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# Distributed Energy System for Sustainability Transition: A Comprehensive Assessment under Uncertainties based on Interval Multi-Criteria Decision Making Method by Coupling Interval DEMATEL and Interval VIKOR

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**Abstract:** Distributed energy system (DES) has been recognized as a promising solution for energy security improvement and emissions mitigation all over the world. However, there are usually various DES configurations with different performances, and it is usually difficult for the decision-makers to select the most sustainable DES solution among multiple choices. This study aims to develop a comprehensive a framework for sustainability prioritization of distributed energy systems under data uncertainties. An interval multi-criteria decision making method which can address data uncertainties was developed by combining the interval Decision Making Trail and Evaluation Laboratory (DEMATEL) and the interval VIKOR method. Four distributed energy systems including gas turbine system, fuel cell system, photovoltaic system, and internal combustion engine system were studied by the proposed method, and photovoltaic system has been recognized as the most sustainable scenario, following by fuel cell system, gas turbine system, and internal combustion engine system in the descending order. In order to investigate the effects of the weights on the final sustainability ranking of the four distributed energy systems, sensitivity analysis was carried out , and the results reveal that the weights of the criteria have significant impacts on the sustainability rankings of these four distributed energy systems.

**Keywords:** distributed energy system; sustainability assessment; interval numbers; multi-criteria decision making; DEMATEL

## NOMENCLATURE

### *Abbreviations*

AHP: Analytic Hierarchy Process

DEMATEL: Decision Making Trail and Evaluation Laboratory

$EC_1$: capital cost (Yuan RMB)

$EC_2$: operations cost (Yuan RMB)

$EC_3$: energy consumption (MW.h)

$EN_1$: annual CO2 emission (tons)

$EN_2$: annual $NO_x$ emission (tons)

Electre: ELimination Et Choix Traduisant la REalité (ELimination and Choice Expressing REality).

PIS: positive ideal solutions

PROMETHEE: Preference Ranking Organization METHod for Enrichment of Evaluations

NIS: negative ideal solutions

$S_1$: social acceptability

$T_1$: utilization rate of the primary energy (%)

$T_1$: technological maturity

VIKOR: VlseKriterijuska Optimizacija I Komoromisno Resenje

### *Symbols*

$A_k^{\pm}$ : the grey direct-influenced matrix determined by the *k*-th group of stakeholders/decision-makers

$A^{\pm}$ : the average interval direct-influenced matrix

$a_{ij}^{\pm}$ : the element of cell (i,j) in the average interval direct-influenced matrix.

$B^{\pm}$ : the normalized average interval direct-influenced matrix

$C_j^{\pm}$ : the total direct and indirect influences received by the *j*-th criterion

$C_i^{-}$ : the lower bound of $C_i^{\pm}$

$C_i^{+}$ : the upper bound of $C_i^{\pm}$

I : the identity matrix

$m\left(x^{\pm}\right)$: the mid-point of the interval number $x^{\pm}$
P: the probability matrix

$P^{+}$: the set of the positive ideal solutions
$P^{-}$: the set of the negative ideal solutions
$p_j^{+}$ : the positive ideal solutions with respect to the j-th criterion

$p_j^{-}$ : the negative ideal solutions with respect to the j-th criterion

$P_{ij}$: the possibility degree of $\left[Q_i^{-} \quad Q_i^{+}\right] \geq \left[Q_j^{-} \quad Q_j^{+}\right]$.

$R_i^{\pm}$: the total influences which were directly and indirectly exerted by the *i*-th criterion, $R_i^{-}$: the lower bound of $R_i^{\pm}$
$R_i^{+}$: the upper bounds of $R_i^{\pm}$
$T^{\pm}$: the total interval relation matrix
$v$: the weight of the strategy with respect to 'the majority of attributes'
$W_i$: the relative weight of the *i*-th alternative
$w\left(x^{\pm}\right)$: the mid-point and half-width of the interval number $x^{\pm}$
$\omega_i^{\pm}$: an interval number represents the interval weight of the *i*-th criterion
$\omega_i^{-}$: the lower bound of the interval weight of the *i*-th criterion $\omega_i^{\pm}$
$\omega_i^{+}$: the upper bound of the interval weight of the *i*-th criterion $\omega_i^{\pm}$
$\left[\omega_j^{-} \quad \omega_j^{+}\right]$: the interval weight of the *j*-th criterion
$x^{\pm}$: interval number, and its lower and upper bounds are $x^{-}$ and $x^{+}$, respectively
$\left[x_{ij}^{-} \quad x_{ij}^{+}\right]$: the data of the *i*-th alternative with respect to the *j*-th evaluation criterion

$y^{\pm}$: interval number, and its lower and upper bounds are $y^{-}$ and $y^{+}$, respectively
$\left[y_{ij}^{-} \quad y_{ij}^{+}\right]$: the element of cell (i,j) in the standardized interval decision-making matrix.

$\lambda$: the parameter for standardizing the average interval direct-influenced matrix

## 1. Introduction

Distributed energy system relying on distributed energy sources (i.e. photovoltaic, microoturbines, gas turbine, internal combustion turbines, and fuel cells) represents the small scale (ranging from less than a kW to tens of MW) power generation system which usually located at or near the end-users, it has attracted more and more attentions recently, because the distributed energy has been recognized as a promising alternative energy scenario to substitute the traditional centralized energy system for its advantages of high energy efficiency, good reliability, and environmentally-friendly performances (Ren *et al*., 2010; Ren and Gao, 2010). Meanwhile, the distributed energy system has three main characteristics including distributed generation (local energy generated from various types of energy), demand response (energy supply based on customer participation), and distributed storage (local energy storage in various devices) (Chicco and Mancarella, 2009). Thus, the distributed energy system can effectively satisfy the customers demand on cooling, heating, and electricity and improve energy use efficiency. Therefore, the promotion of sustainable development of the distributed energy systems is significantly beneficial for emissions reduction and energy saving.

