Selection of Sustainable Prime Mover for Combined Cooling, Heat and Power Technologies under Uncertainties: An Interval Multi-Criteria Decision Making Approach

Jingzheng Ren

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

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

Email: renjingzheng123321@163.com; jzhren@polyu.edu.hk (J.Z. Ren)

Tel: 852-51665316

Abstract: This study aims at developing an interval MCDM method for helping the stakeholders to select the most sustainable prime mover for Combined Cooling, Heat and Power (CCHP) technologies under uncertainties for promoting the sustainable development of CCHP system. The "interval BW method", which can address the vagueness and ambiguity existing in the judgments of the decision-makers, has been developed for determining the weights of the evaluation criteria. The interval VIKOR method which can rank the alternatives with imprecise data has been used to prioritize the alternative prime movers for CCHP technologies. Four alternative prime movers including internal combustion engine, gas turbines, microturbines, and fuel cells were studied by the developed method, and the sustainability order of the four prime movers from the most sustainable to the least is fuel cells, microturbines, gas turbines, and internal combustion engine. Sensitivity analysis was also carried out to investigate the influences of the weights of the sustainability criteria on the sustainability ranking of the alternative prime movers, and the results reveal that the sustainability rankings are very sensitive to the weights of sustainability criteria.

Keywords: Prime mover; Combined Cooling, Heat and Power (CCHP); multi-criteria decision making; sustainability

1. Introduction

CCHP (Combined Cooling, Heat and Power) system, so-called “trigeneration”, which can simultaneously produce cooling, heat and power has been recognized as an outstanding way for improving energy efficiency, reducing GHG emission, and mitigating energy security problems. Jradi and Riffat [1] summarized that the trigeneration has seven main benefits, including delivering multiple products, reducing primary energy consumption, reducing thermal losses, reducing operational cost, improving energy supply reliability, improving energy sector security, and reducing greenhouse gas emissions. With these benefits, the development of CCHP systems has attracted more and more attentions. The prime movers which are the main components of CCHP can determine the configurations of different CCHP technologies [2]. There are also various different prime movers which can be selected by the users, i.e. internal combustion engine, stirling engine, gas turbine, micro gas steam turbine and fuel cells [3]. However, the decision-makers are usually puzzled by the two questions:(i) which is the best or the most sustainable prime mover when establishing a CCHP system? (ii) how can we select the best or the most sustainable prime mover? Because the selection of the best or the most sustainable prime mover among multiple alternatives usually has to consider multiple conflict criteria, a prime mover performs better with respect to one criterion, but may perform worse with respect to another criterion, thus, it is usually difficult for the decision-makers to determine which is the best or the most sustainable prime mover. Therefore, developing the multi-criteria decision-supporting method for helping the decision-makers/stakeholders to select the best or the most sustainable prime mover is critical.

There are a limited number of studies about developing the methods for prioritizing the prime movers. Ebrahimi and Keshavarz [4] employed the criteria in technological, economical, environmental, and social dimensions for evaluating the prime mover for a residential micro-CCHP, and two multi-criteria decision making models of fuzzy logic and grey incidence were used to rank different prime movers. Roman and Alvey [5] employed life cycle analysis and the criteria about energy-saving and environmental performances for the selection of prime mover for combined cooling, heating, and power systems. Besides these, there are also some studies focusing on sustainability assessment and prioritization of polygeneration or trigeneration systems. For instance, Wang *et al*. [6] developed a fuzzy multi-criteria decision making method for the selection and evaluation of trigeneration systems. Nieto-Morote *et al*. [7] employed the fuzzy Analytic Hierarchy Process (AHP) as the multi-criteria decision making method for the selection of trigeneration systems with the considerations of the criteria in four categories including technology, economy, environment, and society. He *et al*. [8] combined the interval ANP and interval TOPSIS method for sustainability prioritization of CCHP systems, and both the subjectivity in human's judgments and the uncertainties in decision-making data have been addressed. Wang *et al*. [9] combined the fuzzy best-worst network method and the interval TOPSIS method for sustainability prioritization of polygeneration systems. These studies focusing on polygeneration or trigeneration systems can be popularized to the selection of the prime movers for CCHP systems, and all these studies are useful for the decision-makers/stakeholders to select the best or the most sustainable prime movers for CCHP among multiple alternatives. However, there are also three research gaps which are needed to be addressed simultaneously:

(i) The lack of the convenient weighting method for the users to determine the weights of the evaluation criteria for evaluating the prime movers for CCHP, and AHP is the most widely used method for weighting; however, it is usually difficult for the users to use the crisp numbers (1 to 9 and their reciprocals) to compare the relative importance of one criterion over another, because there are various vagueness and ambiguity in human's subjective judgments;

(ii) The lack of the multi-criteria decision making method which can address uncertainties for ranking the alternative prime movers for CCHP, because there are usually various uncertainties, because sometime it is difficult for the decision-makers/stakeholders to determine the exact data of the alternatives with respect to the evaluation criteria;

(iii) The lack of the method for quantifying the alternative prime movers with respect to soft criteria, because the decision-makers/stakeholders cannot describe the alternatives with respect to the soft criteria by using data and units.

In fill the above-mentioned three research gaps, the objective of this study is to develop a multi-criteria decision making method for prioritizing the alternative prime movers under uncertainties, the interval best-worst method which allows the decision-makers/stakeholders to use interval numbers to describe the relative priority of a criterion over another and can successfully handle the vagueness and ambiguity in the judgments of the decision-makers/stakeholders was developed for determining the weights of the criteria for evaluating the alternative prime movers, and the interval VIKOR method was employed to rank the alternative prime movers under uncertainties.

2. Models

The framework of the multi-criteria decision making method developed in this study was presented in Figure 1. The interval best-worst method was used to determine the weights of the criteria for sustainability assessment and the data of the alternative prime movers with respect to the soft criteria, and these can be used together with the data of the alternative prime movers with respect to the hard criteria to determine the sustainability ranking of the alternative prime movers. The judgments of the decision-makers were used as the inputs when using the interval best-worst method and the outputs are the weights of the criteria for sustainability assessment and the data of the alternative prime movers with respect to the soft criteria. The weights of the criteria and the data of the alternative prime movers with respect to the hard and soft criteria were used as the inputs when using the VIKOR method and the outputs are the sustainability rankings of the alternative prime movers.

The interval best-worst method for determining the weights of the criteria was firstly developed in Section 2.1; then, the interval VIKOR method for ranking the alternative prime movers was presented in Section 2.2.

2.1 Interval Best-Worst (BW) Method

Rezaei [10-11] developed an innovative comparison weighting method (so-called "Best-Worst" method) for determining the relative priorities of multiple items, and this powerful method replies on establishing the Best-to-Others (BO) vector and the Others-to- Worst (OW) vector, and the Saaty method [12] (see Table 1), namely the numbers from 1 to 9 and their reciprocals can be used for determining the relative priorities. Compared with the traditional AHP method, the BW method has two significant advantages: (i) less times of comparisons with the increase of the number of the items; (ii) easier for achieving consistent over all the comparisons. However, the crisp numbers sometime cannot accurately depict the opinions and preferences of the users. For instance, if the users held the view that the relative priority of an item over another is between 4 and 6,then, 5 will be used to describe this comparison; while the interval [4 6] is more accurate to describe this comparison. Therefore, this study extended the BW method to interval conditions to address this.

Assuming that there are a total of n items $I_1, I_2, \cdots, I_n$, the interval BW method consists of six steps based on the BW method developed by Rezaei [10-11]:

Step 1: Identifying the best (the most important) item and the worst (the least important) item, denotes by I_B and I_W among these n items. This step aims at determining the two representative references items for comparing with all the n items.

