (i.e. coal, petroleum, and natural gas) for power, heat or cooling has leaded to various environmental and social problems (Bose, 2010). The development of renewable energy has high potential for emissions reduction and energy security improvement. However, the use of renewable energy sources (i.e. wind, solar, biomass, geothermal, and hydropower, etc.) also requires various kinds of inputs. For instance, the production of biofuel from biomass requires various inputs, i.e. chemicals, steam, coal and electrifies, etc. (Ren *et al.*, 2014a). There are also various emissions during the whole life cycle of biofuel. Accordingly, it is usually difficult for the decision-makers to know whether or not the energy systems including both non-renewable energy and renewable energy based scenarios are sustainable.

Singh *et al.* (2009) pointed out that the concept of sustainability or sustainable development attracted more and more attentions of the policy makers in the industry. Accordingly, sustainability assessment of energy systems for helping the decision-makers to select the most sustainable scenario is of vital importance (Ren *et al.*, 2016). As for the evaluation of energy systems, There are usually various ways for the evaluation of energy systems, i.e. thermodynamic method, energy cost evaluation and life cycle method (Afgan and Carvalho, 2004). All these method aimed at using a single index to measure the performances of different energy systems. However, sustainability assessment of energy systems is complex due to the involvement of a number of economic, environmental, social and technological parameters (Begić and Afgan, 2007). Therefore, sustainability assessment of energy systems is a multi-criteria decision analysis problem. There are various studies about using the multi-criteria decision analysis for sustainability assessment of energy systems. For instance, Afgan and Carvalho (2002) employed energy resources, environment capacity, economic indicators, and social indicators to have a multi-criteria assessment of power plants. Maxim (2014) employed the weighted sum multi-attribute utility approach and ten indicators to assess the sustainability of electricity generation technologies. Škobalj (2017) the Analysis and Synthesis of Parameters under Information Deficiency (ASPID) method was used to assess the sustainability of the options for electricity generation with the considerations of the indicators in economic, environmental, social and technological aspects. All the above mentioned studies can help the decision-makers to select the most sustainable energy system, but they only considered the hard criteria for sustainability, while the soft criteria for sustainability assessment are usually neglected. There are also some other studies which incorporate the soft criteria for sustainability assessment by quantifying the energy systems with respect to the soft criteria. For instance, Evans *et al*. (2009) used multiple sustainability indicators to assess the comprehensive performances of four renewable energy technologies including photovoltaics, wind, hydro, and geothermal. Ren and Liang (2017a) developed an intuitionistic fuzzy set theory based group multi-attribute decision analysis for ranking the wastewater treatment technologies. Ren and Liang (2017b) combined the fuzzy logarithmic least squares method and the fuzzy TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) to prioritize the marine fuels according to their sustainability performances. Ren and Lützen (2017) combined the Dempster-Shafer theory and the trapezoidal fuzzy AHP (analytic hierarchy process) to rank the alternative energy source under incomplete information condition. However, all these methods reply on using the judgments of the decision-makers to rate the alternative energy systems, and the performances of the energy systems with respect to the criteria for sustainability assessment were determined based on the subjective judgments of the decision-makers. Meanwhile, the data of the energy systems with respect to the criteria for sustainability assessment determined by life cycle sustainability assessment cannot be fully used. Life cycle sustainability assessment can help the decision-makers to collect the data of the energy systems with respect to economic, environmental and social dimensions; this has been illustrated in many studies (Atilgan and Azapagic, 2016). Accordingly, life cycle sustainability assessment has been combined with multi-criteria decision making methods for sustainability ranking of energy systems in more and more studies recently. For instance, Santoyo-Castelazo and Azapagic (2014) combined life cycle tools (life cycle assessment and life cycle costing), social sustainability assessment, and multi-criteria decision analysis for sustainability assessment of energy systems, and the alternative power plant technologies were studied. Ren *et al*. (2015) employed life cycle sustainability assessment and multi-criteria decision making method (VIKOR method) to prioritize the alternative pathways for bioethanol production according to their life cycle sustainability performance. The studies can help the decision-makers to determine the life cycle sustainability order of the energy systems; however, there are usually various uncertainties which cannot be addressed by these methods. Uncertainties refer to the variations of data caused by the influences of external environment, estimations and various assumptions in life cycle sustainability assessment. In addition, the determination of the weights of the criteria sustainability which cannot only reflect the relative importance of the evaluation criteria, but also the preferences of the decision-makers, is of vital importance for determining the sustainability order of energy systems accurately. Most of the studies employed Analytic Hierarchy Process (AHP) and various method derived from AHP to determine the weights of the criteria for sustainability assessment (He et al., 2017). However, all these methods have two weak points: one is the difficulty of addressing the vagueness and ambiguity existing in human's judgments when comparing each pair of factors and another is the difficulty of guarantee the consistency when establishing the comparison matrix. In order to solve these two weak points, various fuzzy AHP methods (Chang, 1996; Zhu *et al*., 1999) were developed to capture the vagueness and ambiguity existing in human's judgments in weights determinations; meanwhile, the Best-Worst method developed by Rezaei (2015) which can reduce the times of comparisons and has better consistency performances for weights determination were widely used for its significant advantages. However, the vagueness and ambiguity existing in human's judgments cannot be addressed. Based on the above-mentioned literature reviews, a method which can simultaneously capture the following issues is prerequisite for sustainability prioritization of energy systems:

(1) The collection of the data with respect to the criteria for sustainability assessment in life cycle perspective instead of only the production stage, the economic, environmental, and social performances should be accounted in a "cradle to grave" approach;
(2) The vagueness and ambiguity existing in human's judgments should be addressed in the determination of the weights of the criteria for sustainability assessment; and
(3) The data uncertainties in multi-criteria decision making for ranking the alternative energy systems.

In order to capture the above-mentioned three issues in sustainability prioritization of energy systems, this study aims at developing a life cycle sustainability prioritization framework for ranking the alternative energy systems under data uncertainties conditions. The fuzzy two-stage logarithmic goal programming method was employed to determine the weights of the criteria for sustainability assessment, and the interval grey relational analysis method was used to determine the sustainability order of the alternative energy systems.

Besides the introduction, the remainder parts of this study were organized as follows: the methods for life cycle sustainability prioritization of energy systems were presented in section 2; an illustrative case has been studied by the proposed method in section 3; the results were discussed in section 4; and finally, this study has been concluded in section 5.

2. Methods

In order to get the data of different alternative energy systems with respect to the criteria in the three categories (environmental impacts, economic performances and social influences) of sustainability in "cradle to grave" thinking, the data with respect to the environmental-economic-social criteria for sustainability assessment of energy systems should be collected in life cycle perspective (Ren *et al.*, 2018). Therefore, life cycle sustainability assessment was employed to determine the data in the decision-making matrix with respect to the criteria in the three pillars of sustainability. The uncertainties of data were incorporated in the life cycle data collection process, and interval numbers were used to replace the crisp numbers to represent the variations of the data.

In order to overcome the vagueness, ambiguity and hesitations existing in human's judgments, the weights of the criteria for life cycle sustainability assessment were determined by the fuzzy two-stage logarithmic goal programming method after determining the decision-making matrix, and the decision-makers can use fuzzy numbers rather than the crisp numbers to address the vagueness, ambiguity and hesitations existing in human's judgments (Wang *et al.*, 2017). The weights of the criteria determined by this method were also interval numbers.

After determining the weights of the criteria, interval grey relational analysis which can address interval numbers in the decision-making matrix was employed to rank the alternative energy systems according to their integrated life cycle sustainability performances by aggregating the criteria in economic, environmental and social pillars into a sustainability index.

The framework of life cycle sustainability prioritization method developed in this study was illustrated in Figure 1, and it can be divided into three stages: (1) stage 1: data collection for multi-criteria sustainability ranking based on life cycle sustainability assessment; (2) stage 2: determining the weights of the criteria for sustainability assessment based on the fuzzy two-stage logarithmic goal programming method; and (3) stage 3: ranking the alternative energy systems based on the data collection in stage 1 and the weights of the criteria in stage 2.

Stage 1: life cycle sustainability assessment (LCSA) which consists of life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (SLCA) was employed to determine the data of the energy systems with respect to economic, environmental, and social criteria. Note that the decision-makers should select the most relevant criteria for measuring each of the three pillars of sustainability according to the concerns and the preferences of the stakeholders. For instance, there are three typical life cycle impact assessment methods including ReCiPe 2008, CML 2001, and Eco-indicator 99 (Ren, 2018). The criteria used for measuring the environmental impacts in midpoint level or endpoint level in these methods are different, and the decision-makers can choose the most suitable criteria according to their concerns. As for the criteria for measuring economic pillar determined by LCC, life cycle production cost, net present value and internal return ratio are the three most commonly used criteria for measuring life cycle economic sustainability of processes or products (Ren, 2018; Ren *et al*., 2018). As for the criteria for measuring the social sustainability, social life cycle assessment focusing on investigating the social influences and contributions of processes or products in life cycle perspective is not mature and still in the developing stage. There are several reasons, and one of the most important reasons is that the social influences and contributions usually involves different stakeholders, it is difficult or even impossible to develop an unique criteria system for social sustainability assessment. For instance, salary, human toxicity potential, safety, and total health impacts from radiation, etc., in social aspect, are the most important criteria for employees; however, employment (created jobs), social contributions to the local community and impact on the local culture, etc., are the most important criteria in the opinions of the governmental agency. Therefore, selecting the most important criteria for measuring the concerns of the critical stakeholders is the most important for measuring the social sustainability.

The interval decision-making matrix can be determined in this stage. It is worth pointing out that the uncertainties were incorporated in LCSA by using the interval numbers;

Stage 2: fuzzy two-stage logarithmic goal programming method was employed to determine the weights of the criteria for sustainability assessment in this stage. This weighting method consists of two stages: the first stage is to minimize the inconsistency of the fuzzy pair-wise comparison matrix, and the second stage is to determine the weights of the criteria for sustainability assessment of energy systems by keeping the inconsistency to be the minimum.