A distributed energy system which is usually a complex configuration consists of a numbers of energy suppliers and energy end-users (Söderman and Pettersson, 2006), and there are also a variety of factors which influence the future role of distributed energy systems (Mehigan *et al*., 2018). In addition, there are usually two or more types of energy outputs (i.e. cooling, heating, electricity, hydrogen, and various chemical substances) in a distributed energy system-so-called "distributed multi-generation" (Chicco and Mancarella, 2009), and the whole system also had intermittent and unstable features. All these characteristics (including both strengths and weak points) make the decision-makers difficult to determine the best distributed energy system among multiple alternatives. Many studies have been carried out to evaluate the energy performance of distributed energy systems (Wang *et al*., 2018). As for helping the decision-makers to determine the best distributed energy system, there are two types of studies: one is focusing on developing mathematical models to help the decision-makers to optimize the distributed energy systems, and another is about selecting the best distributed energy system among multiple scenarios. As for the first type, there are plenty of studies. These studies mainly developed various mathematical models for optimizing the economic objective under various variables in DES, and the total cost or the total annualized cost were employed as the objective function. For instance, Ren and Gao (2010) developed a mixed-integer linear programming (MILP) for optimum design of distributed energy systems, and the total cost was employed as the objective to be minimized. Mehleri *et al.* (2012) developed a MILP superstructure model for optimum selection of energy system components and optimum design of heating pipeline network and finally to achieve optimum design of distributed energy systems at the neighbourhood level, and the total annualized cost was established as the objective function to be minimized. There are also some other studies which employ economic objective in the models for optimal design of distributed energy systems (Yang *et al*., 2015; Mehleri, *et al*., 2013). However, the environmental and social objectives cannot be incorporated in these models. In order to address this, some multi-objective optimization models which can also incorporate environmental or/and social objectives were developed for optimal design of distributed energy systems. These models usually consider both economic objective and environmental or/and social objectives. The total amount of $CO_2$ emissions was usually used as the environmental objective in these models. For instance, Falke *et al*. (2016) developed a bi-objective model which employed both annual costs of energy supply and the environmental impact in terms of emitted CO2 equivalents as the objectives to be minimized for optimal design of distributed energy systems. Ren *et al*. (2010) used annual energy cost and annual $CO_2$ emissions as the two objectives to be optimized for optimal design of distributed energy systems. However, these studies cannot address data uncertainties though they can cope with the environmental impacts. Therefore, some mathematical models for optimizing the distributed energy systems under data uncertainties were also developed. For instance, *Zhou et al*. (2013) employed the two-stage stochastic programming which can incorporate uncertainties to optimize the distributed energy systems. Mavromatidis *et al.* (2018) also developed a two-stage stochastic model for the distributed energy system design under uncertainty conditions, and multiple criteria are used to represent the attitudes on uncertainties.Accordingly, it could be concluded that there are two main research gaps for sustainability-oriented design of distributed energy systems, one is that it lacks the models which can consider economic, environment and social objectives simultaneously, and another is that it lacks the method which can optimize distributed energy systems under uncertainties. As for the selection of the best distributed energy system among different alternatives, there are only a few studies focusing on developing the methods for helping the stakeholders/decision-makers to prioritize the distributed energy systems. Multi-Criteria Decision Making (MCDM) methods (e.g., AHP, Electre, and PROMETHEE, etc.) were usually used to rank the alternative distributed energy systems with the evaluation based on multiple indicators. For instance, Papadopoulos and Karagiannidis (2008) employed the Electre III for the selection of distributed energy systems, the criteria in economic, environmental and network stability categories were used to measure the distributed energy systems. Ren *et al.* (2009) combined AHP and PROMETHEE as the multi-criteria evaluation method for selecting the best distributed residential energy systems in Japan, AHP was employed to determine the weights of the evaluation criteria, and PROMETHEE was employed to rank these alternatives. All these multi-criteria decision making methods can only rank the alternative distributed energy systems when all the data in the decision-making matrix are all crisp numbers. However, there are usually two main kinds of uncertainties in the selection of the best distributed energy system, one is aleatory uncertainties caused by the variations of the external environment, and another is epistemic uncertainties due to the lack of knowledge or information in the decision-making process (Liu and Huang, 2012). Actually, the data of the alternative distributed energy systems with respect to the evaluation criteria in the decision-making matrix are not always crisp numbers, and they usually vary within different intervals. Therefore, these methods cannot address the problem when some data of the alternative distributed energy systems with respect to some criteria are not crisp numbers as well as the case with some soft criteria for the evaluation of distributed energy systems. In order to address these problems, some multi-criteria decision analysis methods based on fuzzy set theory were developed. For instance, Wang *et al*. (2008) employed the fuzzy multi-criteria decision making model for the selection and evaluation of trigeneration systems, linguistic terms corresponding to fuzzy numbers were used to describe the alternative distributed energy systems with respect to the soft criteria (i.e. control property, maturity and maintenance convenience). Kaya and Kahraman (2010) used fuzzy AHP to determine the weights of the evaluation criteria and VIKOR method was employed to rank the alternative renewable energy options by considering the criteria in technical, economic, environmental and social aspects. Xiao *et al*. (2012) employed the interval entropy weight method was used address the uncertainties existing in distributed generation planning when it is difficult the exact numerical values with respect to the evaluation criteria. These methods can address uncertainties when ranking alternative distributed energy systems. However, it still lacks the method which can fill the following research gaps simultaneously, and they are:

(1) The lack of the method for incorporating the preferences/opinions of different stakeholders when determining the weights of the criteria for evaluating the distributed energy systems, and the previous studies determined the weights of the evaluation criteria only based on a specific group of stakeholders rather than different groups of stakeholders;

(2) The lack of the method for addressing the ambiguity and vagueness existing in human

judgments when using the traditional weighting method (i.e. AHP method and various weighting methods derived from AHP) to determine the weights of the evaluation criteria. It is usually difficult for the users to use the crisp numbers (i.e. the numbers from 1 to 9) to describe the relative importance of one criterion over another or the relative influence of one criterion on another;

(3) The lack of the method which can handle the data uncertainties when using the multi-criteria decision making methods for sustainability ranking of the distributed energy systems. In almost all these previous studies, the data of the alternative distributed energy systems with respect to the evaluation criteria were assumed to be fixed, but this assumption does not match well with the actual conditions, because the data usually vary due to the influence of external environment. Meanwhile, it is also difficult for the users to use crisp numbers to describe the performances of the alternative distributed energy systems with respect to the evaluation criteria due to various kinds of uncertainties (Ren *et al*., 2018).

In order to resolve the above-mentioned three research gaps, an interval multi-criteria decision making method was developed for sustainability ranking of the distributed energy systems by combining the interval DEMATEL and the interval VIKOR method. The developed interval DEMATEL was employed to determine the weights of the evaluation criteria for sustainability ranking of distributed energy systems, and the interval VIKOR method which can address uncertainties was used to determine the priority order of the alternative distributed energy systems according to their sustainability.

## 2. Methods

This section consists of four parts including the criteria systems for sustainability ranking of distributed energy systems, the introduction of the interval numbers, the interval DEMATEL, and the interval VIKOR method.

2.1 Criteria system

Chicco and Mancarella (2009) pointed out that the analysis and planning of the distributed energy systems should take into account technical, economic, environmental, and social aspects. Thus, eight criteria in four dimensions were used for sustainability ranking of distributed energy systems based on the works of Zhang *et al.* (2014) and Dong *et al.* (2016) in this study. There are three criteria including capital cost ($EC_1$), operations cost ($EC_2$), and energy consumption ($EC_3$) in economic aspect. The technological aspect consists of the utilization rate of the primary energy ($T_1$) and technological maturity ($T_2$). The environmental aspect includes annual $CO_2$ emission ($EN_1$) and annual $NO_x$ emission ($EN_2$). Social acceptability ($S_1$) is the only criterion in social aspect to measure social performances of distributed energy systems. It is worth pointing out that the users can delete some or add more criteria in each aspect of the criteria system for sustainability ranking of distributed energy systems according to the preferences of the decision-makers and the actual conditions.

2.2 Interval number

Interval numbers which are different from the traditional crisp numbers whose values are exact numbers, they are usually in the format of intervals or ranges. Let $x^{\pm} = \left[x^{-} \quad x^{+}\right]$ be an interval number, and its lower and upper bounds are $x^{-}$ and $x^{+}$, respectively. Different from other theories, the users can adopt the interval approach to represent the uncertainties when knowing the lower and upper bounds, but they have to know to the probability function or the membership function in they employ the stochastic theory or fuzzy theory to address uncertainties. Note that $x^{-}$ and $x^{+}$ are both real numbers, and $x^{-} \leq x^{+}$. Accordingly, a crisp number $x$ can also be rewritten in the format of an interval number $x = \left[x, x\right]$ if $x = x^{-} = x^{+}$.

As for the interval number $x^{\pm} = \left[ x^{-} \quad x^{+} \right]$, its mid-point and half-width can be determined by Eq.1 and Eq.2, respectively (Sengupta and Pal, 2000).

$$m\left(x^{\pm}\right) = \frac{\left(x^{-} + x^{+}\right)}{2} \tag{1}$$

$$w\left(x^{\pm}\right) = \frac{\left(x^{+} - x^{-}\right)}{2} \tag{2}$$

where $m\left(x^{\pm}\right)$ and $w\left(x^{\pm}\right)$ are the mid-point and half-width of the interval number $x^{\pm}$, respectively.

Let $x^{\pm} = \left[ x^{-} \quad x^{+} \right]$ and $y^{\pm} = \left[ y^{-} \quad y^{+} \right]$ be two interval numbers, and $\mu$ be a crisp number, the arithmetic operations were presented in Table 1 based on the works of Li *et al.* (2017) and Sengupta and Pal (2000).

**Table 1:** The operations for the interval numbers

| Arithmetic operations | Formulas | Equation |
|---|---|---|
| Addition | $x^{\pm}+y^{\pm}=\left[x^{-}\quad x^{+}\right]+\left[y^{-}\quad y^{+}\right]=\left[x^{-}+y^{-},x^{+}+y^{+}\right]$ | (3) |
| | $x^{\pm}+\mu=\left[x^{-}\quad x^{+}\right]+\left[\mu\quad \mu\right]=\left[x^{-}+\mu,x^{+}+\mu\right]$ | (4) |
| Subtraction | $x^{\pm}-y^{\pm}=\left[x^{-}\quad x^{+}\right]-\left[y^{-}\quad y^{+}\right]=\left[x^{-}-y^{+},x^{+}-y^{-}\right]$ | (5) |
| | $x^{\pm}-\mu=\left[x^{-}\quad x^{+}\right]-\left[\mu\quad \mu\right]=\left[x^{-}-\mu,x^{+}-\mu\right]$ | (6) |
| Multiplication | $x^{\pm}\times y^{\pm}=\left[x^{-}\quad x^{+}\right]\times\left[y^{-}\quad y^{+}\right]=\left[x^{-}y^{-},x^{+}y^{+}\right]$ | (7) |
| | $x^{\pm}\times\mu=\left[x^{-}\quad x^{+}\right]\times\left[\mu\quad \mu\right]=\left[\mu x^{-},\mu x^{+}\right]$ | (8) |
| Division | $x^{\pm}/y^{\pm}=\left[x^{-}\quad x^{+}\right]/\left[y^{-}\quad y^{+}\right]=\left[x^{-}/y^{+},x^{+}/y^{-}\right]$ | (9) |
| | $x^{\pm}/\mu=\left[x^{-}\quad x^{+}\right]/\left[\mu\quad \mu\right]=\left[x^{-}/\mu,x^{+}/\mu\right]$ | (10) |
| | where $0<x^{-}\le x^{+}, 0<y^{-}\le y^{+}$, and $0<\mu$ | |