Step 2: Determining the Best-to-Others (BO) vector and the Others-to- Worst (OW) vector by comparing the best criterion with all the other criteria and comparing all the criteria with the worst criterion, and the interval composed by nine scales (from 1 to 9) and their reciprocals were employed to establish the BO and OW vectors. Accordingly, the BO and OW vectors can be determined (see Eqs.1-2).

$$BO = \left[\begin{bmatrix} l_{B1} & u_{B1} \end{bmatrix} \begin{bmatrix} l_{B2} & u_{B2} \end{bmatrix} \cdots \begin{bmatrix} l_{Bn} & u_{Bn} \end{bmatrix}\right] \tag{1}$$

$$OW = \left[\begin{bmatrix} l_{1W} & u_{1W} \end{bmatrix} \begin{bmatrix} l_{2W} & u_{2W} \end{bmatrix} \cdots \begin{bmatrix} l_{nW} & u_{nW} \end{bmatrix}\right] \tag{2}$$

where $\begin{bmatrix} l_{Bj} & u_{Bj} \end{bmatrix}(j=1,2,\cdots,n)$ and $\begin{bmatrix} l_{jW} & u_{jW} \end{bmatrix}(j=1,2,\cdots,n)$ are interval numbers representing the relative priorities/preference of the best item over the *j*-th criterion and that of the *j*-th criterion over the worst criterion. l_{Bj} and u_{Bj} are the lower and upper bounds of $\begin{bmatrix} l_{Bj} & u_{Bj} \end{bmatrix}$, respectively. l_{jW} and u_{jW} are the lower and upper bounds of $\begin{bmatrix} l_{jW} & u_{jW} \end{bmatrix}$, respectively.

It is worth pointing out that when $j = B$, then $\begin{bmatrix} l_{Bj} & u_{Bj} \end{bmatrix} = \begin{bmatrix} 1 & 1 \end{bmatrix}$, and when $j = W$, then $\begin{bmatrix} l_{jW} & u_{jW} \end{bmatrix} = \begin{bmatrix} 1 & 1 \end{bmatrix}$.

Step 3: Determining the central BO and OW vectors. The central BO and OW vectors can be determined by Eq.3-6.

$$BO_M = \begin{bmatrix} m_{B1} & m_{B2} & \cdots & m_{Bn} \end{bmatrix} \tag{3}$$

$$OW_M = \begin{bmatrix} m_{1W} & m_{2W} & \cdots & m_{nW} \end{bmatrix} \tag{4}$$

$$m_{Bj} = \frac{l_{Bj} + u_{Bj}}{2} (j = 1, 2, \cdots, n) \tag{5}$$

$$m_{jW} = \frac{l_{jW} + u_{jW}}{2} \, (j = 1, 2, \cdots, n) \tag{6}$$

where $m_{Bj} \, (j = 1, 2, \cdots, n)$ and $m_{jW} \, (j = 1, 2, \cdots, n)$ are the mid-point values of $\begin{bmatrix} l_{Bj} & u_{Bj} \end{bmatrix}$ and $\begin{bmatrix} l_{jW} & u_{jW} \end{bmatrix}$.

Step 4: Determining the central weights of the items.

According to the meaning of the relative preference between each pair of items, the relationships between the central weights of the items can be obtained, as presented in Eq.7-8.

$$\frac{\omega_B^M}{\omega_j^M} = m_{Bj} \, (j = 1, 2, \cdots, n) \tag{7}$$

$$\frac{\omega_j^M}{\omega_W^M} = m_{jW} \, (j = 1, 2, \cdots, n) \tag{8}$$

where ω_j^M is the central weight of the *i*-th item, and ω_B^M and ω_W^M are the central weights of the best and the worst items, respectively.

However, it is usually impossible to obtain the central weights based on the BO and OW vectors which absolutely satisfy all the conditions presented in Eqs.7-8 simultaneously. Rezaei [10-11] developed a programming which aims at minimizing the maximum absolute difference $\left| \frac{\omega_B^M}{\omega_j^M} - m_{Bj} \right|$ and $\left| \frac{\omega_j^M}{\omega_W^M} - m_{jW} \right|$ for all j to determine the weights of the items:

$$\begin{aligned}
& \min \max_j \left\{ \left| \frac{\omega_B^M}{\omega_j^M} - m_{Bj} \right|, \left| \frac{\omega_j^M}{\omega_W^M} - m_{jW} \right| \right\} \\
& s.t. \\
& \sum_{j=1}^{n} \omega_j^M = 1 \\
& \omega_j^M \geq 0, \, j = 1, 2, \cdots, n
\end{aligned} \tag{9}$$

Programming (6) can be transferred into the following problem [10-11]:

$$
\begin{aligned}
&\min \xi \\
&s.t. \\
&\left| \frac{\omega_B^M}{\omega_j^M} - m_{Bj} \right| \le \xi,\ j = 1, 2, \cdots, n \\
&\left| \frac{\omega_j^M}{\omega_W^M} - m_{jW} \right| \le \xi,\ j = 1, 2, \cdots, n \\
&\sum_{j=1}^{n} \omega_j^M = 1 \\
&\omega_j^M \ge 0,\ j = 1, 2, \cdots, n
\end{aligned}
\tag{10}
$$

The ξ^* is the value of the objective function in programming (10) under the optimum conditions $\omega_j^M \ge 0,\ j = 1, 2, \cdots, n$.

Step 5: Consistency check.

The comparison is fully consistent when $m_{Bj} m_{jW} = m_{BW}\,(j = 1, 2, \cdots, n)$, while this condition cannot always be fully satisfied due to the weaknesses (i.e. subjectivity, ambiguity and vagueness) which exist in human's judgments. Rezaei [10-11] developed the consistency ratio which can be calculated by Eq.11 to check the consistency level of the comparisons.

$$
CR = \frac{\xi^*}{CI} \tag{11}
$$

where CR represents the consistency ratio, and CI represents the consistency index.

$$
CI = \frac{2m_{BW} + 1 - \sqrt{8m_{BW} + 1}}{2} \tag{12}
$$

The consistency index CR dependents on the relative preference of the best item over the worst item [10], as presented Eq.12, and it could be obtained according to Table 2 if m_{BW} is an integer, and the consistency ratio varies in the interval $\left[0 \quad 1\right]$ which indicates the consistency level, and the closer the value to zero, the more consistent the comparisons are; on the contrary, the closer the value to one, the less consistent the comparisons are.

Step 6: Determining the interval weights of the items. Assuming that the central weights of the items determined by the BO and OW vectors presented in Eqs.3-4 can be connected to the interval weights of the items determined by the BO and OW vectors presented in Eqs.1-2 through a radius with respect to the weight of each item (denotes the radius with respect to the weight of the *j*-th item by d_j), and denote the interval weights of the *j*-th item by $\omega_j = \left[\omega_j^M - d_j \quad \omega_j^M + d_j \right]$, in this problem, $m_{Bj}(j=1,2,\cdots,n)$ and $m_{jW}(j=1,2,\cdots,n)$ are approximated as $\left[l_{Bj} \quad u_{Bj} \right]$ and $\left[l_{jW} \quad u_{jW} \right]$. thus, the interval weights of the items should satisfy the following conditions according to the work of Entani *et al*. [13].

$$\left[l_{Bj} \quad u_{Bj} \right] \subseteq \frac{\left[\omega_B^M - d_B \quad \omega_B^M + d_B \right]}{\left[\omega_j^M - d_j \quad \omega_j^M + d_j \right]} = \left[\frac{\omega_B^M - d_B}{\omega_j^M + d_j} \quad \frac{\omega_B^M + d_B}{\omega_j^M - d_j} \right] \tag{13}$$

$$\left[l_{jW} \quad u_{jW} \right] \subseteq \frac{\left[\omega_j^M - d_j \quad \omega_j^M + d_j \right]}{\left[\omega_W^M - d_W \quad \omega_W^M + d_W \right]} = \left[\frac{\omega_j^M - d}{\omega_W^M + d_W} \quad \frac{\omega_j^M + d_j}{\omega_W^M - d_W} \right] \tag{14}$$

where d_B represents the radius with respect to the weight of the j-th item

The radius should be minimized subject to the constraints conditions that the relations in Eqs.13-14 for all the elements should be satisfied [13]. Accordingly, the following programming can be obtained for determining the radius:

$$
\begin{aligned}
&\min \quad \lambda \\
&s.t. \quad \frac{\omega_B^M - d_B}{\omega_j^M + d_j} \le l_{Bj} \\
&\quad \frac{\omega_B^M + d_B}{\omega_j^M - d_j} \ge u_{Bj} \\
&\quad \frac{\omega_j^M - d}{\omega_W^M + d_W} \le l_{jW} \\
&\quad \frac{\omega_j^M + d_j}{\omega_W^M - d_W} \ge u_{jW} \\
&\quad d_j \le \lambda \\
&\quad \omega_j^M - d_j \ge 0 \\
&j = 1, 2, \cdots, n
\end{aligned}
\tag{15}
$$

The obtained priority levels can be regarded as the possible ranges deduced from the given data, and the interval importance reveals the acceptable range of a decision maker [13].

