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Combined cooling heating and power systems: Sustainability assessment under uncertainties

Chao He[1], Quanguo Zhang[1*], Jingzheng Ren[2*], Zhaoling Li[3]

[1]Key Laboratory of New Materials and Facilities for Rural Renewable Energy, Ministry of Agriculture, Collaborative Innovation Center of Biomass Energy, College of Mechanical & Electrical Engineering, Henan Agricultural University, Zhengzhou 450002, China

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

[3]Graduate School of Life and Environmental Science, University of Tsukuba, Tsukuba, Ibaraki 305-8506, Japan

Post address: Key Laboratory of New Materials and Facilities for Rural Renewable Energy, Ministry of Agriculture, Collaborative Innovation Center of Biomass Energy, College of Mechanical & Electrical Engineering, Henan Agricultural University, Zhengzhou 450002, China

*Corresponding author.

Email address:

zquanguo@163.com (Zhang, Q.) jzhren@polyu.edu.hk (Ren. J)

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Abstract: Combined cooling, heating, and power (CCHP) systems have been recognized as a promising technology for energy efficiency improvement and emissions mitigation. This study aims at developing a multi-criteria sustainability assessment method to prioritize the alternative CCHP systems under uncertainties. An interval analytic network process (ANP) that can address the vagueness, ambiguity, and subjectivity existing in human judgments and consider the interdependences and interactions among the evaluation criteria was used to determine the weights of the criteria for sustainability assessment, and an interval analytic hierarchy process (AHP) which is a structured technique for organizing and analyzing complex decisions was also employed to quantify the relative performances of the alternative CCHP systems with respect to the soft criteria. An interval technique for order of preference by similarity to ideal solution (TOPSIS) was employed to rank the alternative CCHP systems according to their sustainability. An illustrative case including five CCHP systems has been studied using the proposed method. A solid electrolyte fuel cell (SOFC) combined with a waste heat afterburning absorption refrigerator was recognized as the most sustainable scenario. In addition, the results have been further investigated through sensitivity analysis and validated by the weighted sum method.

Keywords: combined cooling, heating, and power (CCHP); interval; analytic network process (ANP); technique for order of preference by similarity to ideal solution (TOPSIS)

1. Introduction

With the continuous growth of the economy, many countries have faced severe challenges in climate change mitigation and energy supply risk reduction. For example, China consumed about 3249.4 million tons of equivalent standard coal (tce) in 2010, and the total energy consumption also exceeded the United States in that year [1]. Combined cooling, heating, and power (CCHP) systems, as an extension of the combined heat and power (CHP) system, are a promising innovation to satisfy the diverse energy requirements including cooling, heating and power, mitigating the negative environmental impacts, and improving energy efficiency [2] and thus have great development potential for these countries. The CCPH as an "industrial complex" can lead to better global efficiencies compared with the stand-alone power plant and has huge potential to reduce the primary energy consumption and further achieve emissions reduction [3]. Accordingly, the CCHP model has been widely discussed in practice, e.g., for university campuses [4], large-scale public buildings [5], and hospitals [6].

Many studies have been conducted on the evaluation of the CHP or the CCHP system for informing the users about the competitiveness of these cogeneration systems. Most of these studies have focused on merely one aspect of the CHP or CCHP systems, i.e. economic benefit analysis or environmental impact assessment. For instance, Maraver *et al.* employed life cycle assessment to evaluate the environmental feasibility of CCHP systems [3]. Ruzzenenti *et al.* investigated the environmental sustainability of a micro-CHP system through life cycle analysis and exergy life cycle analysis [7]. Jiang *et al.* studied the greenhouse gas emissions of CCHP systems by adopting a multi-product carbon footprint [8].

Some studies have also focused on two or three aspects of the CHP or the CCHP systems. For instance, Kong *et al.* investigated the energy efficiency and analyzed the economic feasibility of a small-scale trigeneration system for CCHP generation [9]. Xu and Qu studied the energy, environmental, and economic performances of the CCHP systems by quantifying the primary energy consumption reduction, CO_2 equivalent emissions, and operational costs [10]. However, Pilavachi *et al.* pointed out that the evaluation of CHP system is a difficult task, and many aspects including economic, social, and environmental concerns should be considered by the decision-makers [11]. Multi-criteria decision-making has been widely used in the energy field. For instance, Vafaeipour *et al.* employed the step-wise weight assessment ratio analysis (SWAMA) to calculate the regional priority for the implementation of solar projects in Iran [12]. Islam *et al.* employed PROMETHEE-GAIA to investigate the effects of the fatty acid profile on fuel properties [13]. Wu and Geng used an analytic hierarchy process (AHP) method to select the location of solar–wind hybrid power stations [14]. Wu *et al.* employed the intuitionistic fuzzy ELECTRE-III method to select the sites for offshore wind power stations [15].

As for the selection of the best or the most sustainable CCHP scenario among multiple systems, there are various multi-criteria decision-making methods that have been developed for the comprehensive evaluation of CCHP systems. Wang *et al*. employed the fuzzy multi-criteria decision-making model (FMCDM) for trigeneration systems selection and evaluation, and triangular fuzzy numbers were used to quantify the data with respect to the soft criteria [16]. Jing *et al*. developed an evaluation model by combining fuzzy theory and multi-criteria decision analysis process for comprehensive analysis of CCHP systems from technology, economic, social, and environmental criteria [17]. Wang *et al.* carried out a multi-criteria analysis of CCHP systems including primary energy saving, CO_2 emission reduction, and annual total cost saving in different climate zones in China [18]. Jing and Zhang developed the weighting methodologies for multi-criteria evaluation of CHP systems [19]. Streimikiene and Baležentis employed the interval technique for order of preference by similarity to ideal solution (TOPSIS) that can address the uncertainties in decision-making to rank the small-scale CHP systems [20]. Nieto-Morote *et al*. developed a fuzzy weighted sum method (WSM) based on fuzzy AHP to prioritize the trigeneration system [21]. Ebrahimi and Keshavarz employed the fuzzy logic and gray incidence methods to select the best prime mover for a micro-CCHP system [22]. All these studies assist the user in selecting the best CCHP system among multiple alternatives; however, there are still some research gaps that should be filled.

(1) A method that is easy and convenient for the decision-makers to express their opinions and capture the vagueness and ambiguity existing in human's judgments on determining the weights of the criteria for the evaluation of CCHP systems is needed.
(2) The interdependences and interactions among the criteria for the evaluation of CCHP systems should be considered when determining the weights of the criteria; however, these criteria are usually assumed to be independent.
(3) A method for quantifying the data of the alternative CCHP systems with respect to the soft criteria that cannot be depicted by numbers with units is also needed.
(4) There are various uncertainties existing in the evaluation of CCHP systems caused by inherent variations, human errors, data estimations, and lack of knowledge, i.e. the economic uncertainties due to the variations of the price of raw materials, environmental uncertainties due to the imprecise measurement of environmental impacts, and the safety uncertainties due to the change of system reliability and stability. A method that can address uncertainties in multi-criteria decision-making is needed.

To develop a method that can fill the above-mentioned gaps, a novel interval multi-criteria decision-making method has been developed in this study that combines interval ANP and interval TOPSIS methods. Interval ANP can incorporate the interdependences and interactions among the criteria for sustainability assessment, and also allows the users to use interval numbers instead of crisp numbers to express their opinions, so has been employed here to determine the weights of the criteria. Meanwhile, Interval AHP was also used to determine the relative performances of the alternative CCHP systems with respect to the soft criteria. Interval AHP method allows the users to use the imprecise information in the format of interval numbers to provide their preference judgments for establishing the pair-wise comparison matrix [23]. Despotis and Derpanis developed a min–max goal programming (GP) approach to priority deviation in AHP with interval judgments [23]. Wang and Elhag developed a novel method of priorities/weights determination by minimizing the overall inconsistency of the comparison matrix composed by the interval numbers [24]. Owing to its advantage of optimizing the overall consistency, the interval AHP developed by Wang and Elhag has been widely used in many fields [24]. Therefore, this interval AHP method was employed to determine the weights of the criteria for sustainability assessment of CCHP systems in this study. An interval TOPSIS method was employed to determine the sustainability sequence of the alternative CCHP systems. The developed multi-criteria decision analysis method for sustainability assessment of CCHP systems has the following innovations:

(1) A novel interval ANP which can not only capture the interdependences and interactions among the criteria for sustainability assessment but also address the vagueness and ambiguity existing in human's judgments was developed for weights determination by combining the interval AHP developed by Wang and Elhag [24] and the thoughts of the traditional ANP method;
(2) All the elements in the decision-making matrix are interval numbers rather than crisp values, and using interval numbers to depict the relative performances of the alternative CCHP systems with respect to the evaluation criteria can effectively address the uncertainties in sustainability assessment and decision-making.

The remainder of this article has been organized as follows: Section 2 presents the interval multi-criteria decision-making method; an illustrative case study is presented in Section 3; the results are discussed in Section 4; and, finally, the conclusions are presented in Section 5.

2. Methods

Interval numbers are introduced in this section; subsequently, the interval ANP method is presented; then, the interval TOPSIS is developed for sustainability assessment of CCHP systems under uncertainties.