**Reference:** Li *et al.* (2017) and Sengupta and Pal (2000)

## 2.3 Interval DEMATEL

Different from the traditional DEMATEL method in which the experts usually were asked to use "No influence (0)", "Low influence (1)", "Medium influence (2)", "High influence (3)", and "Very high influence (4)" which correspond to a crisp number to describe the influence of a criterion over another (Fontela and Gabus, 1974), the developed interval DEMATEL allows the users to use the interval numbers to describe the relative influence or effect of a criterion over another. For instance, if the users hold the view that the relative influence of a criterion over another is between "Medium influence (2)" and "Very high influence (4)", then, the interval [2 4] will be used to represent the corresponding influence. This is similar but different from the grey DEMATEL method (Bai and Sarkis, 2013; Ren *et al*., 2017) which only uses the grey numbers such as [0 0], [0 1], [1 2], [2 3] and [3 4] to describe the influence of an criterion on another, the interval number representing the influence between each pair of criteria can be determined by the users according to their judgments and the actual conditions.

The developed interval DEMATEL for determining the weights of the criteria was specified in the following five steps:

**Step 1:** Ask each of the stakeholders to use interval numbers to establish the direct-influenced matrices;

**Step 2:** Determine the average interval direct-influenced matrix;

**Step 3:** Normalize the average interval direct-influenced matrix;

**Step 4:** Calculate the total interval relation matrix; and

**Step 5:** Determine the interval weights of the criteria.

These five steps were specified as follows based on the works of Gao and Lu (2014) and Bai and Sarkis (2013) :

**Step 1:** Ask each of the stakeholders to use interval numbers to establish the direct-influenced matrices (Feng *et al.,* 2017). This step aims at investigating the complex relationships between each pair of the criteria by using interval numbers, and they can firstly use linguistic terms to express their options and views about the relative influence of a criterion on another.

The participants (i.e. representative experts, stakeholders, and decision-makers) will be asked to determine the effect level of a criterion on another according to their preferences/opinions. Assuming that there are a total n criteria (i=1,2,...,n) to be studied, and the relative influence of the

$i$-th criterion on the $j$-th criterion determined by the participants can be firstly depicted by using the linguistic variables. It is worth pointing out that the participants can firstly use the phase such "between no influence (0) and medium influence (2)" to describe the relationship, then, the qualitative description can be transformed into interval number [0 2]. Note that if the participants used a single linguistic term among "No influence (0)", "Low influence (1)", "Medium influence (2)", "High influence (3)", and "Very high influence (4)" to describe the relative influence, these description should be transformed into crisp numbers. For instance, "Low influence (1)" corresponding to 1 can also be represented in the format of interval number [1 1].

**Step 2:** Determine the average interval direct-influenced matrix (Ren *et al*., 2017). The relative influence of the $i$-th criterion on the $j$-th criterion determined by the $k$-th group of stakeholders/decision-makers (there are a total of K groups of participants) can be denoted by $a_{ij,k}^{\pm} = \left[ a_{ij,k}^{-}, a_{ij,k}^{+} \right]$ .The interval direct-influenced matrix determined by the $k$-th stakeholders/decision-makers is an $n$ by $n$ matrix, as presented in Eq.11.

$$A_k^{\pm} = \begin{bmatrix} [0,0] & a_{12,k}^{\pm} & \cdots & a_{1n,k}^{\pm} \\ a_{21,k}^{\pm} & [0,0] & \cdots & a_{2n,k}^{\pm} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1,k}^{\pm} & a_{n2,k}^{\pm} & & [0,0] \end{bmatrix} \tag{11}$$

where $A_k^{\pm}$ is the grey direct-influenced matrix determined by the $k$-th group of stakeholders/decision-makers.

Then, the average interval direct-influenced matrix can be determined by Eqs.12-13.

$$A^{\pm} = \begin{bmatrix} [0,0] & a_{12}^{\pm} & \cdots & a_{1n}^{\pm} \\ a_{21}^{\pm} & [0,0] & \cdots & a_{2n}^{\pm} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1}^{\pm} & a_{n2}^{\pm} & & [0,0] \end{bmatrix} \tag{12}$$

$$a_{ij}^{\pm} = \frac{\sum_{k=1}^{K} a_{ij,k}^{\pm}}{K} = \left[ \frac{\sum_{k=1}^{K} a_{ij,k}^{-}}{K}, \frac{\sum_{k=1}^{K} a_{ij,k}^{+}}{K} \right] \tag{13}$$

where $A^{\pm}$ represents the average interval direct-influenced matrix, and $a_{ij}^{\pm}$ represents the element of cell (i,j) in the average interval direct-influenced matrix.

**Step 3:** Normalize the average interval direct-influenced matrix (Wu *et al.*, 2018). The normalized average interval direct-influenced matrix $B^{\pm}$ can be determined by Eqs.14-15.

$$\lambda = \max\left( \max_{1 \le i \le n} \sum_{j=1}^{n} a_{ij}^{+}, \max_{1 \le j \le n} \sum_{i=1}^{n} a_{ij}^{+} \right) \tag{14}$$

$$B^{\pm} = \left[ \otimes b_{ij} \right]_{n \times n} = \left[ \left( b_{ij}^{-}, b_{ij}^{+} \right) \right]_{n \times n} = \frac{A^{\pm}}{\lambda} \tag{15}$$

where $B^{\pm}$ is the normalized average interval direct-influenced matrix, and $\lambda$ is the parameter for standardizing the average interval direct-influenced matrix.

**Step 4:** Calculate the total interval relation matrix (Wu *et al.*, 2018). The powers of $B^{\pm}$ represent the indirect effects between each pair of the factors. And, the total relation matrix $T^{\pm}$ could be determined by Eq.16-20.

$$T^{\pm} = \left[ t_{ij}^{\pm} \right]_{n \times n} = \left[ \left( t_{ij}^{-}, t_{ij}^{+} \right) \right]_{n \times n} = \otimes B^{\pm} + \left( \otimes B^{\pm} \right)^{2} + \cdots + \left( \otimes B^{\pm} \right)^{\infty} \tag{16}$$

$$T^{-} = \left[ t_{ij}^{-} \right]_{n \times n} = B^{-} (I - B^{-})^{-1} \tag{17}$$

$$T^{+} = \left[ t_{ij}^{+} \right]_{n \times n} = B^{+} (I - B^{+})^{-1} \tag{18}$$

$$B^{-} = \left[ b_{ij}^{-} \right]_{n \times n} \tag{19}$$

$$B^{+} = \left[ b_{ij}^{+} \right]_{n \times n} \tag{20}$$

where $T^{\pm}$ represents the total interval relation matrix, and $I$ represents the identity matrix.

**Step 5:** Determine the interval weights of the criteria. The total influences which were directly and indirectly exerted by the *i*-th criterion can be determined by Eq.21.

$$R_i^{\pm} = \sum_{j=1}^{n} \otimes t_{ij}^{\pm} = \begin{bmatrix} R_i^- & R_i^+ \end{bmatrix} \tag{21}$$

where $R_i^{\pm}$ represents the total influences which were directly and indirectly exerted by the *i*-th criterion, $R_i^-$ and $R_i^+$ are the lower and upper bounds of $R_i^{\pm}$.

The total direct and indirect influences received by the *j*-th criterion can be determined by Eq.22.

$$C_j^{\pm} = \sum_{i=1}^{n} \otimes t_{ij}^{\pm} = \begin{bmatrix} C_i^- & C_i^+ \end{bmatrix} \tag{22}$$

where $C_j^{\pm}$ represents the total direct and indirect influences received by the *j*-th criterion, $C_i^-$ and $C_i^+$ are the lower and upper bounds of $C_i^{\pm}$.