2.2 The interval VIKOR method

The VIKOR method as a typical multi-criteria decision making method is capable of dealing with the discrete decision making problems with non-commensurable (different units) and conflicting criteria, and it can help the decision-makers to determine the compromise solution for the problems with multiple conflicting criteria [14]. However, the traditional VIKOR method cannot address the multi-criteria decision making problems with imprecise and uncertain information. The interval numbers which can denote the variation range of the uncertain information are suitable for representing the uncertainties in the decision-making matrix. In order to capturing the advantages of both the traditional VIKOR method and the interval numbers, the traditional VIKOR method has been extended to the interval environment, and the interval VIKOR has been developed for multi-criteria decision making under uncertainties. The compromise ranking algorithm of the interval

VIKOR method was specified in the following six steps based on the work of Sayadi *et al*. [14] and that of An *et al*. [15].

Step 1: Determining the decision-making matrix which is composed by the interval numbers.

Assuming that there are m alternatives $A_1, A_2, \ldots, A_m$ and n evaluation criteria $C_1, C_2, \ldots, C_n$ in the multi-criteria decision making problem, the data of the alternative with respect to each of the evaluation criteria and the weights of the evaluation criteria were determined in this step. It is worth pointing out that the data of the alternatives with respect to the hard criteria can be collected from literatures and survey, while the data of the alternatives with respect to the soft criteria can be determined by using the interval BW method. Meanwhile, the interval weights of the criteria for evaluating the alternatives can also be determined by the interval BW method. Then, the interval decision making matrix can be determined, as presented in Eq.15.

$$\begin{array}{ccccc} & C_1 & C_2 & \cdots & C_n \\ A_1 & \left[v_{11}^L \;\; v_{11}^U\right] & \left[v_{12}^L \;\; v_{12}^U\right] & \cdots & \left[v_{1n}^L \;\; v_{1n}^U\right] \\ A_2 & \left[v_{21}^L \;\; v_{21}^U\right] & \left[v_{22}^L \;\; v_{22}^U\right] & \cdots & \left[v_{2n}^L \;\; v_{2n}^U\right] \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & \left[v_{m1}^L \;\; v_{m1}^U\right] & \left[v_{m2}^L \;\; v_{m2}^U\right] & \cdots & \left[v_{mn}^L \;\; v_{mn}^U\right] \\ W & \left[\omega_1^L \;\; \omega_1^U\right] & \left[\omega_2^L \;\; \omega_2^U\right] & \cdots & \left[\omega_n^L \;\; \omega_n^U\right] \end{array} \tag{15}$$

where $A_1, A_2, \ldots, A_m$ are the m alternatives, $C_1, C_2, \ldots, C_n$ are the n criteria, $\left[v_{ij}^L \;\; v_{ij}^U\right]$ is the data of the *i*-th alternative with respect to the *j*-th criterion, W is the weight vector of the criteria, and $\left[\omega_j^L \;\; \omega_j^U\right]$ is the interval weight of the *j*-th criterion.

Step 2: Standardizing the decision-making matrix to obtain the standardized decision-making matrix.

The criteria can be categorized into two types, namely the benefit-criteria (denotes the set of benefit-criteria by B) and the cost-criteria (denotes the set of cost-criteria by C). The benefit-criteria group represents the criteria which have the characteristic that the greater the values with respect to these criteria, the more superior the alternatives will be. While the cost-criteria groups represents the criteria which has characteristic that the greater the values with respect to these criteria, the less superior the alternatives will be. The data of the alternatives regarding the benefit-criteria and the cost-criteria can be standardized by Eqs.16-17, respectively.

$$\begin{bmatrix} x_{ij}^L & x_{ij}^U \end{bmatrix} = \begin{bmatrix} \dfrac{v_{ij}^L}{\max\limits_{i=1,2,\cdots,m}\left\{v_{ij}^U\right\}} & \dfrac{v_{ij}^U}{\max\limits_{i=1,2,\cdots,m}\left\{v_{ij}^U\right\}} \end{bmatrix} \qquad j \in B \tag{16}$$

$$\begin{bmatrix} x_{ij}^L & x_{ij}^U \end{bmatrix} = \begin{bmatrix} \dfrac{\min\limits_{i=1,2,\cdots,m}\left\{v_{ij}^L\right\}}{v_{ij}^U} & \dfrac{\min\limits_{i=1,2,\cdots,m}\left\{v_{ij}^L\right\}}{v_{ij}^L} \end{bmatrix} \qquad j \in C \tag{17}$$

Step 3: Determining the ideal best and the ideal worst solutions.

The ideal best and the ideal worst solutions represent the hypothetical absolutely best and worst alternatives, and they can be determined by Eqs. 18-21.

$$B^U = \left\{x_1^U, x_2^U, \cdots, x_n^U\right\} \tag{18}$$

$$x_j^U = \max_{i=1,2,\cdots,m}\left\{x_{ij}^U\right\} \qquad j = 1, 2, \cdots, n \tag{19}$$

$$W^L = \left\{x_1^L, x_2^L, \cdots, x_n^L\right\} \tag{20}$$

$$x_j^L = \min_{i=1,2,\cdots,m}\left\{x_{ij}^L\right\} \qquad j = 1, 2, \cdots, n \tag{21}$$

where B^U represents the ideal best solution, W^L represents the ideal worst solutions, x_j^U represents the data of the ideal best solution with respect to the *j*-th criterion, and x_j^L represents the data of the ideal worst solution with respect to the *j*-th criterion.

Step 4: Determining $\left[S_i^L \quad S_i^U\right]$ and $\left[R_i^L \quad R_i^U\right]$ according to Eqs. 22-25. It is worth pointing out that the weight of the *j*-th criterion was determined by the interval BW method.

$$S_i^L = \sum_{j=1}^{n} \frac{\omega_j^L (x_j^U - x_{ij}^U)}{\left(x_j^U - x_j^L\right)}, i = 1, 2, \cdots, m \tag{22}$$

$$S_i^U = \sum_{j=1}^{n} \frac{\omega_j^U (x_j^U - x_{ij}^L)}{\left(x_j^U - x_j^L\right)}, i = 1, 2, \cdots, m \tag{23}$$

$$R_i^L = \max_j \frac{\omega_j^L (x_j^U - x_{ij}^U)}{\left(x_j^U - x_j^L\right)}, i = 1, 2, \cdots, m \tag{24}$$

$$R_i^U = \max_j \frac{\omega_j^U (x_j^U - x_{ij}^L)}{\left(x_j^U - x_j^L\right)}, i = 1, 2, \cdots, m \tag{25}$$

The solution which has the minimum value of $\left[S_i^L \quad S_i^U\right]$ has a maximum group utility ("majority" rule), and the solution which has the minimum value of $\left[R_i^L \quad R_i^U\right]$ has a minimum of the individual regret of the "opponent".