2.1 Interval numbers

Let $a=\left[a^{-},a^{+}\right]=\left\{x\middle|a^{-}\leq x\leq a^{+},a^{-}\leq a^{+},a^{-},a^{+}\in R\right\}$. Here $a=\left[a^{-},a^{+}\right]$ is called an interval number and is a positive interval number if $0\leq a^{-}\leq a^{+}$ (see [25]). It is apparent that an interval number can take an arbitrary value between its lower bound and upper bound.

Definition 1 Distance between two interval numbers [25]

If $a=\left[a^{-},a^{+}\right]$ and $b=\left[b^{-},b^{+}\right]$ are two arbitrary interval numbers, the distance from $a=\left[a^{-},a^{+}\right]$ to $b=\left[b^{-},b^{+}\right]$ can be determined by

$$|a-b|=\max\left(\left|a^{-}-b^{-}\right|,\left|a^{+}-b^{+}\right|\right) \quad (1)$$

Definition 2 Number product between a positive real number and an interval number [25]

The number product of a positive real number k and an interval number $a=\left[a^{-},a^{+}\right]$ is defined as

$$k\bullet a=k\left[a^{-},a^{+}\right]=\left[ka^{-},k\,a^{+}\right] \tag{2}$$

Note that a crisp number k could also be transformed into an interval number $k=\left[k,k\right]$.

Definition 3 Addition [26]

If $a=\left[a^{-},a^{+}\right]$ and $b=\left[b^{-},b^{+}\right]$ are two arbitrary interval numbers, the sum of the two interval numbers can be obtained by

$$a+b=\left[a^{-},a^{+}\right]+\left[b^{-},b^{+}\right]=\left[a^{-}+b^{-},a^{+}+b^{+}\right] \tag{3}$$

Definition 4 Subtraction [27, 28]

If $a=\left[a^{-},a^{+}\right]$ and $b=\left[b^{-},b^{+}\right]$ are two arbitrary interval numbers, the subtraction between two interval numbers can be determined by

$$a-b=\left[a^{-},a^{+}\right]-\left[b^{-},b^{+}\right]=\left[a^{-}-b^{+},a^{+}-b^{-}\right] \tag{4}$$

Definition 5 Multiplication [25]

If $a=\left[a^{-},a^{+}\right]$ and $b=\left[b^{-},b^{+}\right]$ are two arbitrary interval numbers, the interval product can be obtained according to the following two cases:

(1) when $b^{+}>0$, the interval product can be determined by

$$a \times b = \left[a^-, a^+\right] \times \left[b^-, b^+\right] = \left[a^- b^-, a^+ b^+\right] \quad (5)$$

(2) when $b^+ < 0$, the interval product can be determined by

$$a \times b = \left[a^-, a^+\right] \times \left[b^-, b^+\right] = \left[a^+ b^-, a^- b^+\right] \quad (6)$$

Definition 6 The possibility of an interval being greater than another

For two arbitrary interval numbers $a = \left[a^-, a^+\right]$ and $b = \left[b^-, b^+\right]$, the possibilities that $a \geq b$ and that $b \geq a$ are defined in the following two equations, respectively [29, 30]:

$$P(a \geq b) = \frac{\max\left\{0, a^U - b^L\right\} - \max\left\{0, a^L - b^U\right\}}{a^U - a^L + b^U - b^L} \quad (7)$$

$$P(b \geq a) = \frac{\max\left\{0, b^U - a^L\right\} - \max\left\{0, b^L - a^U\right\}}{a^U - a^L + b^U - b^L} \quad (8)$$

2.2 Interval analytic network process

The traditional AHP method relies on using the numbers from 1 to 9 and their reciprocals to establish the comparison matrix to determine the weights of the criteria [31]. In the nine-scale system, “1,” “3,” “5,” “7,” and “9” represent that the relative importance of a criterion over another is of “equal importance,” “moderate importance,” “essential importance,” “very strong importance,” and “absolute importance,” respectively. The intermediate values such as 2, 4, 6, and 8 represent that the relative importance of a criterion over another is between two adjacent judgments. For instance, if a decision-maker held the view that the relative importance of a criterion over another is between “moderate importance” (corresponding to 3) and “essential importance” (corresponding to 5), then “4” will be used to describe the relative importance in the comparison matrix. However, it can still be difficult for the decision-maker to use a single crisp value to express their opinions due to the ambiguity, subjectivity, and vagueness existing in human judgments [32]. For instance, if the decision-makers held the view that the relative importance of a criterion over another is between "moderate importance" (corresponding to 3) and "very strong importance" (corresponding to 7), then they cannot find a suitable number among the numbers from 1 to 9 or their reciprocals. However, the users can use the interval $\left[3,7\right]$ to express their opinions accurately in this case. Accordingly, various modified AHP methods by integrating with interval numbers, so-called "interval AHP," that uses interval numbers rather than crisp numbers to establish the comparison matrix, have been developed. Mazurek developed an interval AHP based on an interval comparison matrix, and a geometric mean method was employed to determine the priority vector in this method [33]. Entani and Inuiguchi developed an interval AHP method for determining the interval weights by minimizing the uncertainty of interval probabilities to obtain the least uncertain probabilities [34, 35]. Wang *et al*. [29, 30] developed a two-stage logarithmic programming (TLGP) method to generate weights from interval comparison matrices. Wang and Elhag developed a GP method to determine the interval weights from the interval comparison matrices [24]. Among these methods, the GP method is the most widely used as it has three advantages: (1) it can ensure that the interval weights obtained by this method are normalized; (2) it can generate weights for both crisp and interval comparison matrices; and (3) it can generate weights regardless of the consistency level of the comparison matrix. Therefore, the interval AHP based on a GP method was employed to determine the weights of the four aspects of sustainability including economic, environmental, technological, and social aspects [32] and the local weights of the criteria in each aspect.

After determining the weights of the four aspects of sustainability and the weights of the criteria in each aspect, the global weights of each criterion for sustainability assessment can be determined by calculating the product of the local weight of each criterion and that of the aspect to which the criterion belongs [36, 37]. However, the global weights determined by this method cannot accurately reflect the relative importance of the criteria, because this method assumes that all the criteria are independent, while there are usually various interdependences and interactions among these criteria for sustainability assessment [38]. For instance, the "advancement of technology" of a CCHP system has significant impact on "safety," and the more advanced the technology, the safer the CCHP system. Therefore, the assumption that all the criteria for sustainability are independent is incorrect, and this will also lead to inaccurate weights. ANP is an improved AHP method for dealing with the problems with functional dependences and feedbacks [39]. Therefore, a novel interval ANP that integrates the interval AHP based on a GP method and the methods of ANP has been developed in this study.

The interval ANP is based on the interval AHP based on GP, and the ideas used in the interval AHP method were borrowed from Wang and Elhag [24]. There are three steps in the proposed interval ANP method as follows.

Step 1: Determining the relative importance (weights) of the factors through interval AHP based on GP by assuming that there is no dependence among the factors.

Sub-step 1: Establishing the interval decision-making matrix.

Assume that there are n factors ($i = 1, 2, \ldots, n$) to be studied, and the decision-makers use interval numbers rather than crisp numbers to depict the relative importance of the ith factor over the jth factor. The interval comparison matrix for the n factors is

$$A = \begin{vmatrix} 1 & [l_{12}, u_{12}] & \cdots & [l_{1n}, u_{1n}] \\ [l_{21}, u_{21}] & 1 & \cdots & [l_{2n}, u_{2n}] \\ \vdots & \cdots & \ddots & \vdots \\ [l_{n1}, u_{n1}] & [l_{n2}, u_{n2}] & \cdots & 1 \end{vmatrix} \quad (9)$$

$$l_{ij} = \frac{1}{u_{ij}} \quad i, j = 1, 2, \cdots, n; i \neq j \tag{10}$$

$$u_{ij} = \frac{1}{l_{ij}} \quad i, j = 1, 2, \cdots, n; i \neq j \tag{11}$$

where $\left[l_{ij}, u_{ij}\right]$ represents the relative importance of the *i*th criterion over the *j*th criterion, and l_{ij} and u_{ij} are the lower and upper bounds of the interval number $\left[l_{ij}, u_{ij}\right]$, respectively.

Sub-step 2: Decomposing the fuzzy comparison matrix into two crisp nonnegative matrices.

The fuzzy comparison matrix in Eq. (9) can be decomposed into two crisp nonnegative matrices,

$$A_L = \begin{vmatrix} 1 & l_{12} & \cdots & l_{1n} \\ l_{21} & 1 & \cdots & l_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ l_{n1} & l_{n2} & \cdots & 1 \end{vmatrix} \tag{12}$$

$$A_U = \begin{vmatrix} 1 & u_{12} & \cdots & u_{1n} \\ u_{21} & 1 & \cdots & u_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u_{n1} & u_{n2} & \cdots & 1 \end{vmatrix} \tag{13}$$

Sub-step 3: Determining the interval weights of the criteria.