The interval weights of the criteria can be determined by Eqs.23-25 (Liu *et al.,* 2015).

$$\omega_i^{\pm} = \frac{\sqrt{\left(R_i^{\pm}\right)^2 + \left(C_i^{\pm}\right)^2}}{\sum_{i=1}^{n} \sqrt{\left(R_i^{\pm}\right)^2 + \left(C_i^{\pm}\right)^2}} = \begin{bmatrix} \omega_i^- & \omega_i^+ \end{bmatrix} \tag{23}$$

where $\omega_i^{\pm}$ which is an interval number represents the interval weight of the *i*-th criterion.

The lower and upper bounds of the interval weight of the *i*-th criterion can be determined by Eq.24 and Eq.25, respectively.

$$\omega_i^- = \frac{\sqrt{\left(R_i^-\right)^2 + \left(C_i^-\right)^2}}{\sum_{i=1}^{n} \sqrt{\left(R_i^+\right)^2 + \left(C_i^+\right)^2}} \tag{24}$$

$$\omega_i^+ = \frac{\sqrt{\left(R_i^+\right)^2 + \left(C_i^+\right)^2}}{\sum_{i=1}^{n} \sqrt{\left(R_i^-\right)^2 + \left(C_i^-\right)^2}} \tag{25}$$

where $\omega_i^-$ and $\omega_i^+$ represents the lower and upper bounds of the interval weight of the *i*-th criterion

$\omega_i^{\pm}$, respectively.

2.4 Interval VIKOR method

The compromise ranking algorithm of the interval VIKOR method developed by Ren (2018a) based on the works of Opricovic and Tzeng (2007), Park *et al*. (2011), Vahdani *et al*. (2010), and Sayadi *et al* (2009) was specified in the following six steps:

**Step 1:** Establish the decision-making matrix under data uncertainties.

The decision-making matrix under data uncertainties which can be represented by usingthe interval numbers should be developed in this step, and it consists of two parts, one is the data of the alternatives with respect to the evaluation criteria, and another is the weights of the evaluation criteria, as presented in Eq.26 (Wang *et al*., 2015).

$$\begin{array}{cccccc} & C_1 & C_2 & \cdots & C_n \\ A_1 & x_{11}^{\pm} & x_{12}^{\pm} & \cdots & x_{1n}^{\pm} \\ A_2 & x_{21}^{\pm} & x_{22}^{\pm} & \cdots & x_{2n}^{\pm} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & x_{m1}^{\pm} & x_{m2}^{\pm} & \cdots & x_{mn}^{\pm} \\ & \omega_1^{\pm} & \omega_2^{\pm} & \cdots & \omega_n^{\pm} \end{array} \tag{26}$$

where $A_1$, $A_2$,…, $A_m$ represent the m alternatives (i.e. m alternative distributed energy systems), $C_1$, $C_2$,…, $C_n$ represent the n criteria (i.e. criteria in economic, environmental, technical and social aspects), $x_{ij}^{\pm} = \left[ x_{ij}^{-} \quad x_{ij}^{+} \right]$ represents of the data of the *i*-th alternative with respect to the *j*-th evaluation criterion, $x_{ij}^{-}$ represents the lower bound of the interval number $x_{ij}^{\pm}$, $x_{ij}^{+}$ represents the upper bound of the interval number $x_{ij}^{\pm}$, $\omega_j^{\pm} = \left[ \omega_j^{-} \quad \omega_j^{+} \right]$ represents the interval weight of the *j*-th criterion, $\omega_j^{-}$ represents the lower bound of $\omega_j^{\pm}$, and $\omega_j^{+}$ represents the upper bound of $\omega_j^{\pm}$.

**Step 2:** Normalizing the interval decision-making matrix.

The data with respect to the benefit-type (B) and the cost-type (C) criteria should be normalized by different methods (Ren and Toniolo, 2018). The data with respect to the benefit-type criteria can be normalized by Eq.27.While the data with respect to the cost-type criteria can be normalized by Eq.28 (Ren, 2018a). There are also some other standardizing methods, see the work of Ren (2018b) and that of Xu *et al*. (2018) for more details.

$$y_{ij}^{\pm}=\begin{cases} y_{ij}^{-}=\dfrac{x_{ij}^{-}}{\max\limits_{i=1,2,\cdots,m}\left\{x_{ij}^{+}\right\}} \\ y_{ij}^{+}=\dfrac{x_{ij}^{+}}{\max\limits_{i=1,2,\cdots,m}\left\{x_{ij}^{+}\right\}} \end{cases} \quad j\in B \tag{27}$$

$$y_{ij}^{\pm}=\begin{cases} y_{ij}^{-}=\dfrac{\min\limits_{i=1,2,\cdots,m}\left\{x_{ij}^{-}\right\}}{x_{ij}^{+}} \\ y_{ij}^{+}=\dfrac{\min\limits_{i=1,2,\cdots,m}\left\{x_{ij}^{-}\right\}}{x_{ij}^{-}} \end{cases} \quad j\in C \tag{28}$$

Then, the standardized interval decision-making matrix can be determined, as presented in Eq.29.

$$\begin{array}{cccccc} & C_1 & C_2 & \cdots & C_n \\ A_1 & y_{11}^{\pm} & y_{12}^{\pm} & \cdots & y_{1n}^{\pm} \\ A_2 & y_{21}^{\pm} & y_{22}^{\pm} & \cdots & y_{2n}^{\pm} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & y_{m1}^{\pm} & y_{m2}^{\pm} & \cdots & y_{mn}^{\pm} \\ & \omega_1^{\pm} & \omega_2^{\pm} & \cdots & \omega_n^{\pm} \end{array} \tag{29}$$

where $y_{ij}^{\pm}$ represents the element of cell (i,j) in the standardized interval decision-making matrix, $y_{ij}^{-}$ represents the lower bound of $y_{ij}^{\pm}$, and $y_{ij}^{+}$ represents the upper bound of $y_{ij}^{\pm}$.

**Step 3:** Determine the positive ideal and the negative ideal solutions.

The positive ideal solutions (PIS) and negative ideal solutions (NIS) can be determined by Eqs. 30-

33 (Sayadi *et al*., 2009).

$$P^{+} = \left\{ p_1^{+}, p_2^{+}, \cdots, p_n^{+} \right\} \tag{30}$$

$$p_j^{+} = \max_{i=1,2,\cdots,m} \left\{ y_{ij}^{+} \right\} \qquad j = 1, 2, \cdots, n \tag{31}$$

$$P^{-} = \left\{ p_1^{-}, p_2^{-}, \cdots, p_n^{-} \right\} \tag{32}$$

$$p_j^{-} = \min_{i=1,2,\cdots,m} \left\{ y_{ij}^{-} \right\} \qquad j = 1, 2, \cdots, n \tag{33}$$

where $P^{+}$ represents the set of the positive ideal solutions, $P^{-}$ represents the set of the negative ideal solutions, $p_j^{+}$ and $p_j^{-}$ represent the positive ideal and the negative ideal solutions with respect to the *j*-th criterion, respectively. Note that $P^{+} = \{1, 1, \cdots, 1\}$ after the normalization process.

**Step 4:** Calculating $S_i^{\pm}$ and $R_i^{\pm}$. $S_i^{\pm}$ and $R_i^{\pm}$ can be determined by Eqs.34-37, and it is worth pointing out that the weight of the evaluation criteria were determined by the developed interval DEMATEL in this study.

$$S_i^{\pm} = \left[ S_i^{-} \quad S_i^{+} \right] \tag{34}$$

$$S_i^{\pm} = \begin{cases} S_i^{-} = \sum_{j=1}^{n} \dfrac{\omega_j^{-} (p_j^{+} - y_{ij}^{+})}{\left( p_j^{+} - p_j^{-} \right)} \\ S_i^{+} = \sum_{j=1}^{n} \dfrac{\omega_j^{+} (p_j^{+} - y_{ij}^{-})}{\left( p_j^{+} - p_j^{-} \right)} \end{cases}, i = 1, 2, \cdots, m \tag{35}$$

$$R_i^{\pm} = \left[ R_i^{-} \quad R_i^{+} \right] \tag{36}$$

$$R_i^{\pm} = \begin{cases} R_i^{-} = \max_{j} \dfrac{\omega_j^{-} (p_j^{+} - y_{ij}^{+})}{\left( p_j^{+} - p_j^{-} \right)} \\ R_i^{+} = \max_{j} \dfrac{\omega_j^{+} (p_j^{+} - y_{ij}^{-})}{\left( p_j^{+} - p_j^{-} \right)} \end{cases}, i = 1, 2, \cdots, m \tag{37}$$