Stage 3: the interval grey relational analysis which can address the decision-making matrix composed by interval numbers was used to determine the grey relational degrees of the alternative energy systems, and the sustainability order of the alternative energy systems can be determined according to their grey relational degrees.

This section has been organized as follows: the fuzzy set theory and interval numbers were firstly presented in section 2.1; the fuzzy two-stage logarithmic goal programming method for determining the weights of the criteria for sustainability assessment of energy systems was presented in section 2.2; and the interval grey relational analysis was presented in section 2.3.

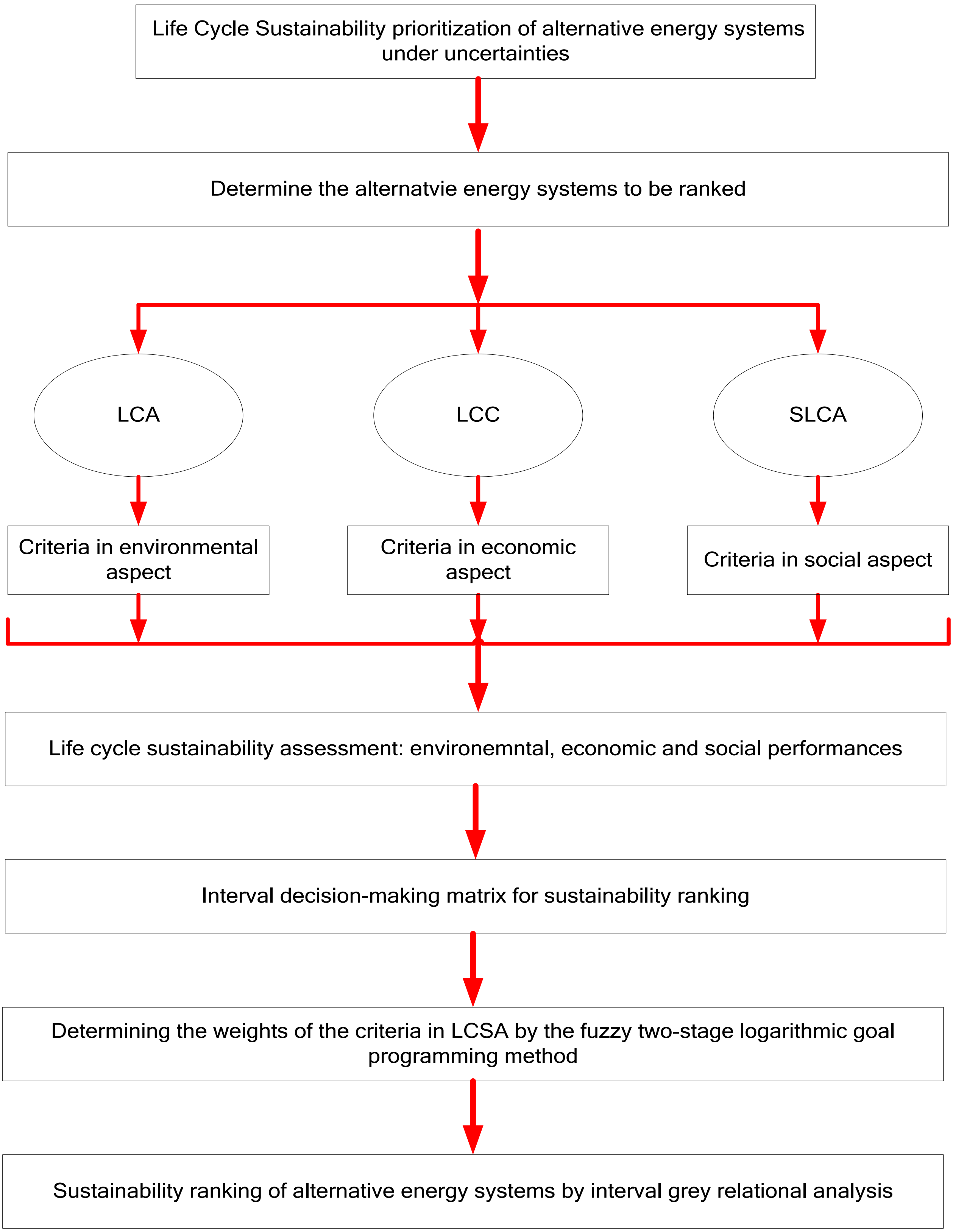

Figure 1: The framework of life cycle sustainability prioritization method (Ren *et al*., 2015)

2.1 Fuzzy set theory and interval numbers

A fuzzy set $\tilde{B}$ in a universe of discourse A is characterized by a membership function $\mu_{\tilde{B}}(a)$ which denotes the level of membership of a in $\tilde{B}$, and the value of the membership is a real number varies within the interval $[0,1]$ (Chen, 2000).

The triangular fuzzy numbers which were defined in the format of triplets were widely used for addressing the problems with uncertainties and incompletion, because the sue of the triangular fuzzy numbers instead of crisp number can effectively address the vagueness and ambiguity existing in human judgment.

The triangular fuzzy number $\tilde{x}$ can be defined as the triplet (x_1, x_2, x_3), and x_1, x_2 and x_3 are the three elements of the fuzzy numbers.

Definition 1 Arithmetic operations of triangular numbers (Krohling and Campanharo, 2011)

Suppose that $\tilde{x} = (x_1, x_2, x_3)$ and $\tilde{y} = (y_1, y_2, y_3)$ are two fuzzy numbers:

$$\tilde{x} + \tilde{y} = (x_1, x_2, x_3) + (y_1, y_2, y_3) = (x_1 + y_1, x_2 + y_2, x_3 + y_3) \quad (1)$$

$$\tilde{x} - \tilde{y} = (x_1, x_2, x_3) - (y_1, y_2, y_3) = (x_1 - y_1, x_2 - y_2, x_3 - y_3) \quad (2)$$

$$\tilde{x}\tilde{y} = (x_1, x_2, x_3) \times (y_1, y_2, y_3) = (x_1 y_1, x_2 y_2, x_3 y_3) \quad (3)$$

$$\tilde{x} / \tilde{y} = (x_1, x_2, x_3) / (y_1, y_2, y_3) = (x_1 / y_3, x_2 / y_2, x_3 / y_1) \quad (4)$$

Definition 2 α -cut (Kaufmann and Gupta, 1988)

As for the triangular fuzzy number $\tilde{x} = (x_1, x_2, x_3)$, its triangular type membership function can be defined in Eq.5.

$$\mu_{\tilde{x}}(a)=\begin{cases}\dfrac{a-x_1}{x_2-x_1} & x_1\le a\le x_2\\ \dfrac{x_3-a}{x_3-x_2} & x_2\le a\le x_3\\ 0 & others\end{cases} \tag{5}$$

If x takes the value within the interval $\left[x_1 \quad x_2\right]$, the function gets the value $\frac{a-x_1}{x_2-x_1}$; if x takes the value within the interval $\left[x_2 \quad x_3\right]$, the function gets the value $\frac{x_3-a}{x_3-x_2}$; while the function gets the value zero if x takes the value which is less than x_1 or greater than x_3 (Ayağ and Özdemir, 2012). Accordingly, the interval of confidence level α can be determined by Eq.6.

$$(\tilde{x})_\alpha=\left[x_1+\alpha\left(x_2-x_1\right) \quad x_3-\alpha\left(x_3-x_2\right)\right] \tag{6}$$

Suppose that $a^{\pm}=\left[a^- \quad a^+\right]=\left\{x \middle| a^-\le x\le a^+, x\in\Re\right\}$, where a^- and a^+ are the left and the right limit of the interval $a^{\pm}$ on the real line $\Re$. If $a^-=a^+$, the interval number $a^{\pm}$ turns into a crisp number (Sengupta *et al*., 2001).

Definition 3 Arithmetic operations of interval numbers (Sengupta *et al*., 2001).

Suppose $a^{\pm}=\left[a^- \quad a^+\right]=\left\{x \middle| a^-\le x\le a^+, x\in\Re\right\}$ and $b^{\pm}=\left[b^- \quad b^+\right]=\left\{x \middle| b^-\le x\le b^+, x\in\Re\right\}$ are two interval numbers:

$$a^{\pm}+b^{\pm}=\left[a^- \quad a^+\right]+\left[b^- \quad b^+\right]=\left[a^-+b^- \quad a^++b^+\right] \tag{7}$$

$$a^{\pm}-b^{\pm}=\left[a^- \quad a^+\right]-\left[b^- \quad b^+\right]=\left[a^--b^+ \quad a^+-b^-\right] \tag{8}$$

Definition 4 The norm of the interval number column (Zhang *et al*., 2005).