Wang and Elhag [24] developed a linear programming (LP) by minimizing the degree of inconsistency of the interval comparison matrix for obtaining the interval weights of *n* factors, as presented in the following equations:

$$Minimize \quad D = e^T (E^+ + E^- + \Gamma^+ + \Gamma^-) \tag{14}$$

$$(A_L - I)W_U - (n-1)W_L - E^{+} + E^{-} = 0 \tag{15}$$

$$(A_U - I)W_L - (n-1)W_U - \Gamma^{+} + \Gamma = 0 \tag{16}$$

$$\omega_i^L + \sum_{j=1, j\neq ?}^{n} \omega_j^U \geq 1, i = 1, 2, \cdots, n \tag{17}$$

$$\omega_i^U + \sum_{j=1, j\neq ?}^{n} \omega_j^L \leq 1, i = 1, 2, \cdots, n \tag{18}$$

$$W_U - W_L \geq 0 \tag{19}$$

$$W_L, E^{+}, E^{-}, \Gamma^{+}, \Gamma^{-} \geq 0 \tag{20}$$

where $\omega_i^{\pm} = \left[\omega_i^L \quad \omega_i^U\right]$ represents the interval weight of the *i*th criterion, ω_i^L and ω_i^U being the lower and upper bounds of $\omega_i^{\pm}$, respectively. Here *D* represents the total deviations to reflect the degree of inconsistency of the interval comparison matrix A, $W_L = \left(\omega_1^L, \omega_2^L, \cdots, \omega_n^L\right)^T$, and $W_U = \left(\omega_1^U, \omega_2^U, \cdots, \omega_n^U\right)^T$ are the lower bound and upper bound weight vectors, respectively, $e^T = \left(1, 1, \cdots, 1\right)$, $E^{+} = \left(\varepsilon_1^{+}, \varepsilon_2^{+}, \cdots, \varepsilon_n^{+}\right)^T$, $E^{-} = \left(\varepsilon_1^{-}, \varepsilon_2^{-}, \cdots, \varepsilon_n^{-}\right)^T$, $\Gamma^{+} = \left(\gamma_1^{+}, \gamma_2^{+}, \cdots, \gamma_n^{+}\right)^T$, and $\Gamma^{-} = \left(\gamma_1^{-}, \gamma_2^{-}, \cdots, \gamma_n^{-}\right)^T$ are all nonnegative deviation vectors.

All the relative importance (weights) of the *n* factors $W_1 = \left(\left[\omega_1^L, \omega_1^U\right], \left[\omega_2^L, \omega_2^U\right], \cdots, \left[\omega_n^L, \omega_n^U\right]\right)^T$ can be determined based on the assumption that there is no interdependences and interactions among these factors.

Step 2: Determining the inner dependency matrix (D).

The elements of the *j*th column vector in matrix *D* represent the relative effects of the factors on the *j*th factor, and this vector can be obtained by establishing the interval comparison matrix with respect to the *j*th factor. Similarly, other column vectors in matrix *D* can also be obtained:

$$D = \begin{vmatrix} 1 & \left[d_{12}^{l}, d_{12}^{u}\right] & \cdots & \left[d_{1n}^{l}, d_{1n}^{u}\right] \\ \left[d_{21}^{l}, d_{21}^{u}\right] & 1 & \cdots & \left[d_{2n}^{l}, d_{2n}^{u}\right] \\ \vdots & \cdots & \ddots & \vdots \\ \left[d_{n1}^{l}, d_{n1}^{u}\right] & \left[d_{n2}^{l}, d_{n2}^{u}\right] & \cdots & 1 \end{vmatrix} \tag{21}$$

where *D* is the inner dependency matrix

It is worth pointing out that $\left[d_{ij}^{l}, d_{ij}^{u}\right] =$ $i, j = 1, 2, \cdots, n; i \neq j$ and is an interval that represents the relative effect of the *i*th factor on the *j*th factor, and all the diagonal elements in matrix *D* are equal to 1 according to [40, 41].

Step 3: Calculating the inter-dependent priorities of the *n* factors using

$$\mathrm{W}^{'} = D \times \mathrm{W}_{1} = \begin{vmatrix} 1 & \left[d_{12}^{l}, d_{12}^{u}\right] & \cdots & \left[d_{1n}^{l}, d_{1n}^{u}\right] \\ \left[d_{21}^{l}, d_{21}^{u}\right] & 1 & \cdots & \left[d_{2n}^{l}, d_{2n}^{u}\right] \\ \vdots & \cdots & \ddots & \vdots \\ \left[d_{n1}^{l}, d_{n1}^{u}\right] & \left[d_{n2}^{l}, d_{n2}^{u}\right] & \cdots & 1 \end{vmatrix} \times \begin{bmatrix} \left[\omega_{1}^{L}, \omega_{1}^{U}\right] \\ \left[\omega_{2}^{L}, \omega_{2}^{U}\right] \\ \vdots \\ \left[\omega_{n}^{L}, \omega_{n}^{U}\right] \end{bmatrix}$$
$$= \left(\left[\omega_{1,L}, \omega_{1,U}\right], \left[\omega_{2,L}, \omega_{2,U}\right], , \left[\omega_{n,L}, \omega_{n,U}\right]\right) \tag{22}$$

then normalizing the inter-dependent priorities of the *n* factors using

$$\mathrm{W} = \left(\left[\omega_{1,L} \Big/ \sum_{i=1}^{n} \omega_{i,U}, \omega_{1,U} \Big/ \sum_{i=1}^{n} \omega_{i,L},\right], \left[\omega_{2,L} \Big/ \sum_{i=1}^{n} \omega_{i,U}, \omega_{2,U} \Big/ \sum_{i=1}^{n} \omega_{i,L},\right], \cdots, \left[\omega_{n,L} \Big/ \sum_{i=1}^{n} \omega_{i,U}, \omega_{n,U} \Big/ \sum_{i=1}^{n} \omega_{i,L},\right]\right)$$

(23)

where W' represents weight vector of the inter-dependent priorities of the *n* factors, and W represents the normalized weight vector of the inter-dependent priorities of the *n* factors.

2.3 Interval TOPSIS

TOPSIS developed by Hwang and Yoon holds the view that the best alternative should have the shortest distance to the ideal solution (the hypothetical best solution) and the farthest distance to the anti-ideal solution (the hypothetical worst solution) [42].

Assume there are *m* alternatives and *n* evaluation criteria, then the decision-making matrix (*D*) can be expressed as in Table 1.

The interval TOPSIS consists of six steps including normalization, determination of the possibility degree matrix, calculation of the weighted normalized matrix, determination of the ideal solution vector and the anti-ideal solution vector, calculation of the closeness coefficients, and ranking the prior sequence. These can be specified as follows.

Step 1: Normalization.

The first step of interval TOPSIS is to normalize the data in the interval decision-making matrix. The data of the alternative CCHP systems with respect to different types of criteria should be normalized by different normalization methods.

As for the data of the alternatives with respect to the benefit criteria, they can be normalized by

$$a_{ij}^L = \frac{x_{ij}^L - \min\limits_{i=1,2,\cdots,m}\{x_{ij}^L\}}{\max\limits_{i=1,2,\cdots,m}\{x_{ij}^U\} - \min\limits_{i=1,2,\cdots,m}\{x_{ij}^L\}} \quad (\mathrm{i}=1,2,\ldots,\mathrm{m};\ \mathrm{j}\in B) \tag{24}$$

$$a_{ij}^{U} = \frac{x_{ij}^{U} - \min\limits_{i=1,2,\cdots,m}\left\{x_{ij}^{L}\right\}}{\max\limits_{i=1,2,\cdots,m}\left\{x_{ij}^{U}\right\} - \min\limits_{i=1,2,\cdots,m}\left\{x_{ij}^{L}\right\}} \quad (\mathrm{i}=1,2,\ldots,\mathrm{m};\ \mathrm{j} \in B) \tag{25}$$

As for the data of the alternatives with respect to the cost-criteria, they can be normalized by

$$a_{ij}^{L} = \frac{\max\limits_{i=1,2,\cdots,m}\left\{x_{ij}^{U}\right\} - x_{ij}^{U}}{\max\limits_{i=1,2,\cdots,m}\left\{x_{ij}^{U}\right\} - \min\limits_{i=1,2,\cdots,m}\left\{x_{ij}^{L}\right\}} \quad (\mathrm{i}=1,2,\ldots,\mathrm{m};\ \mathrm{j} \in C) \tag{26}$$

$$a_{ij}^{U} = \frac{\max\limits_{i=1,2,\cdots,m}\left\{x_{ij}^{U}\right\} - x_{ij}^{L}}{\max\limits_{i=1,2,\cdots,m}\left\{x_{ij}^{U}\right\} - \min\limits_{i=1,2,\cdots,m}\left\{x_{ij}^{L}\right\}} \quad (\mathrm{i}=1,2,\ldots,\mathrm{m};\ \mathrm{j} \in C) \tag{27}$$

where $a_{ij} = \left[a_{ij}^{L}, a_{ij}^{U}\right]$ is the normalized value of the *i*th alternative with respect to the *j*th criterion, B is the set of the benefit criteria representing the criteria that have the characteristic that the greater the value with respect to these criteria, the more superior the alternative will be. While C denotes the set of the cost criteria representing the criteria have the characteristic that the greater the value with respect to these criteria, the more inferior the alternative will be.