**Step 5:** Calculate the values of $Q_i^{\pm}$ according to Eqs. 38-39 (Ren, 2018a).

$$Q_i^{\pm} = \left[ Q_i^{-} \quad Q_i^{+} \right] \tag{38}$$

$$Q_i^{\pm} = \begin{cases} Q_i^{-} = \dfrac{(S_i^{-} - \min\limits_{i=1,2,\cdots,m}\left\{S_i^{-}\right\})}{2\left(\max\limits_{i=1,2,\cdots,m}\left\{S_i^{+}\right\} - \min\limits_{i=1,2,\cdots,m}\left\{S_i^{-}\right\}\right)} + \dfrac{(R_i^{-} - \min\limits_{i=1,2,\cdots,m}\left\{R_i^{-}\right\})}{2\left(\max\limits_{i=1,2,\cdots,m}\left\{R_i^{+}\right\} - \min\limits_{i=1,2,\cdots,m}\left\{R_i^{-}\right\}\right)} \\ Q_i^{-} = \dfrac{(S_i^{+} - \min\limits_{i=1,2,\cdots,m}\left\{S_i^{-}\right\})}{2\left(\max\limits_{i=1,2,\cdots,m}\left\{S_i^{+}\right\} - \min\limits_{i=1,2,\cdots,m}\left\{S_i^{-}\right\}\right)} + \dfrac{(R_i^{+} - \min\limits_{i=1,2,\cdots,m}\left\{R_i^{-}\right\})}{2\left(\max\limits_{i=1,2,\cdots,m}\left\{R_i^{+}\right\} - \min\limits_{i=1,2,\cdots,m}\left\{R_i^{-}\right\}\right)} \end{cases} \tag{39}$$

.

**Step 6:** Ranking the alternatives according to the values of $Q_i^{\pm}$. The value of $Q_i^{\pm}$ with respect to the *i*-th alternative can be recognized as its integrated weakness or disadvantage, and then, these m alternatives can be prioritized. As for the process of using interval VIKOR for sustainability ranking of distributed energy systems, the greater the value of $Q_i^{\pm}$, the less sustainable the corresponding system will be.

According to the work of Li *et al.* (2017), the possibility degree of $Q_p^{\pm} = \left[ Q_p^{-} \quad Q_p^{+} \right] \geq Q_q^{\pm} = \left[ Q_q^{-} \quad Q_q^{+} \right]$ can be calculated by Eq.40.

$$P\left\{Q_p^{\pm} \geq Q_q^{\pm}\right\} = \frac{1}{2}\left(1 + \frac{(Q_p^{+} - Q_q^{+}) + (Q_p^{-} - Q_q^{-})}{\left|Q_p^{+} - Q_q^{+}\right| + \left|Q_p^{-} - Q_q^{-}\right| + L_{pq}}\right) \tag{40}$$

where $L_{pq} = \min\left\{\max\left\{Q_p^{+} - \max\left(Q_p^{-}, Q_q^{-}\right), 0\right\}, \max\left\{Q_q^{+} - \max\left(Q_p^{-}, Q_q^{-}\right), 0\right\}\right\}$, and $P\left\{Q_p^{\pm} \geq Q_q^{\pm}\right\}$ represents the possibility degree of $Q_p^{\pm} \geq Q_q^{\pm}$. It is apparent that $L_{pq}$ represents the length of $\left[ Q_p^{-} \quad Q_p^{+} \right] \cap \left[ Q_q^{-} \quad Q_q^{+} \right]$, and $L_{pq} = 0$ if $\left[ Q_p^{-} \quad Q_p^{+} \right] \cap \left[ Q_q^{-} \quad Q_q^{+} \right] \in \varnothing$.

It is worth pointing out that there are also some other methods for determining the possibility degree of one interval number be greater than another. For instance, the method developed by Wang *et al*. (2005) was employed in the interval VIKOR method developed by Ren (2018a).

According to Eq.40, the probability matrix (P) can be determined by comparing the values of $\left[Q_i^- \quad Q_i^+\right]$ with respect to the alternatives, as presented in Eq.41.

$$P = \begin{vmatrix} P_{11} & P_{12} & \cdots & P_{1m} \\ P_{21} & P_{22} & \cdots & P_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ P_{m1} & P_{m2} & & P_{mm} \end{vmatrix} \tag{41}$$

where P is the probability matrix, and $P_{ij}$ represents the possibility degree of $Q_i^\pm = \left[Q_i^- \quad Q_i^+\right] \geq Q_j^\pm = \left[Q_j^- \quad Q_j^+\right]$.

The relative inferiority weights of the alternatives (Xu and Da, 2003) can then be determined by Eq.42.

$$W_i = \left(\sum_{j=1}^{m} P_{ij} + m/2 - 1\right) \Big/ m(m-1) \tag{42}$$

where $W_i$ represents the relative inferiority weight of the *i*-th alternative.

The users can then prioritize these alternative in the descending order according to the rule that the smaller the value of the relative weight of the alternative, the more superior the alternative will be.

## 3 Case study

In order to illustrate the developed method in this study, four alternative distributed energy systems for a hotel in China were studied in this section, the area of structure is 9600 m$^2$, the total area of the roof is 1600 m$^2$, and the power capacity of the photovoltaic system is assumed to be 260kW (Zhang *et al.*, 2014). These four alternative distributed energy systems were specified as follows (Dong, *et al.*, 2016):

**A$_1$:** Gas turbine system- power grid＋gas turbine＋absorption refrigeration＋gas fired boiler;

**$A_2$:** Fuel cell system- power grid＋fuel cell＋air conditioner by electricity;

**$A_3$:** Photovoltaic system-power grid＋photovoltaic panel＋air conditioner by electricity＋gas fired boiler; and

**$A_4$:** Internal combustion engine system- power grid＋internal combustion engine＋absorption refrigeration＋gas fired boiler.

All the eight criteria including capital cost ($EC_1$), operations cost ($EC_2$), energy consumption ($EC_3$), utilization rate of the primary energy ($T_1$), technological maturity ($T_2$), annual $CO_2$ emission ($EN_1$), annual $NO_x$ emission ($EN_2$), and social acceptability ($S_1$) were employed to comprehensive evaluate these four alternative distributed energy systems. The interval DEMATEL method was firstly employed to determine the weights of the eight criteria. Three groups of representative groups of stakeholders were invited to determine the direct-influenced matrices. One is the scholar group (DM#1) which consists of two professors whose research mainly focused on power engineering, three PhD candidates who are skilled in distributed systems, and three senior researchers who worked on energy conversation and management, another is the engineer and manager group (DM#2) which consists of four experienced engineers of distributed energy systems and two senior managers of distributed energy system projects, and the other is the users and customers group (DM#3) which included three hotel investors and three customers who are interested in distributed energy systems. The authors firstly used the slides to introduce the background and the purposes of this study, then, investigated the potential influential relationships among these eight evaluation criteria, and finally coordinated the focus group meeting for each of three stakeholder groups. The direct-influenced matrices determined by these three groups of stakeholders were presented in Tables 2-4. Taking cell (1, 8) in Table 2 as an example, [3 5] means that the relative influence of $EC_1$ on $S_1$ is between 3 and 5 according to the opinions of the stakeholders in scholar group.