Step 5: Calculating the values of $\left[Q_i^L \quad Q_i^U\right]$ which represent the integrated priorities of the alternatives by Eqs. 26-27.

$$Q_i^L = v \frac{(S_i^L - S^*)}{\left(S^- - S^*\right)} + (1 - v) \frac{(R_i^L - R^*)}{\left(R^- - R^{**}\right)}, i = 1, 2, \cdots, m \tag{26}$$

$$Q_i^U = v \frac{(S_i^U - S^*)}{\left(S^- - S^*\right)} + (1 - v) \frac{(R_i^U - R^*)}{\left(R^- - R^{**}\right)}, i = 1, 2, \cdots, m \tag{27}$$

where $S^* = \min_{i=1,2,\cdots,m} \left\{S_i^L\right\}$; $S^- = \max_{i=1,2,\cdots,m} \left\{S_i^U\right\}$; $R^* = \min_{i=1,2,\cdots,m} \left\{R_i^L\right\}$ and $R^- = \max_{i=1,2,\cdots,m} \left\{R_i^U\right\}$. The factor v is introduced as the weight of the strategy of 'the majority of attributes', which could take a value from [0 1]. It was assumed that $v = 0.50$ in this study.

Step 6: Calculating the relative priorities of the alternatives and ranking the alternatives. The probability of $\left[Q_i^L \quad Q_i^U\right]$ with respect to the i-th alternative be greater than $\left[Q_t^L \quad Q_t^U\right]$ with respect to the t-th alternative can be determined according to the work of Wang *et al*. [16].

$$p_{it} = P\left\{\left[Q_i^L \quad Q_i^U\right] \geq \left[Q_t^L \quad Q_t^U\right]\right\} = \frac{\max\left\{0, Q_i^U - Q_t^L\right\} - \max\left\{0, Q_i^L - Q_t^U\right\}}{Q_i^U - Q_i^L + Q_t^U - Q_t^L} \tag{28}$$

Note that $P\left\{\left[Q_i^L \quad Q_i^U\right] \geq \left[Q_t^L \quad Q_t^U\right]\right\} = 0.5000$ when $\left[Q_i^L \quad Q_i^U\right] = \left[Q_t^L \quad Q_t^U\right]$.

The probability matrix can be determined by comparing each pair of alternatives, and the results can be presented in a m×m matrix, as presented in Eq.29.

$$P = \begin{matrix} 0.5000 & p_{12} & \cdots & p_{1m} \\ p_{21} & 0.5000 & \cdots & p_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & 0.5000 \end{matrix} \tag{29}$$

where P is the probability matrix for comparing each pair of alternatives, and p_{it} represents the probability of $\left[Q_i^L \quad Q_i^U\right]$ with respect to the i-th alternative be greater than $\left[Q_t^L \quad Q_t^U\right]$ with respect to the t-th alternative.

The priority performance index (PPI) of the i-th alternative can be calculated by Eq.30 according to the work of Xu [17].

$$PP_i = \frac{1}{m}\left(\sum_{j=1}^{m} p_{ij} + 1 - \frac{m}{2}\right) \qquad i = 1, 2, \cdots, m \tag{30}$$

Then, these alternative can be ranked according to their priority performances, and the greater the priority performance, the more superior the alternative will be.

3. Case study

In order to illustrate the developed method for selecting the most sustainable prime mover for CCHP technologies (an example was presented in Figure 2) [18], four alternative prime movers including internal combustion engine, gas turbines, microturbines, and fuel cells for CCHP technologies were studied by the developed method in this study.

Internal combustion engine (ICE): ICE which is the most widely used prime mover in small and medium scale CCCHP systems [19]. The fuels used in ICE system are usually natural gas, biogas, propane, and landfill gas [2].

Gas turbines: Gas turbines which is an internal combustion engine that operates with rotational rather than reciprocating motion use heat to move turbine blades that produce electricity [20]. The fuels used in gas turbine system are usually natural gas, biogas, propane, and oil [2].

Microturbines: microturbines which have been industrialized for more than a decade are small gas turbines which burn gaseous and liquid fuels to drive an electrical generator [21]. The fuels used in microturbine system are usually natural gas, biogas, propane, and oil [2].

Fuel cells: fuel cells which are similar to batteries produce a direct current without direct combustion of a fuel source through the electrochemical process for generating electricity and heat [20]. The fuels used in fuel cell system are usually hydrogen, natural gas, propane, and methanol [2].

The selection of the criteria was based on the following three principles including transparent principle (the criteria for sustainability assessment should be understood by the non-experts), relevant principle (the selected criteria should be relevant to the concept of sustainability or sustainable development), and user-oriented principle (the selected criteria for sustainability assessment should reflect the preferences and requirements of the decision-makers) [22]. Based on these three principle, the thirteen criteria including installed cost-EC_1, operation and maintenance cost-EC_2, and equipment life-EC_3 in economic dimension, noise-EN_1, CO_2 emissions-EN_2, and NO_x emissions-EN_3 in environmental dimension, power efficiency-T_1, CCHP overall efficiency-T_2, effective electrical efficiency-T_3, power density-T_4, and start-up time-T_5 in technological dimension, and safety-S_1 and social acceptability-S_2 were employed to evaluate these four prime movers for CCCHP technologies. It is worth pointing out that different decision-makers/stakeholders may select different criteria for sustainability assessment of prime movers because of different preferences and requirements. For instance the emission of SO_2 were not considered in this study, because the decision-makers held the view that the effects of CO_2 and NO_x on environment are much more important than that of SO_2, but some other decision-makers/stakeholders may choose SO_2 as one of the criteria for sustainability assessment of the prime movers for CCHP in some other conditions

The interval BW method was firstly employed to determine the weights of the four dimensions (economic, environmental, technological and social dimensions) and the local weights of the criteria in each dimension. It is worth pointing out that the determinations of the BO and OW vectors used in the interval BW method were based on focus group meeting in which two professors whose research mainly focuses on CCHP systems, two PhD students of power engineering, and two engineers from a power factories were invited to participate in the decision-making process, the technological reports, books and papers related to the topic of this study were firstly provided to the participants before the focus group meeting. Taking the procedures for determining the weights of the four dimensions as an example, the six steps have been specified as follows:

Step 1: Technological dimension and social dimension were recognized as the most important and the least important dimension for sustainability assessment of the prime mover of CCHP technologies, respectively.

Step 2: The BO and OW vectors were determined based on the results of focus group meeting, as presented in Eq.31-32.

$$\begin{array}{ccccc} & EC & EN & T & S \\ BO & [2 \quad 3] & [4 \quad 5] & 1 & [6 \quad 7] \end{array} \tag{31}$$

$$\begin{array}{ccccc} & EC & EN & T & S \\ OW & [3 \quad 5] & [2 \quad 4] & [6 \quad 7] & 1 \end{array} \tag{32}$$

Step 3: The central BO and OW vectors can be determined according to Eqs.3-6, as presented in Eqs.33-34.

$$\begin{array}{ccccc} & EC & EN & T & S \\ BO & 2.5 & 4.5 & 1 & 6.5 \end{array} \tag{33}$$

$$\begin{array}{ccccc} & EC & EN & T & S \\ OW & 4 & 3 & 1 & 6.5 \end{array} \tag{34}$$

Step 4: Determining the central weights of the items by establishing the following programming as presented in (35).

$$
\begin{aligned}
&\min \xi \\
&s.t. \\
&\left|\frac{\omega_T^M}{\omega_{EC}^M} - 2.5\right| \le \xi \\
&\left|\frac{\omega_T^M}{\omega_{EN}^M} - 4.5\right| \le \xi \\
&\left|\frac{\omega_T^M}{\omega_S^M} - 6.5\right| \le \xi \\
&\left|\frac{\omega_{EC}^M}{\omega_S^M} - 4\right| \le \xi \\
&\left|\frac{\omega_{EN}^M}{\omega_S^M} - 3\right| \le \xi \\
&\omega_{EC}^M + \omega_{EN}^M + \omega_T^M + \omega_S^M = 1 \\
&\omega_{EC}^M, \omega_{EN}^M, \omega_T^M, \omega_S^M \ge 0
\end{aligned}
\tag{35}
$$

After solving programming (35), the weights of the four dimensions can be determined, as presented in Table 3.

Step 5: The consistency ratio can be determined after solving programming (35). As $a_{BW} = 6.5$, the consistency index can be determined by Eq.12., and CI=3.3599, then, the consistency ratio can be determined by Eq.11, and CR=0.2750, it is near to zero and far to one, so the consistency of the overall comparisons is acceptable.