In this step, the normalized decision-making matrix (A) can be determined using

$$A = \begin{vmatrix} \left[a_{11}^{L}, a_{11}^{U}\right] & \left[a_{12}^{L}, a_{12}^{U}\right] & \cdots & \left[a_{1n}^{L}, a_{1n}^{U}\right] \\ \left[a_{21}^{L}, a_{21}^{U}\right] & \left[a_{22}^{L}, a_{22}^{U}\right] & \vdots & \left[a_{2n}^{L}, a_{2n}^{U}\right] \\ \vdots & \vdots & \ddots & \vdots \\ \left[a_{m1}^{L}, a_{m1}^{U}\right] & \left[a_{m2}^{L}, a_{m2}^{U}\right] & \cdots & \left[a_{mn}^{L}, a_{mn}^{U}\right] \end{vmatrix} \tag{28}$$

Step 2: Calculation of the weighted normalized matrix (WND)

$$Y = \begin{vmatrix} \left[y_{11}^L, y_{11}^U\right] & \left[y_{12}^L, y_{12}^U\right] & \cdots & \left[y_{1n}^L, y_{1n}^U\right] \\ \left[y_{21}^L, y_{21}^U\right] & \left[y_{22}^L, y_{22}^U\right] & \vdots & \left[y_{2n}^L, y_{2n}^U\right] \\ \vdots & \vdots & \ddots & \vdots \\ \left[y_{m1}^L, y_{m1}^U\right] & \left[y_{m2}^L, y_{m2}^U\right] & \cdots & \left[y_{mn}^L, y_{mn}^U\right] \end{vmatrix} \tag{29}$$

$$\left[y_{ij}^L, y_{ij}^U\right] = \left[a_{ij}^L, a_{ij}^U\right] \times \left[w_j^l, w_j^u\right] = \left[a_{ij}^L w_j^l, a_{ij}^U w_j^u\right], i = 1, 2, \cdots, m;\ j = 1, 2, \cdots, n \tag{30}$$

where $\left[w_j^l, w_j^u\right]$ is the final weight of the *j*th criterion that is calculated by interval ANP in this study, $\left[y_{ij}^L, y_{ij}^U\right], i = 1, 2, \cdots, m;\ j = 1, 2, \cdots, n$ is the element in the weighted normalized matrix

Step 3: Determination of the possibility degree matrix.

In this step, a base interval will be selected for transforming the interval decision-making matrix presented in Eq. (28) into a crisp decision-making matrix [43]. Here $\left[y_{ij}^L, y_{ij}^U\right]$ $i = 1, 2, \cdots, m; j = 1, 2, \cdots, n$ can be transformed into a crisp number using

$$base_j^L = \min_{i=1,2,\cdots,m} y_{ij}^L \qquad j = 1, 2, \cdots, n \tag{31}$$

$$base_j^U = \max_{i=1,2,\cdots,m} y_{ij}^U \qquad j = 1, 2, \cdots, n \tag{32}$$

$$p_{ij} = P(\left[y_{ij}^L, y_{ij}^U\right] \geq \left[base_j^L, base_j^U\right]) = \frac{\max\left\{0, y_{ij}^U - base_j^L\right\} - \max\left\{0, y_{ij}^L - base_j^U\right\}}{y_{ij}^U - y_{ij}^L + base_j^U - base_j^L} \tag{33}$$

Equations (31) and (32) aim to determine the base interval $\left[base_j^L, base_j^U\right]$, and Eq. (33) transforms the interval numbers in the interval decision-making matrix into crisp numbers by calculating the possibility of $\left[y_{ij}^L, y_{ij}^U\right]$ being greater than $\left[base_j^L, base_j^U\right]$.

After this step, the interval decision-making matrix presented in Eq. (28) can be transformed into a crisp-number-based decision-making matrix (CNDM):

$$CNDM = \begin{vmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \vdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mn} \end{vmatrix}, i = 1, 2, \cdots, m;\ j = 1, 2, \cdots, n \tag{34}$$

Note that the possibility degree matrix determined based on Eq. (31) is the same as that determined based on Eq. (28). In other words, the users can use Eq. (28) to determine the possibility degree matrix directly.

Step 4: Determination of the ideal solution vector and the anti-ideal solution vector.

The ideal solutions (ideal best solution) P_j^+ could be calculated using

$$P_j^+ = \max_{i=1,2,\cdots,m}\left(p_{ij}\right) \tag{35}$$

The anti-ideal solutions (hypothetical worst solution) P_j^- could be calculated using

$$P_j^+ = \min_{i=1,2,\cdots,m}\left(p_{ij}\right) \tag{36}$$

Step 5: Determining the closeness coefficients and ranking the alternatives.

Minkowski's distance [44] was used to determine the distance from each alternative to the ideal solution P_j^+, and also that from each alternative to the anti-ideal solution P_j^-:

$$D_{i,L}^{+} = \left\{ \sum_{j=1}^{n} \left[w_j^L (p_{ij} - P_j^+) \right]^2 \right\}^{1/2} \quad (37)$$

$$D_{i,U}^{+} = \left\{ \sum_{j=1}^{n} \left[w_j^U (p_{ij} - P_j^+) \right]^2 \right\}^{1/2} \quad (38)$$

$$D_{i,L}^{-} = \left\{ \sum_{j=1}^{n} \left[w_j^L (p_{ij} - P_j^-) \right]^2 \right\}^{1/2} \quad (39)$$

$$D_{i,U}^{-} = \left\{ \sum_{j=1}^{n} \left[w_j^U (p_{ij} - P_j^-) \right]^2 \right\}^{1/2} \quad (40)$$

where D_i^+ and D_i^- are the distance to the best ideal and the worst ideal solutions

The closeness coefficient (C_i) of each alternative can be determined using

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} = \left[\frac{D_{i,U}^-}{D_{i,U}^+ + D_{i,U}^-}, \frac{D_{i,U}^+}{D_{i,L}^+ + D_{i,L}^-} \right] \quad (41)$$

where C_i represents the closeness coefficient of the *i*th alternative.

According to Eqs. (7) and (8), the closeness coefficients can be ranked. Then, the priority sequence of the alternative can be determined according to the rule that the larger the closeness coefficient is, the better the alternative will be.

3 Case study

To illustrate the proposed method for sustainability assessment of CCHP systems, five alternative CCHP systems for the cooling, heating, and power of a typical five-story building in Shanghai have been studied in this study, and they are [45]:

A_1, Stirling engine＋direct fired absorption water heater/chiller unit;

A_2, combination of micro gas turbine, waste heat afterburning absorption-type water chiller–heater unit, and heat recovery boiler;

A_3, small natural gas internal combustion engine ＋ waste heat afterburning absorption refrigerator;

A_4, solid electrolyte fuel cell (SOFC) ＋ waste heat afterburning absorption refrigerator;

A_5, cooling, heating, and electricity supply separately through purchase.

Pope *et al*. pointed out that sustainability assessment is usually a kind of "integrated assessment" derived from "environmental impact assessment" and is also extended to incorporate economic and social considerations as well as environmental ones [46]. Thus, sustainability assessment of CCHP systems should also simultaneously consider economic, environmental, and social considerations. However, some other aspects of concerns, i.e. technological and political factors, should also be incorporated into sustainability assessment, because these factors can usually effect the factors belonging to the three pillars of sustainability assessment [47]. For more information, the authors can refer to the work of Al Moussawi *et al.* including energy criteria, exergy criteria, economy criteria, and environmental criteria [48].

Based on literature reviews and focus group meeting, a criteria system with twelve criteria in four aspects was used for sustainability assessment of CCHP systems. There are four criteria including investments cost (C_1), payback period (C_2), total annual cost (C_3), and net present value (C_4) in economic aspect. Environmental aspect also consists of four criteria, and they are NO_x emission (C_5), CO emission (C_6), CO_2 emission (C_7), and noise (C_8). Technology advancement (C_9), safety (C_{10}), and convenience for maintenance (C_{11}) are the three criteria of the technological aspect. Social acceptability is the only criterion to measure the social dimension of sustainability. It is worth pointing out that the users can add more criteria or delete some criteria for sustainability assessment of CCHP systems according to the actual conditions and their preferences.

The data of the alternatives with respect to the hard criteria including investments cost (C_1), payback period (C_2), total annual cost (C_3), and net present value (C_4) in the economic aspect, NO_x emission (C_5), CO emission (C_6), CO_2 emission (C_7), and noise (C_8) in the environmental aspect were modified from the literature [45], while other data (the relative performances) of the five alternative CCHP systems with respect to the soft criteria that can only be depicted by using linguistic terms rather than using the quantitative numbers with units to measure them, and the soft criteria include technology advancement (C_9), safety (C_{10}), and convenience for maintenance (C_{11}) in the technological aspect, and social acceptability (C_{12}) were determined by LP-based interval AHP.

The relative performances of the alternatives with respect to technology advancement (C_9) were taken as an example to illustrate the method to use interval AHP to determine the relative priorities.