Suppose $X = \left(\left[x_1^- \quad x_1^+\right], \left[x_2^- \quad x_2^+\right], \cdots, \left[x_m^- \quad x_m^+\right]\right)$ is an arbitrary interval number column vector, and the norm of X can be determined as (Zhang *et al*., 2005):

$$\|X\| = \max\left\{\max\left(\left|x_1^-\right|, \left|x_1^+\right|\right), \max\left(\left|x_2^-\right|, \left|x_2^+\right|\right), \cdots, \max\left(\left|x_m^-\right|, \left|x_m^+\right|\right)\right\} \tag{9}$$

Definition 5 The distance between two int1aQAerval numbers (Zhang *et al*., 2005)

The distance between two interval numbers $a^{\pm} = \left[a^- \quad a^+\right] = \left\{x \middle| a^- \le x \le a^+, x \in \Re\right\}$ and $b^{\pm} = \left[b^- \quad b^+\right] = \left\{x \middle| b^- \le x \le b^+, x \in \Re\right\}$ can be determined by Eq.10.

$$\left|a^{\pm} - b^{\pm}\right| = \max\left(\left|a^- - b^-\right|, \left|a^+ - a^+\right|\right) \tag{10}$$

2.2 Fuzzy Two-Stage Logarithmic Goal Programming

The fuzzy two-stage logarithmic goal programming method in which the fuzzy numbers were allowed to be used for establis47hing the comparison matrix was presented in this section, and the fuzzy set theory can successfully solve the problems with imprecise and incomplete information as well as the problems of vagueness and ambiguity existing in human's preference and opinions. The fuzzy two-stage logarithmic goal programming consists of five steps based on the work of Wang *et al.* (2005), and they were specified as follows:

Step 1: Constructing the hierarchical structure of the multi-criteria decision making problem. The hierarchical structure of the multi-criteria decision making problem with m alternatives (A_1, A_2,…, A_m) and n criteria (C_1, C_2,…, C_n) was illustrated in Figure 2 (Ren *et al.*, 2014 b). It is worth pointing out that there is usually more than one hierarchy in the criteria level which usually consists of multiple criteria and each criteria also consists of several sub-criteria.

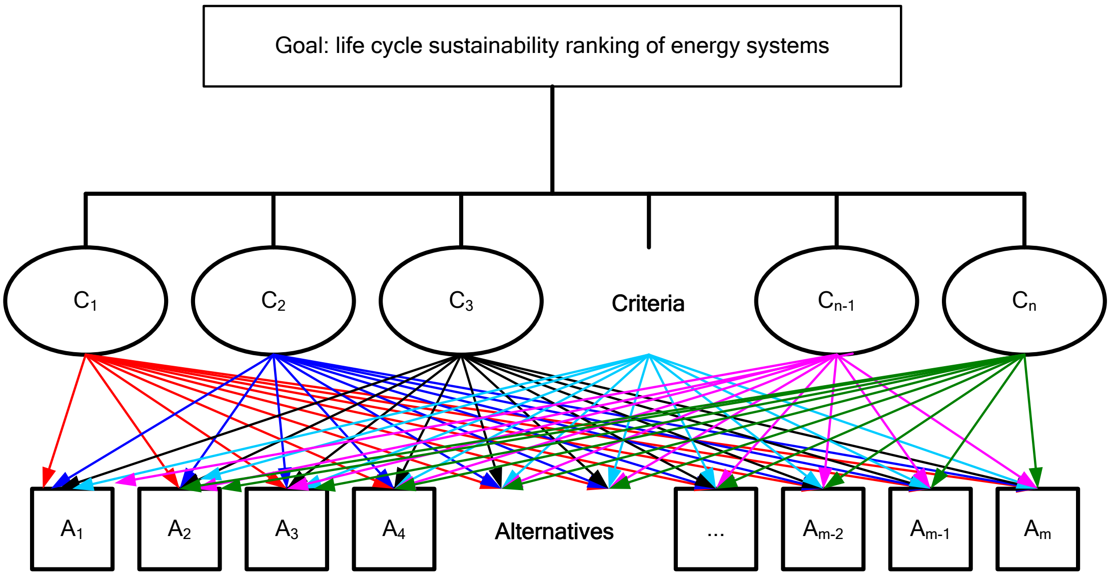

Figure 2: A hierarchical structure of a multi-criteria decision making problem (Ren *et al.*, 2014b)

Step 2: Establishing pairwise comparison matrix by using triangular fuzzy numbers. The decision-makers firstly use the upper triangular pairwise comparison matrix by using linguistic variables presented in Table 1. For instance, the held the view that the relative importance of a criteria over another is "moderately more important", then, the triangular fuzzy number $(3-\delta \quad 3 \quad 3+\delta)$ will be used to describe the relative preference. δ represents the degree of confidence in the judgments of the decision-makers, it can take value among 0.5, 1, and 2, and the smaller the value, the higher the confidence (Bacudio *et al.*, 2016).

After determining the upper triangular pairwise comparison matrix, all the linguistic variables can be transformed into triangular fuzzy numbers. Then, the pairwise comparison matrix comprised by the triangular fuzzy numbers can be determined, as presented in Eq.11.

$$\begin{array}{c|cccc} & C_1 & C_2 & \cdots & C_n \\ C_1 & (1 \quad 1 \quad 1) & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ C_2 & \tilde{a}_{21} & (1 \quad 1 \quad 1) & \vdots & \tilde{a}_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_n & \tilde{a}_{m1} & \tilde{a}_{m2} & \cdots & (1 \quad 1 \quad 1) \end{array} \tag{11}$$

where $\tilde{a}_{ij} = \left(a_{ij}^{L} \quad a_{ij}^{M} \quad a_{ij}^{U} \right)$ is a triangular fuzzy numbers, and the corresponding membership functions can be defined in Eq.12.

$$\mu_{\tilde{a}_{ij}}\left(x\right)\begin{cases} \dfrac{x-a_{ij}^{L}}{a_{ij}^{M}-a_{ij}^{L}} & x\in\left[a_{ij}^{L} \quad a_{ij}^{M}\right] \\ \dfrac{a_{ij}^{U}-x}{a_{ij}^{U}-a_{ij}^{M}} & x\in\left[a_{ij}^{M} \quad a_{ij}^{U}\right] \\ 0 & otherwise \end{cases} \tag{12}$$

All the elements in the fuzzy comparison matrix satisfy (13).

$$\tilde{a}_{ji} = \left(a_{ji}^{L} \quad a_{ji}^{M} \quad a_{ji}^{U} \right) = \frac{1}{a_{ij}} = \left(\frac{1}{a_{ij}^{U}} \quad \frac{1}{a_{ij}^{M}} \quad \frac{1}{a_{ij}^{L}} \right) \tag{13}$$

Table 1: Linguistic variables and corresponding triangular fuzzy numbers for establishing the comparison matrix

Linguistic terms	Abbreviation	Fuzzy scales
Equally important	EI	(1,1,1)
More or less equally important	ML	$\left(\frac{1}{1+\delta} \quad 1 \quad 1+\delta\right)$
Moderately more important	MM	$(3-\delta \quad 3 \quad 3+\delta)$
Strongly more important	SM	$(5-\delta \quad 5 \quad 5+\delta)$
Very strongly more important	VS	$(7-\delta \quad 7 \quad 7+\delta)$
Extremely more important	EM	$(9-\delta \quad 9 \quad 9+\delta)$
Others	The judgment is between each pair of the adjacent terms	$(x-\delta \quad x \quad x+\delta), x = 2,4,6,8$
Reciprocals of the above-mentioned fuzzy numbers		i.e. the reciprocal of $(3-\delta \quad 3 \quad 3+\delta)$ is $\left(\frac{1}{3+\delta} \quad \frac{1}{3} \quad \frac{1}{3-\delta}\right)$

Reference: adapted from Bacudio *et al*. (2016)

Step 3: Transforming the fuzzy comparison matrix into interval comparison through setting α -level sets. All the triangular fuzzy numbers of the upper triangular pairwise comparison matrix presented in Eq.11 can be transformed into inter numbers by setting different confidence levels (α) (Sengupta *et al*., 2001), according to Eqs.14-15.

$$\left(\tilde{a}_{ij}\right)_{\alpha} = \left\{x \middle| \mu_{\tilde{a}_{ij}}(x) \geq \alpha\right\} = \left[a_{ij}^{L} + \left(a_{ij}^{M} - a_{ij}^{L}\right)\alpha \quad a_{ij}^{U} - \left(a_{ij}^{U} - a_{ij}^{M}\right)\alpha\right] = \left[b_{ij}^{L} \quad b_{ij}^{U}\right] \qquad (14)$$

$$
\begin{array}{lllll}
 & C_1 & C_2 & \cdots & C_n \\
C_1 & \left[\begin{pmatrix}1 & 1 & 1\end{pmatrix}\right]_\alpha & \left(\tilde{a}_{12}\right)_\alpha & \cdots & \left(\tilde{a}_{1n}\right)_\alpha \\
C_2 & - & \left[\begin{pmatrix}1 & 1 & 1\end{pmatrix}\right]_\alpha & \vdots & \left(\tilde{a}_{2n}\right)_\alpha \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
C_n & - & - & \cdots & \left[\begin{pmatrix}1 & 1 & 1\end{pmatrix}\right]_\alpha
\end{array} \tag{15}
$$

It is apparent that the triangular fuzzy number $\begin{pmatrix}1 & 1 & 1\end{pmatrix}$ can be transformed into $\begin{bmatrix}1 & 1\end{bmatrix}$ for arbitrary α . Accordingly, the comparison matrix presented in Eq.15 can be simplified into (16).

$$
\begin{array}{lllll}
 & C_1 & C_2 & \cdots & C_n \\
C_1 & \begin{bmatrix}1 & 1\end{bmatrix} & \begin{bmatrix}b_{12}^L & b_{12}^U\end{bmatrix} & \cdots & \begin{bmatrix}b_{1n}^L & b_{1n}^U\end{bmatrix} \\
C_2 & \begin{bmatrix}b_{21}^L & b_{21}^U\end{bmatrix} & \begin{bmatrix}1 & 1\end{bmatrix} & \vdots & \begin{bmatrix}b_{2n}^L & b_{2n}^U\end{bmatrix} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
C_n & \begin{bmatrix}b_{m1}^L & b_{m1}^U\end{bmatrix} & \begin{bmatrix}b_{m2}^L & b_{m2}^U\end{bmatrix} & \cdots & \begin{bmatrix}1 & 1\end{bmatrix}
\end{array} \tag{16}
$$

It is worth pointing out that the elements in the upper triangular pairwise comparison matrix presented in (16) can be determined by Eq.14, and the elements in the lower triangular pairwise comparison matrix can be determined in Eq.17.