**Table 2:** The direct-influenced matrix determined by DM#1

| | $EC_1$ | $EC_2$ | $EC_3$ | $T_1$ | $T_2$ | $EN_1$ | $EN_2$ | $S_1$ |
|---|---|---|---|---|---|---|---|---|
| $EC_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [3 5] |
| $EC_2$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [2 4] |
| $EC_3$ | [0 0] | [1 2] | [0 0] | [4 5] | [0 0] | [3 4] | [3 4] | [2 3] |
| $T_1$ | [0 0] | [2 3] | [3 4] | [0 0] | [0 0] | [4 5] | [4 5] | [3 4] |
| $T_2$ | [1 2] | [3 4] | [2 3] | [3 4] | [0 0] | [2 4] | [2 4] | [3 5] |
| $EN_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [4 5] |
| $EN_2$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [4 5] |
| $S_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] |

**Table 3:** The direct-influenced matrix determined by DM#2

| | $EC_1$ | $EC_2$ | $EC_3$ | $T_1$ | $T_2$ | $EN_1$ | $EN_2$ | $S_1$ |
|---|---|---|---|---|---|---|---|---|
| $EC_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [4 5] |
| $EC_2$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [3 4] |
| $EC_3$ | [0 0] | [1 2] | [0 0] | [2 4] | [0 0] | [3 4] | [2 4] | [1 2] |
| $T_1$ | [0 0] | [1 3] | [2 4] | [0 0] | [0 0] | [3 4] | [3 4] | [2 3] |
| $T_2$ | [0 1] | [2 4] | [3 4] | [2 4] | [0 0] | [3 4] | [3 4] | [4 5] |
| $EN_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [3 5] |
| $EN_2$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [3 5] |
| $S_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 1] | [0 1] | [0 0] |

**Table 4:** The direct-influenced matrix determined by DM#3

| | $EC_1$ | $EC_2$ | $EC_3$ | $T_1$ | $T_2$ | $EN_1$ | $EN_2$ | $S_1$ |
|---|---|---|---|---|---|---|---|---|
| $EC_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [3 4] |
| $EC_2$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [3 5] |
| $EC_3$ | [0 0] | [2 2] | [0 0] | [1 3] | [0 0] | [3 5] | [3 4] | [0 2] |
| $T_1$ | [0 0] | [2 3] | [3 4] | [0 0] | [0 0] | [2 4] | [2 4] | [1 3] |
| $T_2$ | [1 3] | [4 4] | [3 3] | [2 3] | [0 0] | [2 4] | [2 4] | [2 4] |
| $EN_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [2 4] |
| $EN_2$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [2 4] |
| $S_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] |

According to Eqs.12-13, all the elements in the average interval direct-influenced matrix can be determined. Taking the element of cell (1,8) in the average interval direct-influenced matrix as an example:

$$\frac{\left[3 \quad 5\right]+\left[4 \quad 5\right]+\left[3 \quad 4\right]}{3}=\left[3.3333 \quad 4.6667\right] \tag{43}$$

In a similar way, all the elements in the average interval direct-influenced matrix can be determined, and the results were presented in Table 5.

**Table 5:** The average interval direct-influenced matrix

| | $EC_1$ | $EC_2$ | $EC_3$ | $T_1$ | $T_2$ | $EN_1$ | $EN_2$ | $S_1$ |
|---|---|---|---|---|---|---|---|---|
| $EC_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [3.3333 4.6667] |
| $EC_2$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [2.6667 4.3333] |
| $EC_3$ | [0 0] | [1.3333 2] | [0 0] | [2.3333 4] | [0 0] | [3 4.3333] | [2.6667 4] | [1 2.3333] |
| $T_1$ | [0 0] | [1,6667 3] | [2.6667 4] | [0 0] | [0 0] | [3 4.3333] | [3 4.3333] | [2 3.3333] |
| $T_2$ | [0.6667 2] | [3 4] | [2.6667 3.3333] | [2.3333 3.6667] | [0 0] | [2.3333 4] | [2.3333 4] | [3 4.6667] |
| $EN_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [3 4.6667] |
| $EN_2$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [3 4.6667] |
| $S_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0.3333] | [0 0.3333] | [0 0] |

According to Eq.14, $\lambda$ as the parameter for standardizing the average interval direct-influenced matrix can be determined, and it equals to 28.6667. Then, all the elements in the normalized average interval direct-influenced matrix can be determined. Taking the element of cell (1,8) as an example:

$$\frac{\left[3.3333 \quad 4.6667\right]}{28.6667}=\left[0.1163 \quad 0.1628\right] \tag{44}$$

The normalized average interval direct-influenced matrix was presented in Table 6.

**Table 6:** The normalized interval direct-influenced matrix

| | $EC_1$ | $EC_2$ | $EC_3$ | $T_1$ | $T_2$ | $EN_1$ | $EN_2$ | $S_1$ |
|---|---|---|---|---|---|---|---|---|
| $EC_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0.1163 0.1628] |
| $EC_2$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0.0930 0.1512] |
| $EC_3$ | [0 0] | [0.0465 0.0698] | [0 0] | [0.0814 0.1395] | [0 0] | [0.1047 0.1512] | [0.0930 0.1395] | [0.0349 0.0814] |
| $T_1$ | [0 0] | [0.0581 0.1037] | [0.0930 0.1395] | [0 0] | [0 0] | [0.1047 0.1512]] | [0.1047 0.1512] | [0.0698 0.1163] |
| $T_2$ | [0.0233 0.0698] | [0.1047 0.1395] | [0.0930 0.1163] | [0.0814 0.1279] | [0 0] | [0.0814 0.1395] | [0.0814 0.1395] | [0.1047 0.1628] |
| $EN_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0.1047 0.1628] |
| $EN_2$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0.1047 0.1628] |
| $S_1$ | [0 0] | [0 0] | [0 0] | [0 0] | [0 0] | [0 0.0116] | [0 0.0116] | [0 0] |

According to Eqs.16-20, the total interval relation matrix can also be determined, and then, the total influences which were directly and indirectly exerted by each criterion and the total direct and indirect influences received by each criterion can be determined by Eq.21 and Eq.22, respectively (see Table 7). After this, the interval weights of the eight criteria can be determined, and the results were also presented in Table 7.

**Table 7:** The total influences which were directly and indirectly exerted by each criterion, the total direct and indirect influences received by each criterion, and the interval weights

| | $EC_1$ | $EC_2$ | $EC_3$ | $T_1$ | $T_2$ | $EN_1$ | $EN_2$ | $S_1$ |
|---|---|---|---|---|---|---|---|---|
| $R_i^{\pm}$ | [0.1163 0.1672] | [0.0930 0.1553] | [0.4259 0.7601] | [0.4972 0.8388] | [0.6793 1.1754] | [0.1047 0.1672] | [0.1047 0.1672] | [0 0.0271] |
| $C_i^{\pm}$ | [0.0233 0.0698] | [0.2292 0.3672] | [0.2027 0.2990] | [0.1793 0.3092] | [0 0] | [0.3307 0.5606] | [0.3167 0.5455] | [0.7393 1.3072] |
| $\omega_i^{\pm}$ | [0.6545 1.5279] | [0.4265 1.0895] | [0.3378 0.9751] | [0.2307 0.6544] | [0.1960 0.5747] | [0.0856 0.2445] | [0.0722 0.2093] | [0.1247 0.3773] |

There are six hard criteria among these eight evaluation criteria, and they are capital cost ($EC_1$), operations cost ($EC_2$), energy consumption ($EC_3$), utilization rate of the primary energy ($T_1$), annual $CO_2$ emission ($EN_1$), and annual $NO_x$ emission ($EN_2$), and the data of these four alternative distributed energy systems with respect to these six hard criteria were derived from the work of Zhang et al.(2014) by changing the original data with ±5% derivations. While the data of the four distributed energy systems with respect to the soft criteria including technological maturity ($T_2$) and social acceptability ($S_1$) were scored by the interval numbers composed by the crisp numbers from 0 to 10. The decision-making matrix was presented in Table 8. Among these eight evaluation criteria, utilization rate of the primary energy ($T_1$), technological maturity ($T_2$), and social acceptability ($S_1$) are benefit-type criteria which mean that the increase of the data with respect to these criteria can benefit the alternatives; while the other five criteria are cost-type criteria which mean that the increase of the data with respect to these criteria will have negative influences on the priority of the corresponding alternative.

**Table 8:** The interval decision-making matrix

| | | $A_1$ | $A_2$ | $A_3$ | $A_4$ |
|---|---|---|---|---|---|
| $EC_1$ | 1.00E＋04 Yuan | [312.5500 345.4500] | [787.5500 870.4500] | [567.1500 626.8500] | [294.5000 325.500] |
| $EC_2$ | 1.00E＋04 Yuan | [151.0500 166.9500] | [151.0500 166.9500] | [130.1500 143.8500] | [145.3500 160.6500] |
| $EC_3$ | MW.h | [4449.8 4918.2] | [2872.8 3175.2] | [2490.9 2753.1] | [4290.2 4741.8] |
| $T_1$ | % | [71.3450 78.8550] | [110.4850 122.1150] | [127.4900 140.9100] | [74.0050 81.7950] |
| $T_2$ | / | [5 8] | [3 5] | [2 4] | [7 9] |
| $EN_1$ | tons | [91.4850 101.1150] | [48.5450 53.6550] | [69.9200 77.2800] | [83.8850 92.7150] |
| $EN_2$ | tons | [1.4630 1.6170] | [1.4440 1.5960] | [1.8715 2.0685] | [1.2635 1.3965] |
| $S_1$ | / | [6 8] | [7 9] | [8 10] | [5 6] |