Step 6: The programming (36) was established for determining the radius with respect to the weight of each criterion.

$$
\begin{aligned}
&\min \quad \lambda \\
&s.t. \quad \frac{\omega_T^M - d_T}{\omega_{EC}^M + d_{EC}} \le l_{31} \\
&\frac{\omega_T^M + d_T}{\omega_{EC}^M - d_{EC}} \ge u_{31} \\
&\frac{\omega_T^M - d_T}{\omega_{EN}^M + d_{EN}} \le l_{32} \\
&\frac{\omega_T^M + d_T}{\omega_{EN}^M - d_{EN}} \ge u_{32} \\
&\frac{\omega_T^M - d_T}{\omega_S^M + d_S} \le l_{34} \\
&\frac{\omega_T^M + d_T}{\omega_S^M - d_S} \ge u_{34} \\
&\frac{\omega_{EC}^M - d_{EC}}{\omega_S^M + d_S} \le l_{14} \\
&\frac{\omega_{EC}^M + d_{EC}}{\omega_S^M - d_S} \ge u_{14} \\
&\frac{\omega_{EN}^M - d_{EN}}{\omega_S^M + d_S} \le l_{24} \\
&\frac{\omega_{EN}^M + d_{EN}}{\omega_S^M - d_S} \ge u_{24} \\
&d_{EC} \le \lambda \\
&d_{EN} \le \lambda \\
&d_T \le \lambda \\
&d_S \le \lambda \\
&\omega_{EC}^M - d_{EC} > 0 \\
&\omega_{EN}^M - d_{EN} > 0 \\
&\omega_T^M - d_T > 0 \\
&\omega_S^M - d_S > 0
\end{aligned}
\tag{36}
$$

After solving this programming, the radius with respect to the weight of each dimension can be determined, and the results were also presented in Table 3. Then, the interval weights of the four dimensions can be obtained, and the weights were presented in Eqs37-40.

$$\omega_{EC} = \left[\omega_{EC}^{M} - d_{EC} \quad \omega_{EC}^{M} + d_{EC}\right] = \left[0.2759 - 0.0789 \quad 0.2759 + 0.0789\right] = \left[0.1970 \quad 0.3548\right] \tag{37}$$

$$\omega_{EN} = \left[\omega_{EN}^{M} - d_{EN} \quad \omega_{EN}^{M} + d_{EN}\right] = \left[0.1432 - 0.0254 \quad 0.1432 + 0.0254\right] = \left[0.1178 \quad 0.1686\right] \tag{38}$$

$$\omega_{T} = \left[\omega_{T}^{M} - d_{T} \quad \omega_{T}^{M} + d_{T}\right] = \left[0.5120 - 0.0789 \quad 0.5120 + 0.0789\right] = \left[0.4331 \quad 0.5909\right] \tag{39}$$

$$\omega_{S} = \left[\omega_{S}^{M} - d_{S} \quad \omega_{S}^{M} + d_{S}\right] = \left[0.0690 - 0.0269 \quad 0.0690 + 0.0269\right] = \left[0.0421 \quad 0.0959\right] \tag{40}$$

Therefore, the interval weights of the economic, environmental, technological, and social dimensions are [0.1970 0.3548], [0.1178 0.1686], [0.4331 0.5909], and [0.0421 0.0959], respectively.

In a similar way, the local weights of the criteria in each dimension can also be determined, and the results were presented in the Tables 4-6. There are three criteria (installed cost-EC_1, operation and maintenance cost-EC_2, and equipment life-EC_3) in economic dimension, and the local interval weights of the three criteria are [0.5583 0.6857], [0.0995 0.1863], and [0.1714 0.2988], respectively. The interval weights of the three criteria including noise-EN_1, CO_2 emissions-EN_2, and NO_x emissions-EN_3 in environmental dimension are [0.0762 0.1460], [0.5839 0.6667], and [0.2222 0.3050], respectively. The weights of the five criteria including power efficiency-T_1, CCHP overall efficiency-T_2, effective electrical efficiency-T_3, power density-T_4, and start-up time-T_5 in technological dimension are [0.1275 0.2759], [0.3618 0.5102], [0.1275 0.2759], [0.0730 0.1208], and [0.0119 0.1157], respectively. It is worth pointing out that the two criteria (safety and social acceptability) were recognized as equally important, thus, the local weights of these two criteria equal to 0.5000.

The global weights of the criteria can be determined by calculating the product of the local weight of each criterion and the weight of the corresponding dimension to which the criterion belongs to, and the global weights of the criteria were presented in Table 7.

The data of the prime movers for CCHP technologies with respect to the hard criteria (i.e. installed cost, operation and maintenance cost, equipment life, CO_2 emissions, NO_x emissions, power efficiency, CCHP overall efficiency, effective electrical efficiency, power density, and start-up time) can be derived from literature [2, 23]. However, it lacks the quantitative description of the alternative prime movers of CCHP technologies with respect to the soft criteria including noise, safety, and social acceptability. The interval BW method was employed to determine the relative performances of the four prime movers with respect to these three soft criteria based on the judgments of the experts of CCHP systems, and the results were presented in Tables 8-10. Therefore, the developed interval BW method was firstly used for determining the relative weights of the criteria for sustainability assessment of the prime movers for CCHP systems (see Tables 3-7), then, it was used to determine the relative performances of the four alternative prime movers with respect to the soft criteria (see Tables 8-10). Note that the relative performances of the four prime movers (internal combustion engine, gas turbines, microturbines, and fuel cells) with respect to noise are [0.0215 0.1257], [0.1748 0.2790], [0.1748 0.2790], and [0.4204 0.5246], respectively, and it means that fuel cells perform the best among these four alternatives with respect to noise.

Then, the decision-making matrix can be determined, as presented in Table 11. According to the interval VIKOR method, the integrated priorities of the four alternative prime overs for CCHP technologies can be determined, and the results were presented in Table 12. The integrated priorities of the four alternative prime movers (ICE, gas turbines, microtrubines, and fuel cells) are [0 0.5849], [0.0074 0.5838], [0.1843 0.8021], and [0.1534 0.9731], respectively. The range with respect to each alternative prime mover represents the lower and upper values of the integrated priorities of each alternative prime mover. According to Eqs.28-29, the probability matrix for comparing each pair of the alternative prime movers for CCHP technologies can be determined, as presented in Eq.41.

$$\begin{array}{lcccc} & ICE & Gas\ turbines & Microturbines & Fuel\ cells \\ ICE & 0.5000 & 0.4973 & 0.3331 & 0.3072 \\ Gas\ turbines & 0.5027 & 0.5000 & 0.3345 & 0.3083 \\ Microturbines & 0.6669 & 0.6655 & 0.5000 & 0.4513 \\ Fuel\ cells & 0.6928 & 0.6917 & 0.5487 & 0.5000 \end{array} \qquad (41)$$

The priority performance indexes of the four alternative prime movers for CCHP technologies can be determined by Eq.30, and the results were presented in Table 13.

Fuel cell was recognized as the most sustainable prime mover among these four alternatives for CCHP technologies, follows by microturbine, gas turbine, and ICE. The results are reasonable, fuel cell performs the best in environmental and social aspects, it has the least noise, CO_2 emissions, and NO_x emissions, it also has the highest social acceptability and the best safety performance among these four alternative prime movers. Meanwhile, the power efficiency and effective electrical efficiency of fuel cell are comparatively higher than the other prime movers.

In order to test the effects of the weights on the final ranking of the four alternative prime movers, and the following fourteen cases have been studied:

Case 0: an equal weight (0.0769) was assigned to all the thirteen criteria;

Case 1-13: a dominant weight (0.4000) was assigned to a criterion, and an equal weight (0.05) was assigned to the other twelve criteria.

The results of sensitivity analysis were presented in Figure 3. It is apparent that altering the weights of the criteria may change the priority performance indexes of the four alternative prime movers for CCHP technologies. In other words, the priority ranking of the four alternative prime movers may change when changing the weights of the evaluation criteria. In other words, the priority order of the four alternative prime movers determined by different stakeholders may be different, because different stakeholders have different preferences. Accordingly, the developed multi-criteria decision making method can help the stakeholders to select the most sustainable prime mover among various alternatives for CCHP technologies.