$$
\begin{bmatrix}b_{ji}^L & b_{ji}^U\end{bmatrix} = \begin{bmatrix}\dfrac{1}{b_{ij}^U} & \dfrac{1}{b_{ij}^L}\end{bmatrix} \tag{17}
$$

Step 4: Minimizing the inconsistency degree of the judgments. The programming (18) was established to minimize the inconsistency degree of the judgments under the multiplicative constraint, and the objective of this programming is to minimize the total inconsistency (Wang *et al.*, 2005).

$$
\begin{aligned}
&Min\ J = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left(p_{ij} + q_{ij} \right) \\
&s.t. \\
&a_i - b_i - a_j + b_j + p_{ij} \geq \ln b_{ij}^L \qquad i = 1, 2, \cdots, n-1;\ j = i+1, i+2, \cdots, n \\
&a_i - b_i - a_j + b_j - q_{ij} \leq \ln b_{ij}^U \qquad i = 1, 2, \cdots, n-1;\ j = i+1, i+2, \cdots, n \\
&\sum_{i=1}^{n} \left(a_i - b_i \right) = 0 \\
&a_i b_i = 0 \qquad i = 1, 2, \cdots, n \\
&p_{ij} q_{ij} = 0 \qquad i = 1, 2, \cdots, n-1;\ j = i+1, i+2, \cdots, n \\
&a_i, b_i \geq 0 \qquad i = 1, 2, \cdots, n \\
&p_{ij}, q_{ij} \geq 0 \qquad i = 1, 2, \cdots, n-1;\ j = i+1, i+2, \cdots, n
\end{aligned} \tag{18}
$$

where $\omega_i \left(i = 1, 2, \cdots, n \right)$ represents the weight of the *i*-th criterion, $a_i = \dfrac{\ln \omega_i + \left| \ln \omega_i \right|}{2}$, and

$b_i = \dfrac{-\ln \omega_i + \left| \ln \omega_i \right|}{2}$.

Theorem 1. (Wang *et al.*, 2005) The interval comparison matrix is a consistent matrix if and only if $J^* = 0$, where J^* is the minimum value of the objective function after solving programming (18). It is apparent that $p_{ij}, q_{ij} = 0 \quad i = 1, 2, \cdots, n-1;\ j = i+1, i+2, \cdots, n$ when $J^* = 0$.

Step 5: Determining the interval weights of the interval comparison matrix. The programming (19) was proposed to obtain the interval weights of the interval comparison matrix presented in (16) by keeping the total inconsistency the same as the minimum value determined by the programming (18) (Wang *et al.*, 2005).

$$
\begin{aligned}
& Min/Max \quad \ln\omega_i = a_i - b_i \\
& s.t. \\
& a_i - b_i - a_j + b_j + p_{ij} \ge \ln b_{ij}^L \quad i=1,2,\cdots,n-1;\ j=i+1,i+2,\cdots,n \\
& a_i - b_i - a_j + b_j - q_{ij} \le \ln b_{ij}^U \quad i=1,2,\cdots,n-1;\ j=i+1,i+2,\cdots,n \\
& \sum_{i=1}^{n}\left(a_i - b_i\right) = 0 \\
& a_i b_i = 0 \quad i=1,2,\cdots,n \\
& p_{ij} q_{ij} = 0 \quad i=1,2,\cdots,n-1;\ j=i+1,i+2,\cdots,n \\
& a_i, b_i \ge 0 \quad i=1,2,\cdots,n \\
& p_{ij}, q_{ij} \ge 0 \quad i=1,2,\cdots,n-1;\ j=i+1,i+2,\cdots,n \\
& \sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\left(p_{ij} + q_{ij}\right) = J^*
\end{aligned} \tag{19}
$$

If $J^* = 0$, the programming (19) can be simplified into (20).

$$
\begin{aligned}
& Min/Max \quad \ln\omega_i = a_i - b_i \\
& s.t. \\
& a_i - b_i - a_j + b_j \ge \ln b_{ij}^L \quad i=1,2,\cdots,n-1;\ j=i+1,i+2,\cdots,n \\
& a_i - b_i - a_j + b_j \le \ln b_{ij}^U \quad i=1,2,\cdots,n-1;\ j=i+1,i+2,\cdots,n \\
& \sum_{i=1}^{n}\left(a_i - b_i\right) = 0 \\
& a_i b_i = 0 \quad i=1,2,\cdots,n \\
& a_i, b_i \ge 0 \quad i=1,2,\cdots,n
\end{aligned} \tag{20}
$$

After solving the programming (19) or (20), the lower and upper bounds of $\ln\omega_i$ denotes by $\ln\omega_i^L$ and $\ln\omega_i^U$, respectively, can be obtained. Then, the interval weight of the i-th criterion can be determined by Eq.20.

$$
\left[\exp\left(\ln\omega_i^L\right) \quad \exp\left(\ln\omega_i^U\right)\right] = \left[\omega_i^L \quad \omega_i^U\right] \tag{21}
$$

As for the multi-criteria decision making problem with multiple hierarchies, suppose that the weight of the t-th criterion in the L-th hierarchy is $\left[\omega_t^L \quad \omega_t^U\right]$, the t-th criterion consists of K (k=1,2,…,K) sub-criteria in the *(L+1)*-th hierarchy, and the local weight of the *k*-th sub-criterion in the *t*-th criterion $\left[\omega_{ik}^{L} \quad \omega_{ik}^{U}\right]$, then, the global weight of the *k*-th sub-criterion can be determined by Eq.22 according to the meaning of multiplicative constraint.

$$\left[\omega_{k}^{L} \quad \omega_{k}^{U}\right]=\left[\left[\frac{\omega_{t}^{L}\times\left(\omega_{tk}^{L}\right)^{K}}{\prod_{r=1}^{K}\omega_{tr}^{U}}\right]^{1/K} \quad \left[\frac{\omega_{t}^{U}\times\left(\omega_{tk}^{U}\right)^{K}}{\prod_{r=1}^{K}\omega_{tr}^{L}}\right]^{1/K}\right] \tag{22}$$

where $\left[\omega_{k}^{L} \quad \omega_{k}^{U}\right]$ represents the global weight of the *k*-th sub-criterion.

2.3 Interval Grey Relational Analysis

The grey theory from the grey set has been widely used recently, because the grey systems methodology can effectively handle the problems with ambiguities and vagueness generated from imprecise human judgments (Deng, 1982; Rajesh and Ravi, 2015). The Grey Relational Analysis (GRA) based on Deng's grey system theory which is a multi-criteria decision analysis tool for ranking the alternatives by calculating the degree of relationship, based on the geometric distance between the reference and the compared sequences (Yin *et al.*, 2010). The GRA method has been widely used various field, i.e. ranking hydrogen production processes (Manzardo *et al*., 2012), bank operations performance (Ho, 2006), and evaluation of corporate social responsibility of airlines (Wang *et al.*, 2015), etc. However, the traditional GRA method can only address the decision-making matrix with crisp numbers rather than the decision-making matrix composed by interval numbers. The interval GRA method was presented as follows based on the work of Zhang *et al*. (2005):

Step 1: Constructing the decision-making matrix composed by the interval numbers. The decision-making matrix consists of the weights of the decision criteria determined by the fuzzy two-stage logarithmic goal programming method and the values of the alternatives with respect to the criteria.

Assuming that there are a total of m alternatives, namely $A_1, A_2, \cdots, A_m$, to be assessed by n decision attributes $C_1, C_2, \cdots, C_n$, and the interval decision-making matrix can be determined, as presented in Eq.23.

$$\begin{array}{cccccc} & C_1 & C_2 & \cdots & C_n \\ A_1 & \left[x_{11}^- \quad x_{11}^+\right] & \left[x_{12}^- \quad x_{12}^+\right] & \cdots & \left[x_{1n}^- \quad x_{1n}^+\right] \\ A_2 & \left[x_{21}^- \quad x_{21}^+\right] & \left[x_{22}^- \quad x_{22}^+\right] & \cdots & \left[x_{2n}^- \quad x_{2n}^+\right] \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & \left[x_{m1}^- \quad x_{m1}^+\right] & \left[x_{m2}^- \quad x_{m2}^+\right] & \cdots & \left[x_{mn}^- \quad x_{mn}^+\right] \\ W & \omega_1 & \omega_2 & \cdots & \omega_n \end{array} \tag{23}$$

where $\left[x_{ij}^- \; x_{ij}^+\right]$ represents the value of the *i*-th alternative with respect to the *j*-th attribute, and $\omega_j \, (j = 1, 2, \cdots, n)$ represents the weight of the *j*-th criterion.

Step 2: Transforming the contrary criteria into positive criteria by standardization. The criteria are called positive criteria (P) if the greater the values of the alternatives with respect to the criteria the better the alternative will be, while the criteria are called contrary criteria (C) if the smaller the values of the alternatives with respect to the criteria the better the criteria will be.