The interval comparison matrix (Table 2) can be decomposed into two matrices according to Eqs. (12) and (13): A_L and A_U. The results are

$$A_L = \begin{vmatrix} 1 & 1 & 3 & 1/2 & 3 \\ 1/2 & 1 & 2 & 1/3 & 2 \\ 1/4 & 1/3 & 1 & 1/5 & 1 \\ 1 & 2 & 3 & 1 & 5 \\ 1/5 & 1/4 & 1/3 & 1/7 & 1 \end{vmatrix} \tag{42}$$

$$A_U = \begin{vmatrix} 1 & 2 & 4 & 1 & 5 \\ 1 & 1 & 3 & 1/2 & 4 \\ 1/3 & 1/2 & 1 & 1/3 & 3 \\ 2 & 3 & 5 & 1 & 7 \\ 1/3 & 1/2 & 1 & 1/5 & 1 \end{vmatrix} \tag{43}$$

Subsequently, the LP for minimizing the degree of inconsistency of the fuzzy comparison matrix can be obtained according to Eqs. (14)–(20), as presented in Eqs. (44)-(50)

$$\begin{aligned} &Minimize \quad D = \varepsilon_1^+ + \varepsilon_2^+ + \varepsilon_3^+ + \varepsilon_4^+ + \varepsilon_5^+ + \varepsilon_1^- + \varepsilon_2^- + \varepsilon_3^- + \varepsilon_4^- + \varepsilon_5^- \\ &+\gamma_1^+ + \gamma_2^+ + \gamma_3^+ + \gamma_4^+ + \gamma_5^+ + \gamma_1^- + \gamma_2^- + \gamma_3^- + \gamma_4^- + \gamma_5^- \end{aligned} \tag{44}$$

$$\begin{aligned} &\omega_2^U + 3\omega_3^U + \frac{1}{2}\omega_4^U + 3\omega_5^U - 4\omega_1^L - \varepsilon_1^+ + \varepsilon_1^- = 0 \\ &\frac{1}{2}\omega_1^U + 2\omega_3^U + \frac{1}{3}\omega_4^U + 2\omega_5^U - 4\omega_2^L - \varepsilon_2^+ + \varepsilon_2^- = 0 \\ &\frac{1}{4}\omega_1^U + \frac{1}{3}\omega_2^U + \frac{1}{5}\omega_4^U + \omega_5^U - 4\omega_3^L - \varepsilon_3^+ + \varepsilon_3^- = 0 \\ &\omega_1^U + 2\omega_2^U + 3\omega_3^U + 5\omega_5^U - 4\omega_4^L - \varepsilon_4^+ + \varepsilon_4^- = 0 \\ &\frac{1}{5}\omega_1^U + \frac{1}{4}\omega_2^U + \frac{1}{3}\omega_3^U + \frac{1}{7}\omega_4^U - 4\omega_5^L - \varepsilon_4^+ + \varepsilon_4^- = 0 \end{aligned} \tag{45}$$

$$
\begin{aligned}
&2\omega_2^L + 4\omega_3^L + \omega_4^L + 5\omega_5^L - 4\omega_1^U - \gamma_1^+ + \gamma_1^- = 0 \\
&\omega_1^L + 3\omega_3^L + \frac{1}{2}\omega_4^L + 4\omega_5^L - 4\omega_2^U - \gamma_2^+ + \gamma_2^- = 0 \\
&\frac{1}{3}\omega_1^L + \frac{1}{2}\omega_2^L + \frac{1}{3}\omega_4^L + 3\omega_5^L - 4\omega_3^U - \gamma_3^+ + \gamma_3^- = 0 \\
&2\omega_1^L + 3\omega_2^L + 5\omega_3^L + 7\omega_5^L - 4\omega_4^U - \gamma_4^+ + \gamma_4^- = 0 \\
&\frac{1}{3}\omega_1^L + \frac{1}{2}\omega_2^L + \omega_3^L + \frac{1}{5}\omega_4^L - 4\omega_5^U - \varepsilon_4^+ + \varepsilon_4^- = 0
\end{aligned}
\tag{46}
$$

$$
\begin{aligned}
&\omega_1^L + \omega_2^U + \omega_3^U + \omega_4^U + \omega_5^U \geq 1 \\
&\omega_2^L + \omega_1^U + \omega_3^U + \omega_4^U + \omega_5^U \geq 1 \\
&\omega_3^L + \omega_1^U + \omega_2^U + \omega_4^U + \omega_5^U \geq 1 \\
&\omega_4^L + \omega_1^U + \omega_2^U + \omega_3^U + \omega_5^U \geq 1 \\
&\omega_5^L + \omega_1^U + \omega_2^U + \omega_3^U + \omega_4^U \geq 1
\end{aligned}
\tag{47}
$$

$$
\begin{aligned}
&\omega_1^U + \omega_2^L + \omega_3^L + \omega_4^L + \omega_5^L \leq 1 \\
&\omega_2^U + \omega_1^L + \omega_3^L + \omega_4^L + \omega_5^L \leq 1 \\
&\omega_3^U + \omega_1^L + \omega_2^L + \omega_4^L + \omega_5^L \leq 1 \\
&\omega_4^U + \omega_1^L + \omega_2^L + \omega_3^L + \omega_5^L \leq 1 \\
&\omega_5^U + \omega_1^L + \omega_2^L + \omega_3^L + \omega_4^L \leq 1
\end{aligned}
\tag{48}
$$

$$
\begin{aligned}
&\omega_1^U - \omega_1^L \geq 0 \\
&\omega_2^U - \omega_2^L \geq 0 \\
&\omega_3^U - \omega_3^L \geq 0 \\
&\omega_4^U - \omega_4^L \geq 0 \\
&\omega_5^U - \omega_5^L \geq 0
\end{aligned}
\tag{49}
$$

$$\begin{aligned}
&\left(\omega_1^L,\omega_2^L,\omega_3^L,\omega_4^L,\omega_5^L\right)^T \geq 0\\
&\left(\varepsilon_1^+,\varepsilon_2^+,\varepsilon_3^+,\varepsilon_4^+,\varepsilon_5^+\right)^T \geq 0\\
&\left(\varepsilon_1^-,\varepsilon_2^-,\varepsilon_3^-,\varepsilon_4^-,\varepsilon_5^-\right)^T \geq 0\\
&\left(\gamma_1^+,\gamma_2^+,\gamma_3^+,\gamma_4^+,\gamma_5^+\right)^T \geq 0\\
&\left(\gamma_1^-,\gamma_2^-,\gamma_3^-,\gamma_4^-,\gamma_5^-\right)^T \geq 0
\end{aligned} \tag{50}$$

The optimum value of the objective is $D = 0.0236 \neq 0$; thus, this matrix can be regarded as a consistent matrix though it is not an absolute consistent matrix according to [24], because the value is very close to 0. Accordingly, the relative performances of the alternatives with respect to technology advancement (C_9) can be determined, and they are [0.2294 0.2902], [0.1562 0.1980], [0.0731 0.0995], [0.3385 0.3994], and [0.0435, 0.0738], respectively. In a similar way, the relative priorities of the five alternative CCHP systems with respect to safety (C_{10}), and convenience for maintenance (C_{11}) in technological aspect, and social acceptability (C_{12}) can also be determined, and the results are presented in Table 3.

After obtaining the data of all the five alternative CCHP systems with respect to safety (C_{10}) and convenience for maintenance (C_{11}) in the technological aspect, and social acceptability (C_{12}) in social aspect, the data of all the alternatives with respect to the twelve criteria can be obtained, as presented in Table 4.

To obtain the weights of the twelve criteria for sustainability assessment, interval ANP was first used to determine the weights of the four aspects of sustainability with the assumption that all the four aspects are independent, the relative weights of each aspect of sustainability on other aspects, and the relative weights of the criteria in each aspect. The interval comparison matrix for determining relative weights of the four aspects with the assumption that all four aspects are independent and the results are presented in Table 5. The interval weights of the four aspects of sustainability (economic, environmental, technological, and social) are [0.2339 0.3089], [0.1344 0.2040], [0.3631 0.4989], and [0.0982 0.1241], respectively.

In a similar way, the relative effects of the three aspects of sustainability on the other aspect can also be determined, as presented in Table 6. For instance, the relative effects of environmental (EN), technological (T), and social (S) on the economic (EC) are [0.2339 0.3089], [0.1344 0.2040], [0.3631 0.4989], and [0.0982 0.1241], respectively.

Then, the inner dependency matrix can be determined according to Eq. (21), as presented in Table 7.

Finally, according to Eqs. (22) and (23), the inter-dependent weights of the four aspects and that of the inter-dependent weights can be determined, and the results are presented

$$\begin{vmatrix} 1 & [0.1254, 0.2277] & [0.5639, 0.6640] & [0.4407, 0.5763] \\ [0.1171, 0.1485] & 1 & [0.1067, 0.1278] & [0.2373, 0.3898] \\ [0.5371, 0.6468] & [0.5545, 0.6964] & 1 & [0.1695, 0.1864] \\ [0.2361, 0.3143] & [0.1782, 0.2178] & [0.2292, 0.3083] & 1 \end{vmatrix} \times \begin{bmatrix} [0.2339, 0.3089] \\ [0.1344, 0.2040] \\ [0.3631, 0.4989] \\ [0.0982, 0.1241] \end{bmatrix} \tag{51}$$
$$= \left([0.4988, 0.7581], [0.2238, 0.3620], [0.5799, 0.8639], [0.2606, 0.4194]\right)$$

$$\left(\left[\frac{0.4988}{2.4035}, \frac{0.7581}{1.5631}\right], \left[\frac{0.2238}{2.4035}, \frac{0.3620}{1.5631}\right], \left[\frac{0.5799}{2.4035}, \frac{0.8639}{1.5631}\right], \left[\frac{0.2606}{2.4035}, \frac{0.4194}{1.5631}\right]\right) \tag{52}$$
$$= \left([0.2075, 0.4850], [0.0931, 0.2316], [0.2413, 0.5527], [0.1084, 0.2683]\right)$$

Therefore, the interval weights of the four aspects with the considerations of the interdependences and interactions among them are [0.2075 0.4850], [0.0931 0.2316], [0.2413 0.5527], and [0.1084 0.2683], respectively.