4. Conclusion

This study aims at developing a MCDM method for helping the stakeholders to select the most sustainable prime mover for CCHP technologies under uncertainties. A novel subjective weighting method, so-called "interval BW method", which can incorporate the preferences/opinions of the decision-makers, has been developed for determining the weights of the evaluation criteria. The developed interval BW method which allows the decision-makers to use the interval numbers to establish the BO and OW vectors and can overcome the weaknesses of human's judgments (i.e. vagueness, subjectivity and ambiguity) has been developed for weights determination. The interval BW method was used for both weights determination and the relative performances of the alternatives with respect to the soft criteria. The interval VIKOR method which can rank the alternatives with imprecise data has been used to rank the alternative prime movers for CCHP technologies. Four alternative prime movers including internal combustion engine, gas turbines, microturbines, and fuel cells were studied by the developed method, and the sustainability order of the four prime movers from the most sustainable to the least is fuel cells, microturbines, gas turbines, and internal combustion engine. Sensitivity analysis was carried by changing the weights of the criteria for sustainability assessment of the prime movers, and the results of sensitivity analysis show that the weights of the criteria have significant influences on the sustainability rankings of the prime movers.

It is worth pointing out that the sustainability ranking of the four alternative prime movers may change with the technological development of the prime movers for CCHP. Accordingly to the principle of learning curve, the data with respect to the benefit-type criteria (power efficiency and CCHP overall efficiency) will increase and that with respect to the cost-type criteria (CO_2 and NO_x emissions) will decrease with the repetition of the demonstration projects on CCHP projects.

Comparing with the previous MCDM methods for determining the sustainability order of the alternative prime movers for CCHP systems, the proposed method has the following advantages:

(1) The developed interval BW method can reflect the preferences/opinions of the decision-makers accurately by using interval number to resolve the ambiguity and vagueness existed in human's judgments successfully;

(2) The data used in the decision-making matrix are interval numbers rather than the traditional crisp numbers, and the interval numbers can be used to represent the uncertainties in sustainability ranking of the prime movers for CCHP systems.

Besides the advantages, there is also a weak point-the decision-making on selecting the most sustainable prime mover among multiple alternatives usually involves multiple different decision-makers/stakeholders, and the weights of the criteria for sustainability assessment determined by different decision-makers/stakeholders are usually different, and the future work of the authors is to develop a group multi-criteria decision making method which can incorporate the preferences/opinions of all the decision-makers/stakeholders to determine the weights of the criteria for sustainability assessment of prime movers for CCHP systems.

References

1. Jradi M, Riffat S. Tri-generation systems: Energy policies, prime movers, cooling technologies, configurations and operation strategies. Renew Sustain Energy Rev 2014; 32: 396-415.
2. Al-Sulaiman FA, Hamdullahpur F, Dincer I. Trigeneration: a comprehensive review based on prime movers. Int J Energy Res 2011; 35(3): 233-258.
3. Ebrahimi M, Keshavarz A. Sizing the prime mover of a residential micro-combined cooling heating and power (CCHP) system by multi-criteria sizing method for different climates. Energy 2013; 54: 291-301.
4. Ebrahimi M, Keshavarz, A. Prime mover selection for a residential micro-CCHP by using two multi-criteria decision-making methods. Energy and Buildings 2012; 55: 322-331.
5. Roman KK, Alvey JB. Selection of prime mover for combined cooling, heating, and power systems based on energy savings, life cycle analysis and environmental consideration. Energy and Buildings 2016; 110: 170-181.
6. Wang JJ, Jing YY, Zhang CF, Shi GH, Zhang XT. A fuzzy multi-criteria decision-making model for trigeneration system. Energy Policy 2008; 36(10): 3823-3832.
7. Nieto-Morote A, Ruz-Vila F, Cánovas-Rodríguez FJ. Selection of a trigeneration system using a fuzzy AHP multi-criteria decision-making approach. Int J Energy Res 2011; 35(9): 781-794.
8. He C, Zhang Q, Ren J, Li, Z. Combined cooling heating and power systems: Sustainability assessment under uncertainties. Energy 2017; 139: 755-766.

9. Wang Z, Xu G, Ren J, Li Z, Zhang B, Ren, X. Polygeneration system and sustainability: Multi-attribute decision-support framework for comprehensive assessment under uncertainties. J Clean Prod 2017; 167: 1122-1137.
10. Rezaei, J. Best-worst multi-criteria decision-making method. Omega 2015; 53: 49-57.
11. Rezaei, J. Best-worst multi-criteria decision-making method: Some properties and a linear model. Omega 2016; 64: 126-130.
12. Saaty TL. Exploring the interface between the hierarchies, multiple objectives and the fuzzy sets. Fuzzy Sets Sys. 1978; 1: 57–68.
13. Entani T, Ichihashi H, Tanaka H. Optimistic priority weights with an interval comparison matrix. New Frontiers in Artificial Intelligence; 2001. 344 p.
14. Sayadi MK, Heydari M, Shahanaghi K. Extension of VIKOR method for decision making problem with interval numbers. App Math Model 2009; 33(5): 2257-2262.
15. An, D., Yang, Y., Chai, X., Xi, B., Dong, L., Ren, J. Mitigating pollution of hazardous materials from WEEE of China: portfolio selection for a sustainable future based on multi-criteria decision making. Resources, Conservation and Recycling 2015; 105:198-210.
16. Wang YM, Yang JB, Xu DL. A preference aggregation method through the estimation of utility intervals. Comput Oper Res 2005; 32(8): 2027-2049.
17. Xu Z. A method for priorities of triangular fuzzy number complementary judgment matrices. Fuzzy Systems and Math. 2002; 16(1): 47-50. (in Chinese).
18. Tassou SA, Lewis JS, Ge YT, Hadawey A, Chaer I. A review of emerging technologies for food refrigeration applications. Appl Thermal Eng 2010; 30(4): 263-276.
19. Wang J, Wu J. Investigation of a mixed effect absorption chiller powered by jacket water and exhaust gas waste heat of internal combustion engine. Int J Refrigeration 2015; 50: 193-206.

20. U.S. Environmental Protection Agency (U.S.EPA). Biomass combined heat and power catalog of technologies. Spetember 2007. This file is available at: https://www.epa.gov/sites/production/files/2015-07/documents/biomass_combined_heat_and_power_catalog_of_technologies_v.1.1.pdf
21. U.S. Environmental Protection Agency (U.S.EPA). Combined heat and power partnership. Catalog of CCHP Technologies. March 2015. This file is available at: https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_CCHP_technologies.pdf (access on 2, June 2017)
22. Popovic T, Kraslawski A. Quantitative Indicators of Social Sustainability and Determination of Their Interdependencies. Example Analysis for a Wastewater Treatment Plant. Periodica Polytechnica Chemical Engineering. 2017, 2017: 1-12. DOI: 10.3311/PPch.10526
23. U.S. Environmental Protection Agency (U.S.EPA). Combined heat and power partnership. Catalog of CCHP Technologies. December 2008. This file is available at: https://www.epa.gov/sites/production/files/2015-07/documents/catalog_of_CCHP_technologies.pdf (access on 1, June 2017)