As for the positive-type criteria (Ren and Toniolo, 2018),

$$\left[r_{ij}^- \quad r_{ij}^+\right] = \left[\frac{x_{ij}^- - \min\limits_{i=1,2,\cdots,m}\left\{x_{ij}^-\right\}}{\max\limits_{i=1,2,\cdots,m}\left\{x_{ij}^+\right\} - \min\limits_{i=1,2,\cdots,m}\left\{x_{ij}^-\right\}} \quad \frac{x_{ij}^+ - \min\limits_{i=1,2,\cdots,m}\left\{x_{ij}^-\right\}}{\max\limits_{i=1,2,\cdots,m}\left\{x_{ij}^+\right\} - \min\limits_{i=1,2,\cdots,m}\left\{x_{ij}^-\right\}}\right] \quad (\mathrm{i} = 1, 2, \ldots, \mathrm{m}; \mathrm{j} \in P) \tag{24}$$

As for the contrary-type criteria (Ren and Toniolo, 2018),

$$\left[r_{ij}^- \quad r_{ij}^+\right] = \left[\frac{\max\limits_{i=1,2,\cdots,m}\left\{x_{ij}^+\right\} - x_{ij}^+}{\max\limits_{i=1,2,\cdots,m}\left\{x_{ij}^+\right\} - \min\limits_{i=1,2,\cdots,m}\left\{x_{ij}^-\right\}} \quad \frac{\max\limits_{i=1,2,\cdots,m}\left\{x_{ij}^+\right\} - x_{ij}^-}{\max\limits_{i=1,2,\cdots,m}\left\{x_{ij}^+\right\} - \min\limits_{i=1,2,\cdots,m}\left\{x_{ij}^-\right\}}\right] \quad (\mathrm{i} = 1, 2, \ldots, \mathrm{m}; \mathrm{j} \in C) \tag{25}$$

where $\left[r_{ij}^{-} \quad r_{ij}^{+} \right]$ represents the value of the *i*-th alternative with respect to the *j*-th criterion the normalized decision-making matrix.

Step 3: Determining the weighted normalized decision-making matrix. After determining the normalized decision-making matrix, the weighted normalized decision-making matrix can be determined by Eqs.26-27.

$$\begin{array}{cccccc} & C_1 & C_2 & \cdots & C_n \\ A_1 & \left[y_{11}^{-} \quad y_{11}^{+} \right] & \left[y_{12}^{-} \quad y_{12}^{+} \right] & \cdots & \left[y_{1n}^{-} \quad y_{1n}^{+} \right] \\ A_2 & \left[y_{21}^{-} \quad y_{21}^{+} \right] & \left[y_{22}^{-} \quad y_{22}^{+} \right] & \cdots & \left[y_{2n}^{-} \quad y_{2n}^{+} \right] \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & \left[y_{m1}^{-} \quad y_{m1}^{+} \right] & \left[y_{m2}^{-} \quad y_{m2}^{+} \right] & \cdots & \left[y_{mn}^{-} \quad y_{mn}^{+} \right] \\ W & \omega_1 & \omega_2 & \cdots & \omega_n \end{array} \tag{26}$$

$$\left[y_{ij}^{-} \quad y_{ij}^{+} \right] = \left[\omega_j^{-} x_{ij}^{-} \quad \omega_j^{+} x_{ij}^{+} \right] \tag{27}$$

where $\left[y_{ij}^{-} \quad y_{ij}^{+} \right]$ represents the value of the *i*-th alternative with respect to the *j*-th criterion the weighted normalized decision-making matrix.

Step 4: Determining the reference sequence. The reference sequence can be determined by Eqs.28-30 (Zhang *et al.*, 2005).

$$R_0 = \left(\left[r_1^{-} \quad r_1^{+} \right], \left[r_2^{-} \quad r_2^{+} \right], \cdots, \left[r_m^{-} \quad r_m^{+} \right] \right) \tag{28}$$

$$r_j^{-} = \max_{i=1}^{m} \left\{ y_{ij}^{-} \right\},\ j = 1, 2, \cdots, n \tag{29}$$

$$r_j^{+} = \max_{i=1}^{m} \left\{ y_{ij}^{+} \right\},\ j = 1, 2, \cdots, n \tag{30}$$

where $\left[r_j^{-} \quad r_j^{+} \right],\ j = 1, 2, \cdots, n$ represents the reference with respect to the *j*-th criterion.

Step 5: Determining the distance between each of the alternatives and the reference sequence with respect to each of the decision criteria. The distance between each of the alternatives and the reference sequence with respect to each of the decision criteria can be determined according to Eq.10, as presented in Eq.31.

$$\Delta_i(j) = \left\| \begin{bmatrix} y_{ij}^- & y_{ij}^+ \end{bmatrix} - \begin{bmatrix} r_j^- & r_j^+ \end{bmatrix} \right\|, j = 1, 2, \cdots, n \tag{31}$$

where $\Delta_i(j)$ represents the distance between the *i*-th alternative and the reference sequence with respect to the *j*-th criterion.

Step 6: Calculating the grey relational coefficients. The connection coefficients can be determined by Eq.32.

$$\xi_i(j) = \frac{\min_i \min_j \{\Delta_i(j)\} + \rho \max_i \max_j \{\Delta_i(j)\}}{\Delta_i(j) + \rho \max_i \max_j \{\Delta_i(j)\}} \tag{32}$$

Step 7: Determining the grey relational degrees of the alternatives and the priority sequence. The grey relational degrees of the alternatives can be determined by Eq.33.

$$r_i = \sum_{j=1}^{n} \xi_i(j) \tag{33}$$

The priority sequence of the alternatives can be ranked according to the rule that the greater the value of the grey relational degree, the more superior the alternative will be. As for the life cycle sustainability ranking of the alternative energy systems, the sustainability sequence of these energy systems can be determined according to the grey relational degrees which can be recognized as the integrated sustainability performances of the energy systems.

3. Case study

In order to illustrate the proposed method for life cycle sustainability prioritization of energy systems under uncertainties, the alternative energy systems for electricity generation were studied in this section. There are two main reasons for selecting the electricity generation systems to be studied by the proposed method. One is that electricity generation systems are typical energy systems, and another is that the data of the electricity generation systems with respect to each of the criteria in economic, environmental and social pillars are usually not crisp numbers and vary within different intervals, thus, these energy systems are very suitable for demonstrating the developed method in this study. Four typical alternative energy systems for electricity generation under the conditions of UK was studied, and they are coal-pulverised (A_1), combined cycle gas turbines (A_2), nuclear-pressurised water reactor (A_3), offshore wind powder based electricity (A_4). A total of ten life cycle sustainability criteria including capital cost (EC_1), operation and maintenance cost (EC_2), and fuel cost (EC_3) in economic aspect, global warming potential (EN_1), acidification potential (EN_2), photochemical smog (EN_3), and land occupation (EN_4) in environmental aspect, employment (S_1), human toxicity potential (S_2), and total health impacts from radiation (S_3) in social aspect were employed for sustainability assessment of the four alternative energy generation scenarios. The data of the four energy systems for electricity generation was derived from the work of Stamford and Azapagic (2012), as presented in Table 2.

Table 2: The interval decision-making matrix

		A_1	A_2	A_3	A_4
EC_1	$GBP.MWh^{-1}$	[28.40 61.70]	[11.10 12.40]	[51.30 79.40]	[88.50 144.60]
EC_2	$GBP.MWh^{-1}$	[10.70 13.10]	[6.00 6.00]	[10.90 14.30]	[23.00 45.80]
EC_3	$GBP.MWh^{-1}$	[13.00 24.40]	[25.40 66.40]	[4.20 6.30]	[0 0]
EN_1	kg CO_2 $eq.kWh^{-1}$	[9.65E-01 1.48E+00]	[3.66E-01 4.96E-01]	[5.13E-03 1.31E-02]	[4.73E-03 1.42E-02]
EN_2	kg SO_2 $eq.kWh^{-1}$	[1.66E-03 9.80E-03]	[1.22E-04 3.70E-04]	[3.76E-05 9.34E-05]	[3.35E-05 8.41E-05]
EN_3	kg C_2H_4 $eq.kWh^{-1}$	[1.33E-04 4.57E-04]	[2.31E-05 6.30E-05]	[4.50E-06 8.08E-06]	[3.47E-06 9.81E-06]
EN_4	M^{2yr}	[2.07E-02 4.04E-02]	[2.76E-04 3.79E-03]	[5.28E-04 7.71E-04]	[1.56E-04 4.61E-04]
S_1	person-years.MWh^{-1}	[5.56E+01 1.91E+02]	[2.66E+01 6.24E+01]	[5.59E+01 8.08E+01]	[3.11E+01 3.68E+01]
S_2	kg DCB $eq.kWh^{-1}$	[7.28E-02 4.58E-01]	[3.68E-03 1.41E-02]	[1.35E-02 1.35E-01]	[3.03E-02 7.52E-02]
S_3	$DALY.kWh^{-1}$	[2.15E-10 2.21E-09]	[1.16E-11 2.53E-09]	[2.03E-08 3.19E-08]	[1.86E-11 6.66E-11]

Reference: Stamford and Azapagic (2012)

The fuzzy two-stage logarithmic goal programming method was employed to determine the weights of the three dimensions and the local weights of the criteria in each of the three dimensions. Taking the weights of the three dimensions of sustainability as an example, the five steps were specified as follows:

Step 1: The criteria system for life cycle sustainability consists of three dimensions including economic, environmental, and social dimensions, there are three criteria in the economic and social dimensions, and there are four criteria in environmental dimension.

Step 2: Establishing pairwise comparison matrix for determining the weights of the three dimensions by using triangular fuzzy numbers. The decision-makers firstly used the linguistic variables to express the opinions and preferences of the decision-makers on the relative importance of one dimension over another. The results were presented in Table 3

Table 3: The comparison matrix for determining the weights of the three dimensions

	Economic	Environmental	Social
Economic	EI	ML	SM
Environmental		EI	MM
Social			EI

All the linguistic terms presented in Table 3 can be transformed into triangular fuzzy numbers, and the results were presented in Table 4.

Table 4: The fuzzy comparison matrix for determining the weights of the three dimensions

	Economic	Environmental	Social
Economic	(1,1,1)	$\left(\frac{1}{1+\delta} \quad 1 \quad 1+\delta\right)$	$\left(5-\delta \quad 5 \quad 5+\delta\right)$
Environmental		(1,1,1)	$\left(3-\delta \quad 3 \quad 3+\delta\right)$
Social			(1,1,1)

Step 3: The fuzzy comparison matrix can transformed into interval comparison by setting α . Then, the interval comparison matrix for determining the weights of the three dimensions can be determined according to Eqs.15-17, and the results were presented in Table 5.