After determining the interval decision-making matrix, the developed interval VIKOR method was employed to rank these four alternative distributed energy systems. The data with respect to the benefit-type criteria and the cost-type criteria in the interval decision-making matrix can be normalized according to Eq.27 and Eq.28, respectively. Taking the data of $A_1$ with respect to the benefit-type criterion $T_1$ and the cost-type criterion $EC_1$ as an example:

$$\left[y_{A_1T_1}^- \quad y_{A_1T_1}^+\right]=\left[\frac{x_{A_1T_1}^-}{\max\limits_{i=1,2,\cdots,4}\left\{x_{A_iT_1}^+\right\}} \quad \frac{x_{A_1T_1}^+}{\max\limits_{i=1,2,\cdots,4}\left\{x_{A_iT_1}^+\right\}}\right] \qquad (45)$$

$$=\left[\frac{127.4900}{140.9100} \quad \frac{140.9100}{140.9100}\right]=\left[0.9048 \quad 1.0000\right]$$

$$\left[y_{A_1EC_1}^- \quad y_{A_1EC_1}^+\right]=\left[\frac{\min\limits_{i=1,2,\cdots,4}\left\{x_{A_iEC_1}^-\right\}}{x_{A_1EC_1}^+} \quad \frac{\min\limits_{i=1,2,\cdots,4}\left\{x_{A_iEC_1}^-\right\}}{x_{A_1EC_1}^-}\right] \qquad (46)$$

$$=\left[\frac{294.5500}{626.8500} \quad \frac{294.5500}{567.1500}\right]=\left[0.4698 \quad 0.5193\right]$$

In a similar way, all the elements in the interval decision-making matrix can be normalized, and the normalized interval decision-making matrix can be determined (See Table 9).

**Table 9:** The normalized interval decision-making matrix

| | $A_1$ | $A_2$ | $A_3$ | $A_4$ |
|---|---|---|---|---|
| $T_1$ | [0.5063 0.5596] | [0.7841 0.8666] | [0.9048 1.0000] | [0.5252 0.5905] |
| $T_2$ | [0.5556 0.8889] | [0.3333 0.5556] | [0.2222 0.4444] | [0.7778 1.0000] |
| $S_1$ | [0.6000 0.8000] | [0.7000 0.9000] | [0.8000 1.0000] | [0.5000 0.6000] |
| $EC_1$ | [0.8525 0.9422] | [0.3383 0.3739] | [0.4698 0.5193] | [0.9048 1.0000] |
| $EC_2$ | [0.7796 0.8616] | [0.7796 0.8616] | [0.9048 1.0000] | [0.8101 0.8954] |
| $EC_3$ | [0.5065 0.5598] | [0.7845 0.8671] | [0.9048 1.0000] | [0.5153 0.5806] |
| $EN_1$ | [0.4801 0.5306] | [0.9048 1.0000] | [0.6282 0.6943] | [0.5236 0.5787] |
| $EN_2$ | [0.7814 0.8636] | [0.7917 0.8750] | [0.6108 0.6751] | [0.9048 1.0000] |

According to Eqs.30-33, the positive ideal solutions and the negative ideal solutions can be determined, and the results were presented in Table 10.

**Table 10:** The positive ideal and negative ideal solutions

| | $T_1$ | $T_2$ | $S_1$ | $EC_1$ | $EC_2$ | $EC_3$ | $EN_1$ | $EN_2$ |
|---|---|---|---|---|---|---|---|---|
| PIS | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| NIS | 0.5063 | 0.2222 | 0.5000 | 0.3383 | 0.7796 | 0.5065 | 0.4801 | 0.6108 |

Subsequently, $S_i^{\pm}$ and $R_i^{\pm}$ can be determined by Eqs.34-35 and Eqs.36-37, respectively. The results were presented in Table 11. Then, the values of $Q_i^{\pm}$ with respect to the four alternative distributed energy systems. Taking $Q_i^{\pm}$ as an example:

$$\begin{aligned} Q_1^- &= 0.5\times\frac{(S_1^- - 0.5577)}{(3.6981-0.5577)}+(1-0.5)\frac{(R_i^- - 0.2141)}{(1.6409-0.2141)} \\ &= 0.5\times\frac{(0.9584-0.5577)}{(3.6981-0.5577)}+(1-0.5)\frac{(0.6373-0.2141)}{(1.6409-0.2141)} \\ &= 0.2121 \end{aligned} \tag{47}$$

$$\begin{aligned} Q_1^+ &= 0.5\times\frac{(S_1^+ - 0.5577)}{(3.6981-0.5577)}+(1-0.5)\frac{(R_i^+ - 0.2141)}{(1.6409-0.2141)} \\ &= 0.5\times\frac{(3.5728-0.5577)}{(3.6981-0.5577)}+(1-0.5)\frac{(1.6409-0.2141)}{(1.6409-0.2141)} \\ &= 0.9801 \end{aligned} \tag{48}$$

In a similar way, all the values of $Q_i^{\pm}$ with respect to the four alternative distributed energy systems can be determined, and the results were presented in Table 11. Accordingly, it relative inferiority weights of these four alternative distributed energy systems are [0.0817 0.7623], [0.1545 0.7350], [0.2121 0.9801] and [0 0.4612], respectively. The smaller the value of $Q_i^{\pm}$, the more sustainable the corresponding alternative will be.

**Table 11:** $S_i^{\pm}$, $R_i^{\pm}$ and $Q_i^{\pm}$ with respect to the four alternative distributed energy systems

| | A1 | A2 | A3 | A4 |
|---|---|---|---|---|
| $\left[S_i^- \quad S_i^+\right]$ | [0.8877 3.6981] | [0.8396 2.7846] | [0.9584 3.5728] | [0.5577 2.3860] |
| $\left[R_i^- \quad R_i^+\right]$ | [0.2974 0.9625] | [0.5268 1.2998] | [0.6373 1.6409] | [0.2141 0.6996] |
| $\left[Q_i^- \quad Q_i^+\right]$ | [0.0817 0.7623] | [0.1545 0.7350] | [0.2121 0.9801] | [0  0.4612] |

According to Eq.40, the possibility degree of the values of $Q_i^{\pm} = \left[Q_i^- \quad Q_i^+\right]$ with respect to an alternative distributed energy system being greater than that with respect to another can be determined. Taking the $P\left\{\left[Q_{A_1}^- \quad Q_{A_1}^+\right] \geq \left[Q_{A_2}^- \quad Q_{A_2}^+\right]\right\}$

$$P\left\{\left[Q_{A_1}^- \quad Q_{A_1}^+\right] \geq \left[Q_{A_2}^- \quad Q_{A_2}^+\right]\right\} = \frac{1}{2}\left(1 + \frac{(Q_{A_1}^+ - Q_{A_2}^+) + (Q_{A_1}^- - Q_{A_2}^-)}{\left|Q_{A_1}^+ - Q_{A_2}^+\right| + \left|Q_{A_1}^- - Q_{A_2}^-\right| + L_{A_1A_2}}\right)$$
$$= \frac{1}{2}\left(1 + \frac{(0.9801 - 0.7350) + (0.2121 - 0.1545)}{\left|0.9801 - 0.7350\right| + \left|0.2121 - 0.1545\right| + L_{A_1A_2}}\right) \quad (49)$$

$L_{A_1A_2}$ can be determined by Eq.50.

$$L_{A_1A_2} = \min\left\{\max\left\{Q_{A_1}^+ - \max\left(Q_{A_1}^-, Q_{A_2}^-\right), 0\right\}, \max\left\{Q_{A_2}^+ - \max\left(Q_{A_1}^-, Q_{A_2}^-\right), 0\right\}\right\}$$
$$= \min\left\{\max\left\{0.9801 - \max\left(0.2121, 0.1515\right), 0\right\}, \max\left\{0.7350 - \max\left(0.2121, 0.1515\right), 0\right\}\right\}$$
$$= 0.5229$$
(50)

Therefore, it could be obtained that $P\left\{\left[Q_{A_1}^- \quad Q_{A_1}^+\right] \geq \left[Q_{A_2}^- \quad Q_{A_2}^+\right]\right\} = 0.6833$. In a similar way, all the elements in the possibility degree matrix can be determined, and the results were presented in

Table 12.