In a similar way, the local weights of the criteria in each aspect with the assumption that they are independent can also be determined, and the results are presented in Table 8. It is worth pointing out that there is only one criterion in the social aspect, so its local weight is equal to 1.

The global weight of each criterion for sustainability assessment of CCHP systems can be determined by calculating the product of the local weight of the criterion and the weight of the aspect to which it belongs to, and the results are presented in Table 9.

After determining the interval decision-making matrix, the novel interval TOPSIS has been employed to rank these five CCHP systems. According to Eqs. (24)–(27), the normalized interval decision-making matrix can be obtained, and the results are presented in Table 11. Note that the criteria including C_1, C_2, C_3, C_5, C_6, C_7, and C_8 are cost type, while the others (C_4, C_9, C_{10}, C_{11}, and C_{12}) are benefit type. Accordingly, the data of the alternatives with respect to C_4, C_9, C_{10}, C_{11}, and C_{12} can be normalized by Eqs. (24) and (25), and the data with respect to C_1, C_2, C_3, C_5, C_6, C_7, and C_8 can be normalized by Eqs. (26) and (27).

The weighted normalized decision-making matrix can also be determined by Eqs. (29) and (30). For instance, the weighted value of A_1 with respect to C_1 can be determined by

$$\left[0.7536\ 0.8822\right]\times\left[0.0341\ 0.1046\right]=\left[0.0257\ 0.0923\right] \qquad (53)$$

In a similar way, all the elements in Table 10 can be weighted, and the results were presented in Table 11.

According to Table 12, the base-intervals with respect to the twelve criteria can be determined by Eqs. (31) and (32). The base intervals with respect to C_1, C_2, C_3, C_5, C_6, C_7, C_8, C_4, C_9, C_{10}, C_{11}, and C_{12} are [0 0.1046], [0 0.0407], [0 0.1617], [0 0.0561], [0 0.0456], [0 0.1316], [0 0.0154], [0

0.2295], [0 0.1822], [0 0.3799], [0 0.0753], and [0 0.2683], respectively. According to Eqs. (33) and (34), the possibility degree matrix can be determined, as presented in Table 12.

The closeness coefficients of the five alternative CCHP systems can be determined according to Eqs. (35)–(41), and the results are presented in Table 13.

After determining the closeness coefficients, the closeness coefficients can be compared according to Eqs. (7) and (8), and the results are

$$\begin{array}{cccccc} & A_1 & A_2 & A_3 & A_4 & A_5 \\ A_1 & 0.5000 & 0.7940 & 0.2702 & 0 & 0.2504 \\ A_2 & 0.2060 & 0.5000 & 0 & 0 & 0 \\ A_3 & 0.7298 & 1 & 0.5000 & 0.1872 & 0.4795 \\ A_4 & 1 & 1 & 0.8128 & 0.5000 & 0.7933 \\ A_5 & 0.7496 & 1 & 0.5205 & 0.2067 & 0.5000 \end{array} \qquad (54)$$

It is apparent that A_4 is the most sustainable, and this is followed by A_5, A_3, A_1, and A_2 in descending order.

The results determined by the proposed method in this study are different from those determined by Huang *et al*. [45] for several reasons: (1) the uncertainties of the data have been considered in this study by modifying the original data presented in the work of Huang *et al*. [45]; (2) the weights of the criteria for sustainability assessment of CCHP systems used in this study are different from that used in the work of Huang *et al*. [45]; and (3) a novel interval TOPSIS addressing the interval decision-making matrix was used to rank the alternative CCHP systems rather than the gray rational analysis method dealing with the crisp decision-making matrix used in the work of Huang *et al*. [45].

4 Discussion

The weights used in multi-criteria decision-making usually have a significant impact on the final ranking. A sensitivity analysis has been performed to investigate the effects of the weights on the closeness coefficients of the five alternative CCHP systems by setting the thirteen hypothetical cases: **Case 1:** $w_1 = w_2 = w_3 \cdots = w_{12} = \frac{1}{12}$; **Case 2:** $w_1 = 0.45, w_2 = w_3 \cdots = w_{12} = 0.05$; **Case 3:** $w_2 = 0.45, w_1 = w_3 \cdots = w_{12} = 0.05$;...; **Case 13:** $w_{12} = 0.45, w_1 = w_2 \cdots = w_{11} = 0.05$ (the sequence of the dominant criterion that was assigned a weight of 0.45 is based on the sequence of the criteria presented in Table 11). After determining the possibility degree matrix, the traditional TOPSIS can be used to obtain the results because all of the elements in the weight vectors set in the sensitivity analysis are crisp numbers.

The results of sensitivity analysis are presented in Figure 1, and it is obvious that results are sensitive to the relative weights of the criteria for sustainability assessment of CCHP systems. Different stakeholders may obtain different results, because different stakeholders have different concerns and motivations that lead to different weights. Therefore, accurate determination of the weights in multi-criteria decision-making is of vital importance for the users to select the most sustainable scenario among multiple choices, and the interval AHP has the ability to address this.

To validate the results obtained by the proposed method, the WSM was also employed to rank the alternative CCHP systems according to their sustainability. After determining the weighted decision-making matrix according to Eq. (29) and Eq. (30), the integrated sustainability performances (ISPs) of the alternatives can be determined using

$$P_i = \sum_{j=}^{n} \left[y_{ij}^L, y_{ij}^U \right] \quad i = 1, 2, \cdots, m \tag{55}$$

Note the ISP of the *i*th CCHP system P_i is an interval number, and these alternatives can be ranked using Eqs. (7) and (8) to compare their ISP, and the results are presented in Table 14.

A_4 was also recognized as the most sustainable by the WSM method and this is consistent with that determined by the method posed in this study. However, the sequences of other alternatives determined by the two methods are different. There are several reasons: (1) although the WSM method can delete the dimensions of the data through normalization, the simple summation will lose some real information concerning the sustainability difference between each pair of alternatives; (2) the proposed interval TOPSIS method used the base intervals to determine the priority difference of the alternatives with respect to each criterion that can more accurately compare the relative integrated priorities of the alternatives.

5 Conclusion

This study has developed a method for ranking the alternative CCHP systems according to their sustainability performances. A novel interval multi-criteria decision-making method that can address uncertainties has been employed for sustainability prioritization of the alternative CCHP systems. Interval ANP in which the interferences and interactions among the criteria can be considered when determining the weights of the criteria and the users can use interval numbers to establish the comparison matrix has been employed to determine the weights of the criteria for sustainability assessment; meanwhile, interval AHP has been used to quantify the relative scores of the alternative CCHP systems with respect to the soft criteria. After determining the interval decision-making matrix, a novel interval TOPSIS has been employed to prioritize these alternatives. The proposed interval TOPSIS first determined the normalized interval decision-making matrix and the weighted interval decision-making matrix;

subsequently, the weighted interval decision-making matrix was transformed into a CNDM; then, the thought of the traditional TOPSIS was used to determine the interval closeness coefficients of the alternatives; finally, the priority sequence was determined by ranking the interval closeness coefficients.

All in all, the proposed method has the following advantages.

(1) Both the hard criteria and the soft criteria can be incorporated for sustainability assessment of the alternative CCHP systems, and the data of the alternative scenarios with respect to the soft criteria can be quantified in a relative way.

(2) The uncertainties in decision-making have also been incorporated. Unlike the traditional method, the elements in the decision-making matrix are intervals rather than crisp numbers.

(3) An interval AHP method can help the decision-makers to determine the weights of the criteria for sustainability assessment accurately.

In addition to the advantages, this study cannot incorporate the concerns and willingness of all the stakeholders. In other words, the method proposed here does not have the ability for group decision-making. The authors will develop an interval multi-actor multi-criteria decision-making model for sustainability assessment of CCHP systems in future.