Table 5: The fuzzy comparison matrix for determining the weights of the three dimensions

	Economic	Environmental	Social
Economic	$[1 \quad 1]$	$\left[\frac{1}{1+\delta}+\frac{\delta\alpha}{1+\delta} \quad 1+\delta-\delta\alpha\right]$	$[5-\delta+\delta\alpha \quad 5+\delta-\delta\alpha]$
Environmental		$[1 \quad 1]$	$[3-\delta+\delta\alpha \quad 3+\delta-\delta\alpha]$
Social			$[1 \quad 1]$

The confidence degree of the judgments of the decision-makers was recognized to be moderate, and δ takes the value 1 in this study, and α takes the value of 0.50 as the confidence level. Then, the fuzzy comparison matrix can be rewritten in Eq.34.

$$\begin{array}{cccc} & EC & EN & S \\ EC & [1 \quad 1] & \left[\frac{3}{4} \quad \frac{3}{2}\right] & \left[\frac{9}{2} \quad \frac{11}{2}\right] \\ EN & & [1 \quad 1] & \left[\frac{5}{2} \quad \frac{7}{2}\right] \\ S & & & [1 \quad 1] \end{array} \tag{34}$$

Step 4: The programming (35) was established to minimize the inconsistency degree of the judgments under the multiplicative constraint.

$$
\begin{aligned}
& Min\ J = p_{12} + q_{12} + p_{13} + q_{13} + p_{23} + q_{23} \\
& s.t. \\
& a_1 - b_1 - a_2 + b_2 + p_{12} \geq \ln b_{12}^L \\
& a_1 - b_1 - a_2 + b_2 - q_{12} \leq \ln b_{12}^U \\
& a_1 - b_1 - a_3 + b_3 + p_{13} \geq \ln b_{13}^L \\
& a_1 - b_1 - a_3 + b_3 - q_{13} \leq \ln b_{13}^U \\
& a_2 - b_2 - a_3 + b_3 + p_{23} \geq \ln b_{23}^L \\
& a_2 - b_2 - a_3 + b_3 - q_{23} \leq \ln b_{23}^U \\
& a_1 - b_1 + a_2 - b_2 + a_3 - b_3 = 0 \\
& a_1 b_1 = 0 \\
& a_2 b_2 = 0 \\
& a_3 b_3 = 0 \\
& p_{12} q_{12} = 0 \\
& p_{13} q_{13} = 0 \\
& p_{23} q_{23} = 0 \\
& a_1, b_1, a_2, b_2, a_3, b_3 \geq 0 \\
& p_{12}, q_{12}, p_{13}, q_{13}, p_{23}, q_{23} \geq 0
\end{aligned}
\tag{35}
$$

After substituting the elements of the upper triangular pairwise comparison matrix, programming (35) can be solved, and the minimum inconsistency degree can be obtained, and the minimum value of the inconsistency degree $J^* = 0$. Then, programming (20) can be used to determine the weights of the three dimensions. Taking the determination of the weight of economic dimension as an example, the following programming can be established:

$$
\begin{aligned}
& Min/Max \quad \ln\omega_1 = a_1 - b_1 \\
& s.t. \\
& a_1 - b_1 - a_2 + b_2 \geq \ln b_{12}^L \\
& a_1 - b_1 - a_2 + b_2 \leq \ln b_{12}^U \\
& a_1 - b_1 - a_3 + b_3 \geq \ln b_{13}^L \\
& a_1 - b_1 - a_3 + b_3 \leq \ln b_{13}^U \\
& a_2 - b_2 - a_3 + b_3 \geq \ln b_{23}^L \\
& a_2 - b_2 - a_3 + b_3 \leq \ln b_{23}^U \\
& a_1 - b_1 + a_2 - b_2 + a_3 - b_3 = 0 \\
& a_1 b_1 = 0 \\
& a_2 b_2 = 0 \\
& a_3 b_3 = 0 \\
& a_1, b_1, a_2, b_2, a_3, b_3 \geq 0
\end{aligned} \tag{36}
$$

After solving programming (36), the lower and upper bounds of $\ln\omega_1$ denoting by $\ln\omega_i^L$ and $\ln\omega_i^U$ can be determined: $\left[\ln\omega_i^L \quad \ln\omega_i^U\right] = [0.5851 \quad 0.6879]$. Then, the interval weight of the economic dimension can be determined according to Eq.21, and the results were presented in Eq.37.

$$
\left[\omega_1^L \quad \omega_1^U\right] = \left[\exp\left(\ln\omega_1^L\right) \quad \exp\left(\ln\omega_1^U\right)\right] = [1.7952 \quad 1.9895] \tag{37}
$$

In a similar way, the interval weights of the other two dimensions can also be determined, and the weights of environmental and social dimensions are $[1.2599 \quad 1.3963]$ and $[0.3790 \quad 0.4200]$.

The local weights of the criteria in each dimension can also be determined, and the results were presented in Table 6.

Table 6: The local weights of the criteria in each of the three dimensions of sustainability

Economic: $J^* = 0$	EC_1	EC_2	EC_3
EC_1	$[1 \quad 1]$	$\left[\frac{3}{2} \quad \frac{5}{2}\right]$	$\left[\frac{7}{2} \quad \frac{9}{2}\right]$
EC_2		$[1 \quad 1]$	$\left[\frac{5}{2} \quad \frac{7}{2}\right]$
EC_3			$[1 \quad 1]$
Local weights	$[1.7784 \quad 2.0083]$	$[1.1157 \quad 1.2599]$	$[0.4200 \quad 0.4743]$

Environmental: $J^* = 0.4055$	EN_1	EN_2	EN_3	EN_4
EN_1	$[1 \quad 1]$	$\left[\frac{5}{2} \quad \frac{7}{2}\right]$	$\left[\frac{11}{2} \quad \frac{13}{2}\right]$	$\left[\frac{3}{2} \quad \frac{5}{2}\right]$
EN_2		$[1 \quad 1]$	$\left[\frac{5}{2} \quad \frac{7}{2}\right]$	$\left[\frac{3}{2} \quad \frac{5}{2}\right]$
EN_3			$[1 \quad 1]$	$\left[\frac{7}{24} \quad \frac{5}{12}\right]$
EN_4				$[1 \quad 1]$
Local weights	$[2.2519 \quad 2.5757]$	$[1.0000 \quad 1.3136]$	$[0.3846 \quad 0.4082]$	$[0.8829 \quad 1.0099]$

Social: $J^* = 0$	S_1	S_2	S_3
S_1	$[1 \quad 1]$	$\left[\frac{3}{2} \quad \frac{5}{2}\right]$	$\left[\frac{5}{2} \quad \frac{7}{2}\right]$
S_2		$[1 \quad 1]$	$\left[\frac{3}{2} \quad \frac{5}{2}\right]$
S_3			$[1 \quad 1]$

Local weights	$[1.5536 \quad 2.0138]$	$[0.8631 \quad 1.1587]$	$[0.4966 \quad 0.6437]$	$J^* = 0$

Note: the relative preference of EN_3 over EN_4 is $\left(\frac{1}{3+\delta} \quad \frac{1}{3} \quad \frac{1}{3-\delta}\right)$, and the interval $\left[\frac{7}{24} \quad \frac{5}{12}\right]$ when δ and α take the value of 1 and 0.5, respectively.

According to Eq.22, the global weights of these ten criteria for sustainability assessment of energy systems can be determined. Taking the three criteria in economic aspects as an example, the local weights of the three criteria are $[1.7784 \quad 2.0083]$, $[1.1157 \quad 1.2599]$, and $[0.4200 \quad 0.4743]$, respectively. The weight of the economic dimension is $[1.7952 \quad 1.9895]$. The global weights of the three criteria in economic dimension can be determined by Eqs.38-40.

$$\begin{aligned}
\left[\omega_{EC_1}^L \quad \omega_{EC_1}^U\right] &= \left[\left[\frac{\omega_{EC}^L \times \left(\omega_{EC_1}^L\right)^3}{\omega_{EC_1}^U \times \omega_{EC_2}^U \times \omega_{EC_3}^U}\right]^{1/3} \quad \left[\frac{\omega_{EC}^U \times \left(\omega_{EC_1}^U\right)^3}{\omega_{EC_1}^L \times \omega_{EC_2}^L \times \omega_{EC_3}^L}\right]^{1/3}\right] \\
&= \left[\left[\frac{1.7952 \times (1.7784)^3}{2.0083 \times 1.2599 \times 0.4743}\right]^{1/3} \quad \left[\frac{1.9895 \times (2.0083)^3}{1.7784 \times 1.1157 \times 0.4200}\right]^{1/3}\right] \\
&= [2.0339 \quad 2.6841]
\end{aligned} \tag{38}$$

$$\begin{aligned}
\left[\omega_{EC_2}^L \quad \omega_{EC_2}^U\right] &= \left[\left[\frac{\omega_{EC}^L \times \left(\omega_{EC_2}^L\right)^3}{\omega_{EC_1}^U \times \omega_{EC_2}^U \times \omega_{EC_3}^U}\right]^{1/3} \quad \left[\frac{\omega_{EC}^U \times \left(\omega_{EC_2}^U\right)^3}{\omega_{EC_1}^L \times \omega_{EC_2}^L \times \omega_{EC_3}^L}\right]^{1/3}\right] \\
&= \left[\left[\frac{1.7952 \times (1.1157)^3}{2.0083 \times 1.2599 \times 0.4743}\right]^{1/3} \quad \left[\frac{1.9895 \times (1.2599)^3}{1.7784 \times 1.1157 \times 0.4200}\right]^{1/3}\right] \\
&= [1.2760 \quad 1.6839]
\end{aligned} \tag{39}$$

$$\begin{bmatrix}\omega_{EC_3}^L & \omega_{EC_3}^U\end{bmatrix} = \left[\left[\frac{\omega_{EC}^L \times \left(\omega_{EC_3}^L\right)^3}{\omega_{EC_1}^U \times \omega_{EC_2}^U \times \omega_{EC_3}^U}\right]^{1/3} \quad \left[\frac{\omega_{EC}^U \times \left(\omega_{EC_3}^U\right)^3}{\omega_{EC_1}^L \times \omega_{EC_2}^L \times \omega_{EC_3}^L}\right]^{1/3}\right]$$

$$= \left[\left[\frac{1.7952 \times (0.4200)^3}{2.0083 \times 1.2599 \times 0.4743}\right]^{1/3} \quad \left[\frac{1.9895 \times (0.4743)^3}{1.7784 \times 1.1157 \times 0.4200}\right]^{1/3}\right] \tag{40}$$

$$= \begin{bmatrix}0.4803 & 0.6339\end{bmatrix}$$

In a similar way, the global weights of all the ten criteria for sustainability assessment of energy systems can be determined, and the results were presented in Table 7.