Figures

Figure captions

Figure 1: The inputs and outputs in the multi-criteria decision making method

Figure 2: Framework of CCHP system

Figure 3: The results of sensitivity analysis

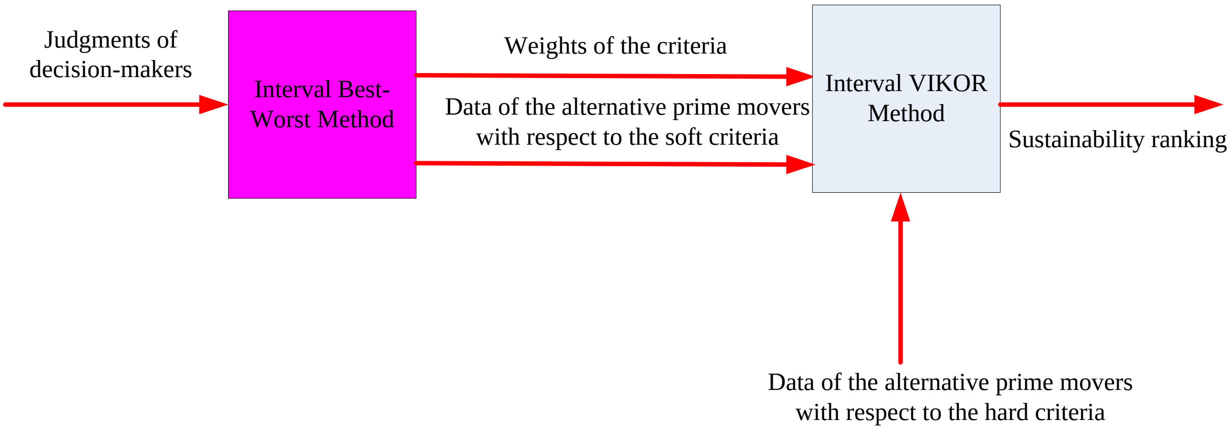

Figure 1: The inputs and outputs in the multi-criteria decision making method

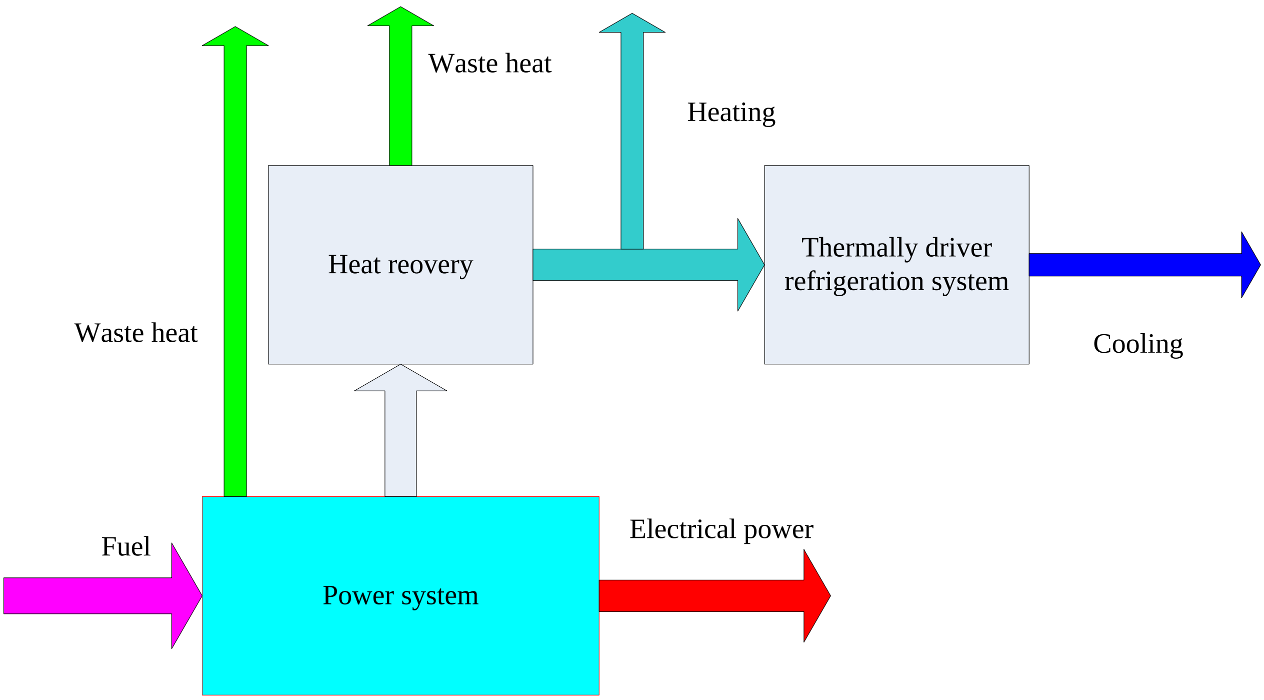

Figure 2: Framework of CCHP system [18]

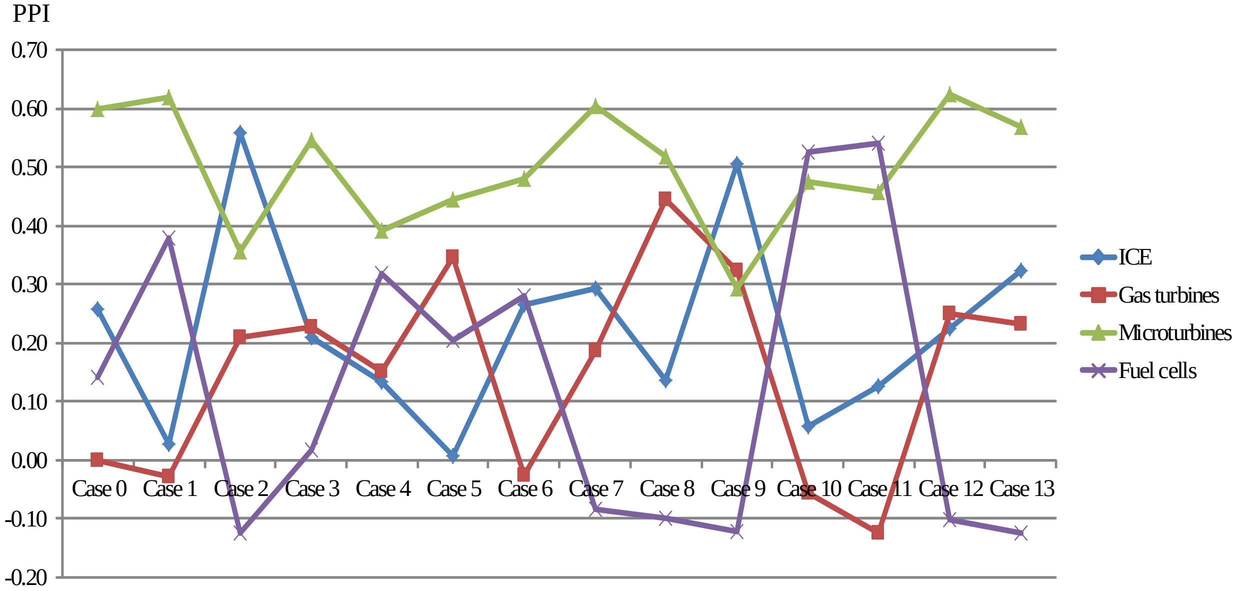

Figure 3: The results of sensitivity analysis

Tables

Table 1: Nine-scale in Saaty method

Scale	Definition	Note
1	Equal importance	*i* is equally important to *j*
3	Moderate importance	*i* is moderately important to *j*
5	Essential importance	*i* is essentially important to *j*
7	Very Strong importance	*i* is very strongly important to *j*
9	Absolute importance	*i* is very absolutely important to *j*
2, 4, 6, 8	Intermediate value	The relative importance of *i* to *j* is between the two adjacent judgments

Reference: [12]

Table 2: Consistency Index (CI) table

m_{BW}	1	2	3	4	5	6	7	8	9
Consistency index (max ξ)	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

Reference: [10-11]

Table 3: The results of the programming (35) and (36)

ξ^*	ω_{EC}^M	ω_{EN}^M	ω_T^M	ω_S^M
0.9240	0.2759	0.1432	0.5120	0.0690
λ	d_{EC}	d_{EN}	d_T	d_S
0.0789	0.0789	0.0254	0.0789	0.0269

Table 4: The BO and OW vectors for determining the weights of the three criteria (installed cost-EC_1, operation and maintenance cost-EC_2, and equipment life-EC_3) in economic dimension