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Figure captions

Figure 1: The results of sensitivity analysis

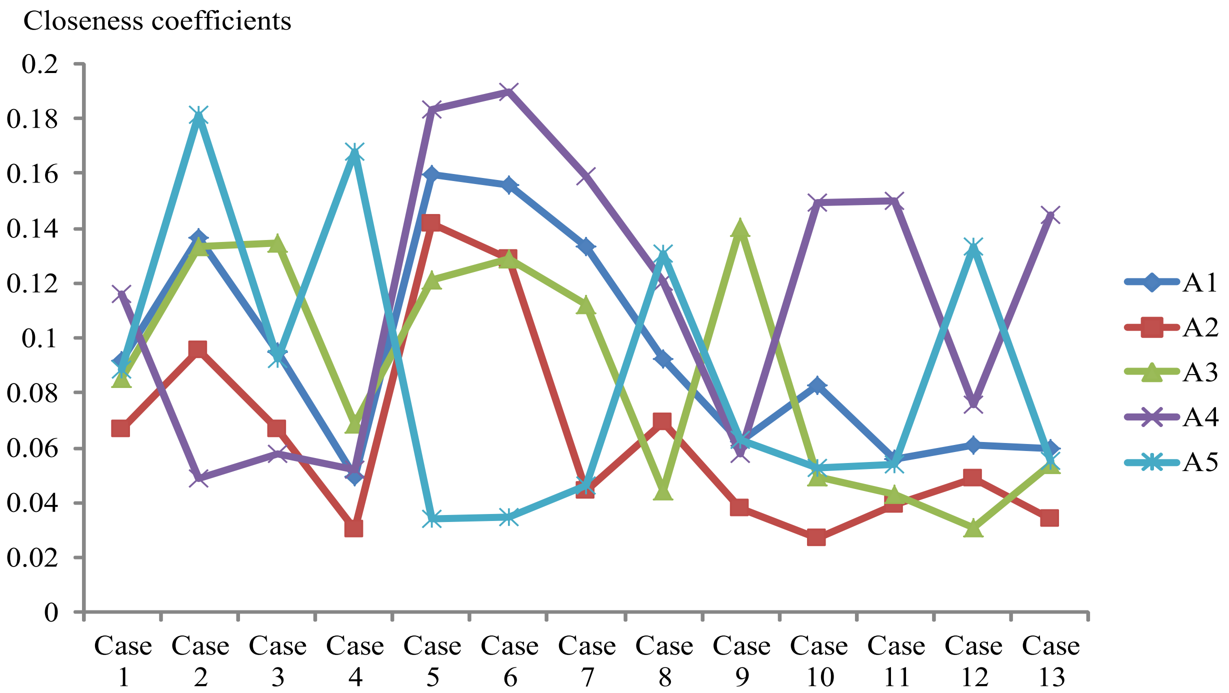

Figure 1: The results of sensitivity analysis

Table 1: Interval decision-making matrix

	C_1	C_2	$\cdots$	C_n
A_1	$\left[x_{11}^l, x_{11}^u\right]$	$\left[x_{12}^l, x_{12}^u\right]$	$\cdots$	$\left[x_{1n}^l, x_{1n}^u\right]$
A_2	$\left[x_{21}^l, x_{21}^u\right]$	$\left[x_{22}^l, x_{22}^u\right]$	$\cdots$	$\left[x_{2n}^l, x_{2n}^u\right]$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
A_m	$\left[x_{m1}^l, x_{m1}^u\right]$	$\left[x_{m2}^l, x_{m2}^u\right]$	$\cdots$	$\left[x_{mn}^l, x_{mn}^u\right]$
Weights	$\left[w_1^l, w_1^u\right]$	$\left[w_2^l, w_2^u\right]$	$\cdots$	$\left[w_n^l, w_n^u\right]$

where $\left[x_{ij}^l, x_{ij}^u\right]$ $i = 1, 2, \cdots, m; j = 1, 2, \cdots, n$ represents the value of the *i*-th alternative with respect to the *j*-th criterion, and $\left[w_j^l, w_j^u\right]$ $j = 1, 2, \cdots, n$ represents the interval weight of the *j*-th criterion.

Table 2: The interval comparison matrix for determining the relative priorities of the five alternative industrial systems with respect to technology advancement (C_9)

	A_1	A_2	A_3	A_4	A_5
A_1	1	[1 2]	[3 4]	[1/2 1]	[3 5]
A_2	[1/2 1]	1	[2 3]	[1/3 1/2]	[2 4]
A_3	[1/4 1/3]	[1/3 1/2]	1	[1/5 1/3]	[1 3]
A_4	[1 2]	[2 3]	[3 5]	1	[5 7]
A_5	[1/5 1/3]	[1/4 1/2]	[1/3 1]	[1/7 1/5]	1

Table 3: The interval comparison matrices for determining the relative priorities of the five alternative CCHP systems with respect to safety (C_{10}), and convenience for maintenance (C_{11}) in technological aspect, and social acceptability (C_{12}) in social aspect

C_{10}	A_1	A_2	A_3	A_4	A_5	Weights
A_1	1	1	[2 3]	[1/3 1]	[2 4]	[0.1828 0.2329]
A_2	1	1	[1 3]	[1/2 1]	[3 5]	[0.1874 0.2395]
A_3	[1/3 1/2]	[1/3 1]	1	[1/6 1/5]	[2 3]	[0.0893 0.1105]
A_4	[1 3]	[1 2]	[5 6]	1	[6 8]	[0.3527 0.4266]
A_5	[1/4 1/2]	[1/5 1/3]	[1/3 1/2]	[1/8 1/6]	1	[0.0309 0.0643]

C_{11}	A_1	A_2	A_3	A_4	A_5	Weights
A_1	1	[1/2 1]	[1/3 1/2]	[1/5 1/3]	[1/7 1/5]	[0.0570 0.0734]
A_2	[1 2]	1	[1/2 1]	[1/3 1/2]	[1/5 1/3]	[0.0860 0.1178]
A_3	[2 3]	[1 2]	1	[1/2 1]	[1/3 1/2]	[0.1371 0.1816]
A_4	[3 5]	[2 3]	[1 2]	1	[1/2 1]	[0.2114 0.2902]
A_5	[5 7]	[3 5]	[2 3]	[1 2]	1	[0.3435 0.4158]

C_{12}	A_1	A_2	A_3	A_4	A_5	Weights
A_1	1	[2 3]	[4 6]	[1/3 1/2]	[5 7]	[0.2629 0.2739]
A_2	[1/3 1/2]	1	[1 3]	[1/5 1/3]	[3 5]	[0.1067 0.1511]
A_3	[1/6 1/4]	[1/3 1]	1	[1/7 1/5]	[1 2]	[0.0547 0.0814]
A_4	[2 3]	[3 5]	[5 7]	1	[7 9]	[0.4421 0.4990]
A_5	[1/7 1/5]	[1/5 1/3]	[1/2 1]	[1/9 1/7]	1	[0.0323 0.0515]

Table 4: The data of the five alternative CCHP systems with respect to the criteria for sustainability assessment

		A_1	A_2	A_3	A_4	A_5
C_1	Yuan	[428000 642000]	[544000 816000]	[403654.40 605481.60]	[1264000 1896000]	[232000 348000]
C_2	Year	[5.1360 7.7040]	[5.3040 7.9560]	[3.8880 5.8320]	[7.0400 10.56]	[5.3840 8.0760]
C_3	Yuan	[384109.60 576164.40]	[385099.20 577648.80]	[310280.80 465421.20]	[431304.80 646957.20]	[157743.20 236614.80]
C_4	Yuan	[42065.60 63098.40]	[22486.40 33729.60]	[437306.40 655959.60]	[-483703.20 -322468.80]	[25708.80 38563.20]
C_5	g/kWh	[0.1840 0.2760]	[0.1784 0.2676]	[0.5600 0.8400]	[0.0056 0.0084]	[2.56 3.84]
C_6	g/kWh	[0.36 0.54]	[0.48 0.72]	[0.64 0.96]	[0.0008 0.0012]	[3.20 4.80]
C_7	g/kWh	[320 480]	[471.20 706.80]	[344 516]	[289.60 434.40]	[560 840]
C_8	db	[52 78]	[52 78]	[64 96]	[48 72]	[44.80 67.20]
C_9	/	[0.2294 0.2902]	[0.1562 0.1980]	[0.0731 0.0995]	[0.3385 0.3994]	[0.0435, 0.0738]
C_{10}	/	[0.1828 0.2329]	[0.1874 0.2395]	[0.0893 0.1105]	[0.3527 0.4266]	[0.0309 0.0643]
C_{11}	/	[0.0570 0.0734]	[0.0860 0.1178]	[0.1371 0.1816]	[0.2114 0.2902]	[0.3435 0.4158]
C_{12}	/	[0.2629 0.2739]	[0.1067 0.1511]	[0.0547 0.0814]	[0.4421 0.4990]	[0.0323 0.0515]

Table 5: The interval comparison matrix for determining relative weights of the four aspects including economic (EC), environmental (EN), technological (T) and social (S) with the assumption that all the four aspects are independent

	EC	EN	T	S	Weights
EC	1	[1 2]	[1/2 1]	[2 3]	[0.2339 0.3089]
EN	[1/2 1]	1	[1/4 1/2]	[1 2]	[0.1344 0.2040]
T	[1 2]	[2 4]	1	[3 5]	[0.3631 0.4989]
S	[1/3 1/2]	[1/2 1]	[1/5 1/3]	1	[0.0982 0.1241]

Table 6: The relative effects of the three aspects of sustainability on the other aspect