**Table 12:** The possibility degree matrix

| | $A_1$ | $A_2$ | $A_3$ | $A_4$ |
|---|---|---|---|---|
| $A_1$ | 0.5000 | 0.4666 | 0.3062 | 0.7511 |
| $A_2$ | 0.5334 | 0.5000 | 0.3167 | 0.7913 |
| $A_3$ | 0.6938 | 0.6833 | 0.5000 | 0.8729 |
| $A_4$ | 0.2489 | 0.2087 | 0.1271 | 0.5000 |

Finally, the relative inferiority weights of the four alternative distributed energy systems can be determined according to Eq.42, and the results were presented in Table 13.

**Table 13:** The relative weights of the four alternative distributed energy systems

| | $A_1$ | $A_2$ | $A_3$ | $A_4$ |
|---|---|---|---|---|
| Relative weights | 0.2520 | 0.2618 | 0.3125 | 0.1737 |
| Ranking | 2 | 3 | 4 | 1 |

According to the results presented in Table 13, internal combustion engine system which was composed by power grid, internal combustion engine, absorption refrigeration and gas fired boiler was recognized as the most sustainable among these four alternative distributed energy systems, followed by gas turbine system, fuel cell system and photovoltaic system in the descending order.

In order to investigate the effects of the weights of the eight evaluation criteria, a comprehensive sensitivity analysis has been carried out by studying the following ten cases:

**Base case**: ranking the four distributed energy systems by using the weights determined the proposed interval DEMATEL method;

**Case 1:** an equal weight (0.1250) was assigned to these eight criteria;

**Case (2-9):** a dominant weight (0.3700) was assigned to a criterion, and an equal weight (0.0900) was assigned to the other eight criteria.

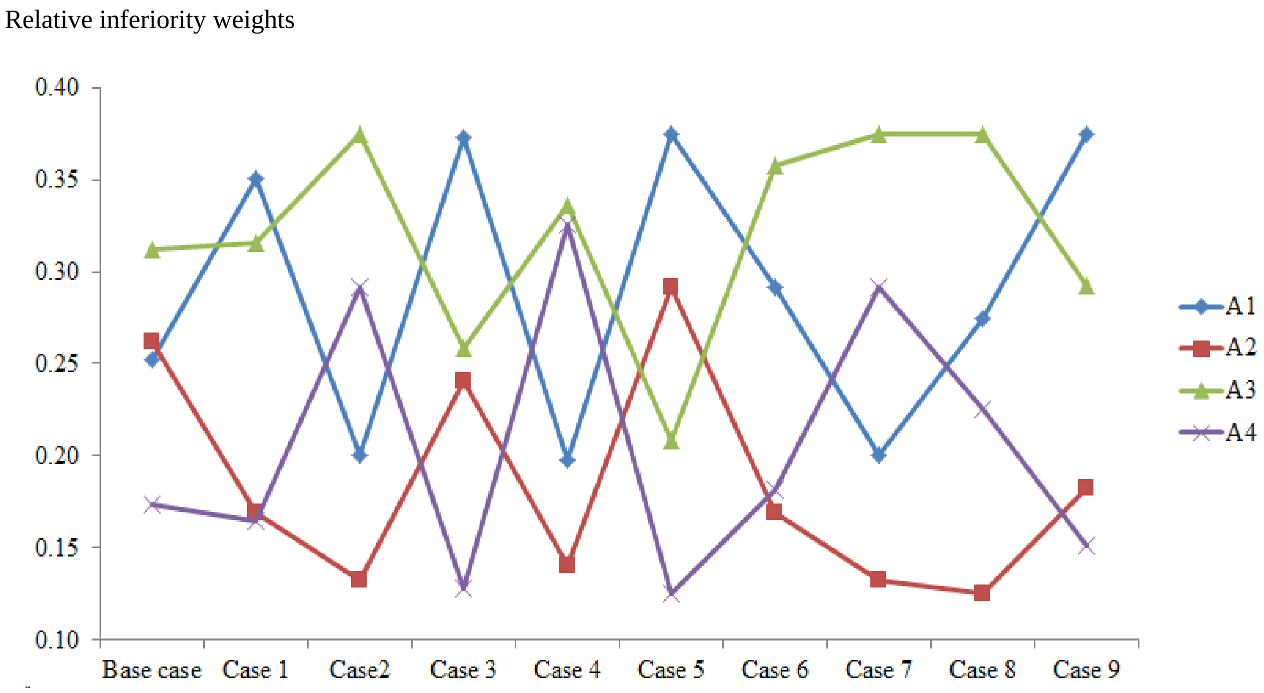


**Figure 1:** The results of sensitivity analysis

The results of sensitivity analysis were presented in Figure 1. It is apparent that the relative inferiority weights of these four distributed energy vary with the change of the weights of the eight evaluation criteria. Accordingly, the accurate determination of the weights of the evaluation criteria is critical for determine the priority order of the distributed energy systems accurately.

## 4 Discussion

The sustainability order of the four distributed energy systems is internal combustion engine system, gas turbine system, fuel cell system and photovoltaic system in the descending order based on the weights determined by the interval DEMETEL method. The result of recognizing internal combustion engine system as the most sustainable is reasonable, because this scenario has the least capital cost, the highest technological maturity, the lowest annual NOx emission, and relatively lower operation cost.

The interval DEMATEL method was employed to determine the weights of the evaluation criteria for distributed energy systems, and it can not only solve the subjectivity and ambiguity existing in human's judgments, but also incorporate the interdependences among these evaluation criteria. The interval VIKOR was employed to rank the alternative distributed energy systems, and it can address the decision-making matrix with interval numbers which represent data uncertainties. In other words, data uncertainties can be incorporated in this method.

All in all, the method used in this study has the following innovations and contributions comparing with the previous works, and they are:

(1) A criteria system for sustainability ranking of distributed energy system was developed with the considerations of the criteria in economic, environmental, technical and social categories;

(2) The preferences of different stakeholders were incorporated in determining the weights of the criteria for sustainability ranking of distributed energy systems;

(3) The criteria used for sustainability ranking of distributed energy systems were assumed to be not independent, and the interacted and interdependent relationships were incorporated when using interval DEMATEL to determine the weights of the criteria;

(4) The subjectivity of human judgments can be addressed by using the interval numbers to describe the influence of a criterion on another; and

(5) The sustainability ranking of distributed energy systems under data uncertainties can also be achieved by using interval VIKOR method.

## 5. Conclusions

Distributed energy system which can effectively improve energy use efficiency has been recognized as a promising scenario for emissions reduction and energy-saving. This study aims at developing an interval multi-criteria decision making method by combining interval DEMATEL and interval VIKOR method for sustainability ranking of alternative distributed energy systems, the interval DEMATEL which allows the users to use the interval numbers to establish the direct-influenced matrix was determined for calculating the weights of the evaluation criteria. A criteria system including eight criteria (capital cost, operations cost, energy consumption, utilization rate of the primary energy, technological maturity, annual $CO_2$ emission, annual $NO_x$ emission and social acceptability) were developed for sustainability assessment of distributed energy systems. Four distributed energy systems (i.e., gas turbine system, fuel cell system, photovoltaic system, and internal combustion engine system were studied by the proposed method), the sustainability order from the most sustainable to the least is photovoltaic system, fuel cell system, gas turbine system, and internal combustion engine system.

Different from the traditional weighting method which usually assumes that all the criteria are independent, the developed interval DEMATEL method can not only address the problems caused by ambiguity and vagueness existing in human judgments, but also incorporate the complex interacted relationships among the evaluation criteria. The interval VIKOR which can address the data uncertainties was also proposed to rank the alternative distributed energy systems under data uncertainty conditions. All in all, the proposed interval multi-criteria decision making method for prioritizing the alternative distributed energy systems has the following four advantages:

(1) The independent relationships among these evaluation criteria can be incorporated when using the interval DEMATEL to determine the weights of the evaluation criteria;

(2) The ambiguity and vagueness existing in human judgments when determining the weights

of the evaluation criteria can be successfully addressed;

(3) The preferences/opinions of different stakeholders can be incorporated simultaneously. In other words, the proposed method can achieve group decision-making when ranking the alternative distributed energy systems;

(4) The uncertainties can be considered when using the proposed interval VIKOR method to rank the alternative distributed energy systems.

Besides the advantages, there is also a weak point besides these advantages-the proposed interval multi-criteria decision making method cannot consider the relative importance of different decision-makers in the process of sustainability ranking of different distributed energy systems. However, this is an important issue, because the roles of different decision-makers are different when selecting the distributed energy systems. Therefore, the future work will focus on developing the multi-criteria decision analysis which can not only consider the preferences of different stakeholders and address uncertainties, but also consider the role weights of different groups of stakeholders to achieve decision-making, to rank the alternative distributed energy systems.

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