Table 7: The global weights of all the ten criteria for sustainability assessment of energy systems

Criteria	EC_1	EC_2	EC_3	EN_1	EN_2
Weights	$[2.0339 \quad 2.6841]$	$[1.2760 \quad 1.6839]$	$[0.4803 \quad 0.6339]$	$[2.1954 \quad 2.9941]$	$[0.9749 \quad 1.5270]$
Criteria	EN_3	EN_4	S_1	S_2	S_3
Weights	$[0.3749 \quad 0.4745]$	$[0.8607 \quad 1.1740]$	$[0.9817 \quad 1.7270]$	$[0.5454 \quad 0.9937]$	$[0.3138 \quad 0.5520]$

After determining the global weights of the criteria for sustainability assessment of energy systems, the interval GRA was employed to prioritize the four pathways for electricity generation, and the interval decision-making matrix was firstly normalized by Eq.24 and Eq.25. There is only one positive-type criterion-employment (S_1), and the other nine criteria are contrary-type criteria. The elements of the standardized interval decision-making matrix can be determined. Taking the data of A_1 with respect to the positive-type criterion-S_1 and that of A_1 with respect to the contrary-type criterion-EC_1 as an example.

As for the data of A_1 with respect to the positive-type criterion-S_1:

$$\left[r_{A_1S_1}^- \quad r_{A_1S_1}^+\right]=\left[\frac{55.6-26.6}{191-26.6} \quad \frac{191-26.6}{191-26.6}\right]=\left[0.1764 \quad 1\right] \tag{41}$$

As for the data of A_1 with respect to the contrary-type criterion-EC_1:

$$\left[r_{A_1EC_1}^- \quad r_{A_1EC_1}^+\right]=\left[\frac{144.60-61.70}{144.60-11.10} \quad \frac{144.60-28.40}{144.60-11.10}\right]=\left[0.6210 \quad 0.8704\right] \tag{42}$$

In a similar way, all the elements in the standardized interval decision-making matrix can be determined, and the results were presented in Table 8.

Table 8: The standardized interval decision-making matrix

	A_1	A_2	A_3	A_4
EC_1	[0.6210 0.8704]	[0.9903 1.0000]	[0.4884 0.6989]	[0 0.4202]
EC_2	[0.8216 0.8819]	[1.0000 1.0000]	[0.7915 0.8769]	[0 0.5729]
EC_3	[0.6325 0.8042]	[0 0.6175]	[0.9051 0.9367]	[1.0000 1.0000]
EN_1	[0 0.3491]	[0.6670 0.7551]	[0.9943 0.9997]	[0.9936 1.0000]
EN_2	[0 0.8335]	[0.9655 0.9909]	[0.9939 0.9996]	[0.9948 1.0000]
EN_3	[0 0.7144]	[0.8687 0.9567]	[0.9898 0.9977]	[0.9860 1.0000]
EN_4	[0 0.4895]	[0.9097 0.9970]	[0.9847 0.9908]	[0.9924 1.0000]
S_1	[0.1764 1.0000]	[0 0.2178]	[0.1782 0.3297]	[0.0274 0.0620]
S_2	[0 0.8479]	[0.9771 1.0000]	[0.7110 0.9784]	[0.8426 0.9414]
S_3	[0.0064 0.0689]	[0 0.0790]	[0.6362 1.0000]	[0.0002 0.0017]

The weighted normalized decision-making matrix can be determined by Eq.26 and Eq.27. Taking the element of cell (1,1) in Table 8 as an example, it can be weighted by Eq.43.

$$[0.6210 \quad 0.8704] \times [2.0339 \quad 2.6841] = [1.2630 \quad 2.3363] \tag{43}$$

In a similar way, all the elements in the weighted normalized decision-making matrix can be determined, and the results were presented in Table 9. The reference sequence can be determined by Eqs.28-30, and the results were also presented in Table 9.

Table 9: The weighted normalized interval decision-making matrix

	A_1	A_2	A_3	A_4	References sequence
EC_1	[1.2630 2.3363]	[2.0141 2.6841]	[0.9933 1.8759]	[0 1.1279]	[2.0141 2.6841]
EC_2	[1.0484 1.4850]	[1.2760 1.6839]	[1.0099 1.4766]	[0 0.9646]	[1.2760 1.6839]
EC_3	[0.3038 0.5098]	[0 0.3914]	[0.4347 0.5938]	[0.4803 0.6339]	[0.4803 0.6339]
EN_1	[0 1.0452]	[1.4643 2.2609]	[2.1829 2.9933]	[2.1813 2.9941]	[2.1829 2.9941]
EN_2	[0 1.2727]	[0.9413 1.5132]	[0.9689 1.5264]	[0.9698 1.5270]	[0.9698 1.5270]
EN_3	[0 0.3390]	[0.3157 0.4540]	[0.3711 0.4734]	[0.3697 0.4745]	[0.3711 0.4745]
EN_4	[0 0.5747]	[0.7830 1.1705]	[0.8475 1.1631]	[0.8542 1.1740]	[0.8542 1.1740]
S_1	[0.1732 1.7270]	[0 0.3761]	[0.1750 0.5694]	[0.0269 0.1071]	[0.1750 0.5694]
S_2	[0 0.8425]	[0.5329 0.9937]	[0.3878 0.9722]	[0.4595 0.9355]	[0.5329 0.9937]
S_3	[0.0020 0.0381]	[0 0.0436]	[0.1996 0.5520]	[0.0001 0.0010]	[0.1996 0.5520]

After determining the reference sequence, the distance between each of the alternatives and the reference sequence with respect to each of the decision criteria can be determined by Eq.31, and the results were presented in Table 10.

Table 10: The distance between each of the alternatives and the reference sequence with respect to each of the decision criteria

$\Delta_i(j)$	A_1	A_2	A_3	A_4
EC_1	0.7511	0	1.0208	2.0141
EC_2	0.2276	0	0.2661	1.2760
EC_3	0.1765	0.4803	0.0456	0
EN_1	2.1829	0.7332	0.0008	0.0016
EN_2	0.9698	0.0285	0.0009	0
EN_3	0.3711	0.0454	0.0011	0.0014
EN_4	0.8542	0.0712	0.0109	0
S_1	0.5329	0	0.1451	0.0733
S_2	0.5139	0.5084	0	0.5510
S_3	0.0018	1.3509	1.1576	1.6199

The values of $\min_i \min_j \{\Delta_i(j)\}$ and $\max_i \max_j \{\Delta_i(j)\}$ are 0 and 2.1829 according to Table 10, then, the grey relational coefficients can be determined according to Eq.32, and the results were presented in Table 11.

Table 11: The grey relational coefficients

$\xi_i(j)$	A_1	A_2	A_3	A_4
EC_1	0.5924	1.0000	0.5167	0.3515
EC_2	0.8274	1.0000	0.8040	0.4610
EC_3	0.8608	0.6944	0.9599	1.0000
EN_1	0.3333	0.5982	0.9993	0.9985
EN_2	0.5295	0.9745	0.9992	1.0000
EN_3	0.7463	0.9601	0.9990	0.9987
EN_4	0.5610	0.9388	0.9902	1.0000
S_1	0.6719	1.0000	0.8826	0.9370
S_2	0.6799	0.6822	1.0000	0.6645
S_3	0.9984	0.4469	0.4853	0.4026

Finally, the grey relational degrees of the four alternatives for electricity generation can be determined by Eq.33, and the results were presented in Figure 3. It is apparent that the scenario-nuclear-pressurised water reactor for electricity generation was recognized as the most sustainable, followed by combined cycle gas turbines, offshore wind powder, and coal-pulverised in the descending order. Therefore, some policies and strategic measures should be drafted for promoting the development of nuclear-pressurized water reactor for electricity generation in UK among these four energy systems.