	The most important: installed cost		The least important: operation and maintenance cost
Criteria	EC_1	EC_2	EC_3
BO	1	[3 5]	[2 4]
OW	[3 5]	1	[1 3]
Central weights	0.6220	0.1429	0.2351
Radius	0.0637	0.0434	0.0637
Interval weights	[0.5583 0.6857]	[0.0995 0.1863]	[0.1714 0.2988]
$\xi^* = 0.3542$	CI=1.63	$CR = \frac{\xi^*}{CI} = \frac{0.3542}{1.63} = 0.2173$	

Table 5: The BO and OW vectors for determining the weights of the three criteria (noise-EN_1, CO_2 emissions-EN_2, and NO_x emissions-EN_3) in environmental dimension

	The most important: CO_2 emission		The least important: Noise
Criteria	EN_1	EN_2	EN_3
BO	[4 7]	1	[2 3]
OW	1	[4 7]	[2 3]
Central weights	0.1111	0.6253	0.2636
Radius	0.0349	0.0414	0.0414
Interval weights	[0.0762 0.1460]	[0.5839 0.6667]	[0.2222 0.3050]
$\xi^* = 0.1277$	CI=2.6459	$CR = \frac{\xi^*}{CI} = \frac{0.1277}{2.6459} = 0.0483$	

Table 6: The BO and OW vectors for determining the weights of the four criteria (power efficiency-T_1, CCHP overall efficiency-T_2, effective electrical efficiency-T_3, power density-T_4, and start-up time-T_5) in technological dimension

	The most important: CCHP overall efficiency			The least important: Start-up time	
Criteria	T_1	T_2	T_3	T_4	T_5
BO	[2 4]	1	[2 4]	[3 6]	[5 7]
OW	[3 5]	[5 7]	[3 5]	[1 3]	1
Central weights	0.2017	0.4360	0.2017	0.0969	0.0638
Radius	0.0742	0.0742	0.0742	0.0239	0.0519
Interval weights	[0.1275 0.2759]	[0.3618 0.5102]	[0.1275 0.2759]	[0.0730 0.1208]	[0.0119 0.1157]
$\xi^* = 0.8377$	CI=3.0	$CR = \frac{\xi^*}{CI} = \frac{0.8377}{3.0} = 0.2792$			

Table 7: The global weights of the criteria for sustainability assessment of the prime movers for CCHP technologies

Dimension	Weights	Criteria	Local weights	Global weights
Economic	[0.1970 0.3548]	Installed cost-EC_1	[0.5583 0.6857]	[0.1100 0.2433]
		Operation and maintenance cost-EC_2	[0.0995 0.1863]	[0.0196 0.0661]
		Equipment life-EC_3	[0.1714 0.2988]	[0.0338 0.1060]
Environmental	[0.1178 0.1686]	Noise-EN_1	[0.0762 0.1460]	[0.0090 0.0246]
		CO_2 emissions-EN_2	[0.5839 0.6667]	[0.0688 0.1124]
		NO_x emissions-EN_3	[0.2222 0.3050]	[0.0262 0.0514]
Technological	[0.4331 0.5909]	Power efficiency-T_1	[0.1275 0.2759]	[0.0552 0.1630]
		CCHP overall efficiency-T_2	[0.3618 0.5102]	[0.1567 0.3015]
		Effective electrical efficiency-T_3	[0.1275 0.2759]	[0.0552 0.1630]
		Power density-T_4	[0.0730 0.1208]	[0.0316 0.0714]
		Start-up time-T_5	[0.0119 0.1157]	[0.0052 0.0684]
Social	[0.0421 0.0959]	Safety-S_1	[0.5000 0.5000]	[0.0210 0.0480]
		Social acceptability-S_2	[0.5000 0.5000]	[0.0210 0.0480]

Table 8: The relative performances of the four prime movers for CCHP technologies with respect to noise

	The best: Fuel cells		The worst: ICE	
Alternative	ICE	Gas turbines	Microturbines	Fuel cells
BO	[5 7]	[2 3]	[2 3]	1
OW	1	[3 4]	[3 4]	[5 7]
Central weights	0.0736	0.2269	0.2269	0.4725
Radius	0.0521	0.0521	0.0521	0.0521
Interval weights	[0.0215 0.1257]	[0.1748 0.2790]	[0.1748 0.2790]	[0.4204 0.5246]
$\xi^* = 0.4178$	CI=3.0	$CR = \frac{\xi^*}{CI} = \frac{0.4178}{3.0} = 0.1393$		

Table 9: The relative performances of the four prime movers for CCHP technologies with respect to safety

	The best: Fuel cells		The worst: Gas turbines	
Alternative	ICE	Gas turbines	Microturbines	Fuel cells
BO	[2 3]	[4 7]	[3 6]	1
OW	[3 5]	1	[2 3]	[4 7]
Central weights	0.2896	0.0789	0.1343	0.4971
Radius	0.0929	0.0774	0.0360	0.0929
Interval weights	[0.1967 0.3825]	[0.0015 0.1563]	[0.0983 0.1703]	[0.4042 0.5900]
$\xi^* = 0.7984$	CI=2.6459	$CR = \frac{\xi^*}{CI} = \frac{0.7984}{2.6459} = 0.3017$		

Table 10: The relative performances of the four prime movers for CCHP technologies with respect to social acceptability

	The best: Fuel cells		The worst: ICE	
Alternative	ICE	Gas turbines	Microturbines	Fuel cells
BO	[2 4]	[2 3]	[1 2]	1
OW	1	[2 3]	[1 3]	[2 4]
Central weights	0.1099	0.2085	0.2859	0.3957
Radius	0.0880	0.0880	0.0880	0.0218
Interval weights	[0.0219 0.1979]	[0.1205 0.2965]	[0.1979 0.3739]	[0.3739 0.4175]
$\xi^* = 0.6021$	CI=1.00	$CR = \frac{\xi^*}{CI} = 0.6021$		

Table 11: The decision-making matrix for sustainability assessment of prime movers for CCHP technologies

		ICE	Gas turbines	Microturbines	Fuel cells
Installed cost-EC_1	$/kWe	[1100 2200]	[970 1300]	[2400 3000]	[5000 6500]
Operation and maintenance cost-EC_2	$/kWe	[0.009 0.022]	[0.004 0.011]	[0.012 0.025]	[0.032 0.038]
Equipment life-EC_3	Years	[20 20]	[20 20]	[10 10]	[10 10]
Noise-EN_1	/	[0.0215 0.1257]	[0.1748 0.2790]	[0.1748 0.2790]	[0.4204 0.5246]
CO_2 emissions-EN_2	$kg.MWh^{-1}$	[504 651]	[525 680]	[725 725]	[430 490]
NO_x emissions-EN_3	$kg.MWh^{-1}$	[0.23 9.9]	[0.14 0.50]	[0.18 0.18]	[0.0045 0.014]
Power efficiency-T_1	%	[22 40]	[22 36]	[18 27]	[30 50]
CCHP overall efficiency-T_2	%	[70 80]	[70 75]	[65 75]	[55 80]
Effective electrical efficiency-T_3	%	[70 80]	[50 70]	[50 70]	[55 80]
Power density-T_4	kWm^{-2}	[35 50]	[20 500]	[5 70]	[5 20]
Start-up time-T_5	s	[10 10]	[600 3600]	[60 60]	[10800 172800]
Safety-S_1	/	[0.1967 0.3825]	[0.0015 0.1563]	[0.0983 0.1703]	[0.4042 0.5900]
Social acceptability-S_2	/	[0.0219 0.1979]	[0.1205 0.2965]	[0.1979 0.3739]	[0.3739 0.4175]

References: [2,23]

Table 12: The integrated priorities of the four alternative prime movers for CCHP technologies

Prime movers	ICE	Gas turbines	Microturbines	Fuel cells
Integrated priorities	[0 0.5849]	[0.0074 0.5838]	[0.1843 0.8021]	[0.1534 0.9731]

Table 13: The priority performance indexes of the four alternative prime movers for CCHP technologies

Prime movers	ICE	Gas turbines	Microturbines	Fuel cells
PPI	0.1594	0.1614	0.3209	0.3583
Ranking	4	3	2	1