EC	EN	T	S	Weights
EN	1	[1/5 1/3]	[1/3 1/2]	[0.1171 0.1485]
T	[3 5]	1	[2 3]	[0.5371 0.6468]
S	[2 3]	[1/3 1/2]	1	[0.2361 0.3143]
EN	EC	T	S	Weights
EC	1	[1/4 1/2]	[1/2 1]	[0.1254 0.2277]
T	[2 4]	1	[3 5]	[0.5545 0.6964]
S	[1 2]	[1/5 1/3]	1	[0.1782 0.2178]
T	EC	EN	S	Weights
EC	1	[4 6]	[2 3]	[0.5639 0.6640]
EN	[1/6 1/4]	1	[1/3 1/2]	[0.1067 0.1278]
S	[1/3 1/2]	[2 3]	1	[0.2292 0.3083]
S	EC	EN	T	Weights
EC	1	[1 2]	[3 4]	[0.4407 0.5763]
EN	[1/2 1]	1	[1 2]	[0.2373 0.3898]
T	[1/4 1/3]	[1/2 1]	1	[0.1695 0.1864]

Table 7: The inner dependency matrix

	EC	EN	T	S
EC	1	[0.1254 0.2277]	[0.5639 0.6640]	[0.4407 0.5763]
EN	[0.1171 0.1485]	1	[0.1067 0.1278]	[0.2373 0.3898]
T	[0.5371 0.6468]	[0.5545 0.6964]	1	[0.1695 0.1864]
S	[0.2361 0.3143]	[0.1782 0.2178]	[0.2292 0.3083]	1

Table 8: The weights of the criteria in each aspect with the assumption that all the criteria are independent

EC	C_1	C_2	C_3	C_4	Weights
Investment cost (C_1)	1	[2 3]	[1/2 1]	[1/3 1/2]	[0.1642 0.2157]
Payback period (C_2)	[1/3 1/2]	1	[1/4 1/3]	[1/6 1/4]	[0.0762 0.0840]
Total annual cost(C_3)	[1 2]	[3 4]	1	[1/2 1]	[0.2348 0.3334]
Net present value (C_4)	[2 3]	[4 6]	[1 2]	1	[0.3669 0.4731]
EN	C_5	C_6	C_7	C_8	Weights
NO_x emission (C_5)	1	[1 2]	[1/3 1/2]	[3 4]	[0.1955 0.2423]
CO emission (C_6)	[1/2 1]	1	[1/5 1/3]	[2 4]	[0.1227 0.1971]
CO_2 emission (C_7)	[2 3]	[3 5]	1	[7 9]	[0.5142 0.5683]
Noise (C_8)	[1/4 1/3]	[1/4 1/2]	[1/9 1/7]	1	[0.0561 0.0667]
T	C_9		C_{10}	C_{11}	Weights
Technology advancement (C_9)	1		[1/4 1/2]	[2 3]	[0.1891 0.3297]
Safety (C_{10})	[2 4]		1	[3 5]	[0.5341 0.6873]
Convenience for maintenance (C_{11})	[1/3 1/2]		[1/5 1/3]	1	[0.1237 0.1363]

Table 9: The global weights of the criteria for sustainability assessment

Aspect	Weight	Criteria	Local weight	Global weight
		C_1	[0.1642 0.2157]	[0.0341 0.1046]
		C_2	[0.0762 0.0840]	[0.0158 0.0407]
Economic	[0.2075 0.4850]	C_3	[0.2348 0.3334]	[0.0487 0.1617]
		C_4	[0.3669 0.4731]	[0.0761 0.2295]
		C_5	[0.1955 0.2423]	[0.0182 0.0561]
		C_6	[0.1227 0.1971]	[0.0114 0.0456]
Environmental	[0.0931 0.2316]	C_7	[0.5142 0.5683]	[0.0479 0.1316]
		C_8	[0.0561 0.0667]	[0.0052 0.0154]
		C_9	[0.1891 0.3297]	[0.0456 0.1822]
Technological	[0.2413 0.5527]	C_{10}	[0.5341 0.6873]	[0.1289 0.3799]
		C_{11}	[0.1237 0.1363]	[0.0298 0.0753]
Social	[0.1084 0.2683]	C_{12}	1	[0.1084 0.2683]

Table 10: normalized interval decision-making matrix

	A_1	A_2	A_3	A_4	A_5
C_1	[0.7536 0.8822]	[0.6490 0.8125]	[0.7756 0.8968]	[0 0.3798]	[0.9303 1]
C_2	[0.4281 0.8129]	[0.3903 0.7878]	[0.7086 1.0000]	[0 0.5276]	[0.3723 0.7758]
C_3	[0.1447 0.5373]	[0.1417 0.5353]	[0.3711 0.6882]	[0 0.4408]	[0.8388 1]
C_5	[0.9295 0.9535]	[0.9317 0.9549]	[0.7824 0.8554]	[0.9993 1]	[0 0.3338]
C_6	[0.8876 0.9252]	[0.8501 0.9002]	[0.8001 0.8668]	[0.9999 1]	[0 0.3334]
C_7	[0.6541 0.9448]	[0.2420 0.6701]	[0.5887 0.9012]	[0.7369 1]	[0 0.5087]
C_8	[0.3516 0.8594]	[0.3516 0.8594]	[0 0.6250]	[0.4688 0.9375]	[0.5625 1]
C_4	[0.4613 0.4798]	[0.4442 0.4540]	[0.8081 1]	[0 0.1415]	[0.4470 0.4583]
C_9	[0.5223 0.6932]	[0.3167 0.4341]	[0.0832 0.1573]	[0.8289 1]	[0 0.0851]
C_{10}	[0.3839 0.5105]	[0.3955 0.5272]	[0.1476 0.2012]	[0.8132 1]	[0 0.0844]
C_{11}	[0 0.0457]	[0.0808 0.1695]	[0.2232 0.3473]	[0.4303 0.6499]	[0.7985 1]
C_{12}	[0.4941 0.5177]	[0.1594 0.2546]	[0.0480 0.1052]	[0.8781 1]	[0 0.0411]

Table 11: The weighted decision-making matrix

	A_1	A_2	A_3	A_4	A_5
C_1	[0.0257 0.0923]	[0.0221 0.0850]	[0.0264 0.0938]	[0 0.0397]	[0.0317 0.1046]
C_2	[0.0068 0.0331]	[0.0062 0.0321]	[0.0112 0.0407]	[0 0.0215]	[0.0059 0.0316]
C_3	[0.0070 0.0869]	[0.0069 0.0866]	[0.0181 0.1113]	[0 0.0713]	[0.0408 0.1617]
C_5	[0.0169 0.0535]	[0.0170 0.0536]	[0.0142 0.0480]	[0.0182 0.0561]	[0 0.0187]
C_6	[0.0101 0.0422]	[0.0097 0.0410]	[0.0091 0.0395]	[0.0114 0.0456]	[0 0.0152]
C_7	[0.0313 0.1243]	[0.0116 0.0882]	[0.0282 0.1186]	[0.0353 0.1316]	[0 0.0669]
C_8	[0.0018 0.0132]	[0.0018 0.0132]	[0 0.0096]	[0.0024 0.0144]	[0.0029 0.0154]
C_4	[0.0351 0.1101]	[0.0338 0.1042]	[0.0615 0.2295]	[0 0.0325]	[0.0340 0.1052]
C_9	[0.0238 0.1263]	[0.0144 0.0791]	[0.0038 0.0287]	[0.0378 0.1822]	[0 0.0155]
C_{10}	[0.0495 0.1939]	[0.0510 0.2003]	[0.0190 0.0764]	[0.1048 0.3799]	[0 0.0321]
C_{11}	[0 0.0034]	[0.0024 0.0128]	[0.0067 0.0261]	[0.0128 0.0489]	[0.0238 0.0753]
C_{12}	[0.0536 0.1389]	[0.0173 0.0683]	[0.0052 0.0282]	[0.0952 0.2683]	[0 0.0110]

Table 12: The possibility degree matrix

	A_1	A_2	A_3	A_4	A_5
C_1	0.5391	0.5075	0.5455	0.2753	0.5894
C_2	0.4937	0.4814	0.5797	0.3454	0.4756
C_3	0.3597	0.3586	0.4366	0.3059	0.5723
C_5	0.5772	0.5778	0.5341	0.5967	0.2503
C_6	0.5432	0.5334	0.5201	0.5714	0.2500
C_7	0.5536	0.4236	0.5342	0.5774	0.3372
C_8	0.4937	0.4937	0.3846	0.5269	0.5525
C_4	0.3616	0.3474	0.5774	0.1239	0.3498
C_9	0.4436	0.3204	0.1384	0.5579	0.0785
C_{10}	0.3699	0.3784	0.1748	0.5800	0.0778
C_{11}	0.0437	0.1490	0.2758	0.4393	0.5938
C_{12}	0.3928	0.2139	0.0969	0.6078	0.0395

Table 13: The closeness coefficients of the five alternative CCHP systems and ranking

	A_1	A_2	A_3	A_4	A_5
Closeness coefficients	[0.0263 0.0565]	[0.0170 0.0365]	[0.0369 0.0793]	[0.0587 0.1263]	[0.0380 0.0817]

Table 14: The integrated sustainability performance (ISP) of the four CCHP systems and their ranking

	A_1	A_2	A_3	A_4	A_5
ISP	[0.2617 1.0182]	[0.1942 0.8643]	[0.2034 0.8505]	[0.3180 1.2920]	[0.1392 0.6532]
Ranking	2	3	4	1	5