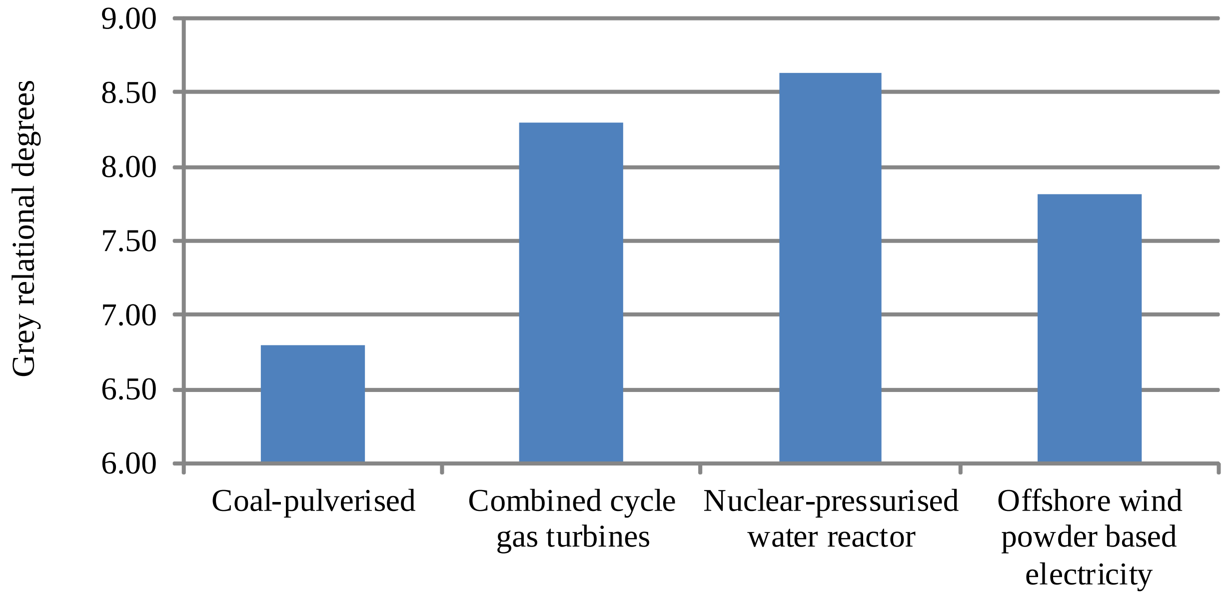

Figure 3: The grey relational degrees of the four alternatives for electricity generation

4. Discussion

The result of recognizing nuclear-pressurized water reactor for electricity generation the most sustainable scenario is reasonable. This scenario performs relatively better on employment, fuel cost, global warming potential, acidification potential, photochemical smog and land occupation though it is not the best on these aspects. Meanwhile, the weights of global warming potential and employment are relative greater than most of the other evaluation criteria.

Both this study and the study of Ren (2018) recognized nuclear-pressurised water reactor and combined cycle gas turbines as the two most sustainable scenarios for electricity generation among these four alternatives; however the sequences of these four energy systems for electricity generation determined by these two studies are different, and one of the main reasons is that the weights of the ten criteria used in these two studies are different.

In order to validate the sustainability sequence of the four alternatives for electricity generation, the interval TOPSIS method (Wang *et al*., 2017) was also employed to rank these four alternatives based on the weighted normalized interval decision-making matrix presented in Table 9, the results were presented in Table 12. It is apparent that the sustainability sequence of the four alternatives determent by the interval TOPSIS is the same to that that determined by the interval GRA method used in this study. To some extent, it could be deduced that the result of ranking nuclear-pressurised water reactor for electricity generation as the most sustainable is reliable.

Table 12: The comparison of the results determined by the interval GRA and the interval TOPSIS method

	A_1	A_2	A_3	A_4
Closeness coefficients by interval TOPSIS	0.4621	0.6334	0.6393	0.5165
Ranking by interval TOPSIS	4	2	1	3
Ranking by interval GRA	4	2	1	3

In order to investigate the effects of the relative importance of the criteria on the final sustainability order of these four alternatives for electricity generation determined by the interval GRA method, sensitivity analysis was carried out by studying the following eleven cases:

Case 1: assigning an equal weight (0.10000) to the ten criteria;

Case 2-11: assigning a dominant weight (0.3700) to one of the ten criteria, and an equal weight (0.0700) to the other nine criteria. For instance, 0.3700 was assigned to EC_1 and 0.0070 was assigned as the weights of the other nine criteria.

The results of sensitivity analysis were presented in Figure 4. It is apparent that the grey relational degrees of the four alternatives for electricity vary when changing the weights of the ten criteria. The scenario of nuclear-pressurized water reactor was recognized as the most sustainable and the coal-pressurized scenario was recognized as the least sustainable in all the eleven cases. However, the rankings of combined cycle gas turbines and offshore wind power based electricity usually change when changing the weights of the criteria for sustainability assessment of energy systems.

To some extent, it could be concluded that the sustainability order of the four alternatives for electricity generation may change with the change of the decision-makers/stakeholders, because different decision-makers/stakeholders have different preferences and opinions. Therefore, the accurate determination of the weights is of vital importance for accurately determining the sustainability order of the alternative energy systems.

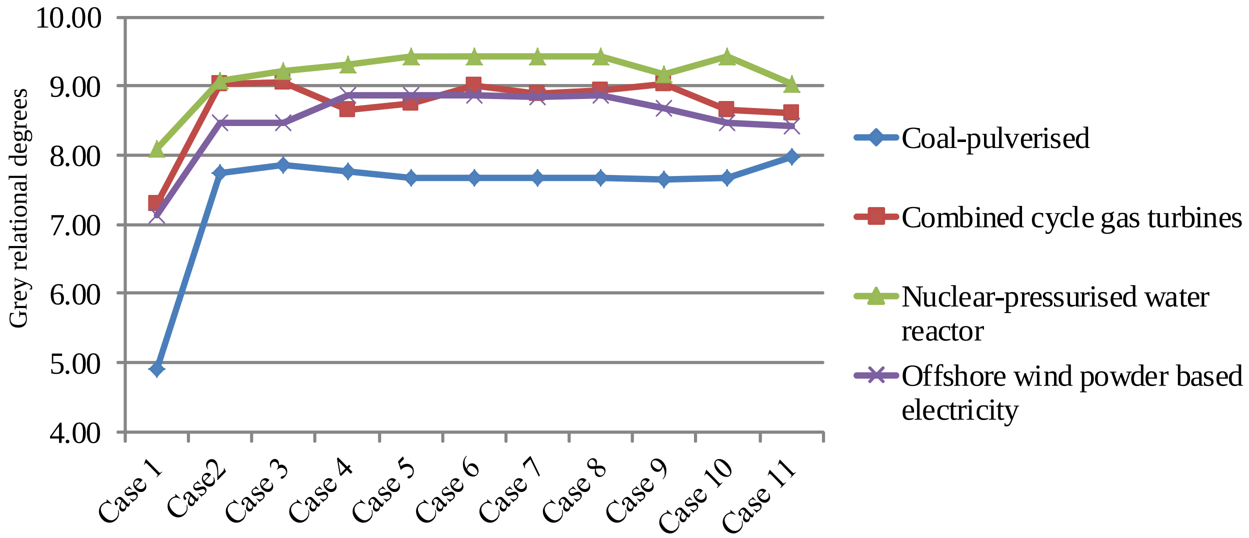

Figure 4: The results of sensitivity analysis

5. Conclusion

This study aims at developing a life cycle sustainability prioritization framework for ranking different alternative energy systems under uncertainty conditions. In order to address the various uncertainties existing in human's judgments, the data in the decision-making matrix obtained by life cycle sustainability assessment are interval numbers rather than the crisp numbers. The fuzzy two-stage logarithmic goal programming method which can not only allow the decision-makers to use linguistic variables and triangular fuzzy numbers to express their opinions and preferences for capturing vagueness and ambiguity, but also minimize the inconsistency degree of the pair-wise comparison matrix, was employed for determining the weights of the criteria for life cycle sustainability assessment of energy systems. The weights determined by this method can accurately reflect the preferences of the decision-makers. The interval multi-criteria decision-making method, namely, the interval GRA method, which can address data uncertainties, was used to rank the alternative energy systems. An illustrative case was studied by ranking four alternative scenarios (coal-pulverised, combined cycle gas turbines, nuclear-pressurised water reactor, and offshore wind powder based electricity) for electricity generation, the sustainability order of the four alternatives from the most sustainable to the least is nuclear-pressurised water reactor, combined cycle gas turbines, offshore wind powder, and coal-pulverised. The interval TOPSIS method was also employed to validate the results determined by the interval GRA method, and the results determined by these two methods are the same. Sensitivity analysis was also carried to investigate the effects of the weights on the final sustainability order of the four alternative energy systems, and the results revealed that the sustainability order of the four alternatives is highly sensitive to the weights of the criteria.

All in all, the proposed life cycle sustainability prioritization framework for ranking different alternative energy systems under uncertainty conditions has the following advantages compared with the traditional decision-making framework:

(1) The developed framework can help the decision-makers/stakeholders to select the most sustainable energy system among multiple alternatives in life cycle perspective by the integrated considerations of the criteria in the three pillars of sustainability simultaneously. In other words, the data for measuring economic, environmental and social sustainability were collected in “cradle to grave” approach rather than merely the production stage;

(2) The developed framework can address data uncertainties when ranking the alternative energy systems, and interval numbers were employed instead of the crisp numbers to depict the relative performances of the alternative energy systems with respect to the evaluation criteria. In other words, the developed framework can successfully rank the alternative energy systems when the data of each alternative with respect to each evaluation criterion in the decision-making matrix are not crisp numbers but vary within a range;

(3) The fuzzy two-stage logarithmic goal programming method for determining the weights of the criteria for sustainability assessment can not only address the vagueness and ambiguity existing in human’s judgments, but also minimize the inconsistency degree of the pair-wise comparison matrix.

Besides the advantages, there are two weak points which need to be overcome in future:

(1) The developed method does not allow multiple groups of decision-makers/stakeholders to participate in the process of sustainability periodization;

(2) The interval numbers can be used to describe data uncertainties, but sometime it is still difficult for the users to use interval numbers to describe the relative performances of the alternative energy systems with respect to the criteria for sustainability assessment. For instance, it is difficult or even impossible to use interval numbers to describe the relative performances with respect to some soft criteria, i.e. technological maturity, impact on local

culture, working environment and discriminations, etc. The linguistic terms corresponding to fuzzy numbers are more suitable to be used for depicting these soft criteria.

The future work of the authors is to develop a life cycle based group multi-criteria decision making method for ranking the alternative energy systems based on hybrid information including crisp numbers, interval numbers and fuzzy numbers.

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