https://doi.org/10.1016/j.ijhydene.2021.01.018

Multi-criteria Sustainability Assessment and Decision-making Framework for Hydrogen Pathways Prioritization: An Extended ELECTRE Method under Hybrid Information

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Abstract

Hydrogen has been received more and more attentions because of its advantage in terms of low environmental impact and high energy density. However, the sustainability priorities of different hydrogen production pathways have not been determined. To assist the sustainability-oriented selection of hydrogen production pathways, a prioritization framework needs to be built. However, the data collected from different sources consisting of hybrid information, such as crisp numbers, interval numbers, and fuzzy numbers, increases the difficulty of sustainability-oriented decision-making. Therefore, this study aims to develop a sustainability prioritization framework for hydrogen production pathways under hybrid information. The Z-number Best Worst Method (ZBWM) is applied to quantify the weight of each criterion from the views of decision-makers in the forms of Z-number. The ELECTRE method has been extended to prioritize the alternatives under the context of hybrid information. An illustrative case including five hydrogen production processes is used to illustrate the proposed prioritization framework from environmental, social, economic, and technical aspects, and the results show that biomass hydrogen technology is the most sustainable choice. In order to validate the feasibility of the proposed model, other three multi-criteria decision making methods were also used to determine the sustainability rankings of these five hydrogen production pathways, and the comparisons reveal that this method is feasible.

Keywords: Sustainability assessment; hydrogen production; multi-criteria decision making; best-worst method

1. Introduction

Hydrogen is a superior energy carrier with a higher energy conversion rate, higher energy density, and lower environmental impacts comparing with other energy sources or fossil fuels [1,2]. A rapid increase in the demand for hydrogen accelerates the development of hydrogen production technologies and their applications in the industry. Among all hydrogen production pathways, the steam methane reforming technology and coal gasification are two classic, cheap, and well-developed technologies that having been studied for years [3,4]. Some other hydrogen production technologies such as biomass gasification [5,6] and electrolysis [7] also attracted attentions because of their environmental sustainability performances. Although the environmental impact of hydrogen energy is less than other energy sources, the positive and negative impacts of hydrogen production processes vary significantly between each other. For example, the steam methane reforming technology is a well-developed technology with existing infrastructure, but its main disadvantage is high equipment investment and low conversion efficiency [8,9]. The coal gasification technology is economic and easily-accessed, but this technology depends on fossil fuel and generates the by-products such as CO_2, SO_x, and NO_x, etc. [10,11]. The biomass gasification uses CO_2-neutral, abundant and cheap feedstock, but the purity of the product is difficult to control due to seasonal availability and feedstock impurity [12,13]. Therefore, the selection of hydrogen production technologies based on their sustainability performances has become a critical problem to be solved.

The selection of the sustainable production process is a typical multi-criteria decision-making (MCDM) problem, which requires a scientific and comprehensive analysis method to assist decision-makers to make informed decisions. Therefore, the MCDM method, which can analyze multiple alternatives by considering multiple aspects, can be adopted and developed for hydrogen production selection. In the previous studies, MCDM methods have been widely applied in the sustainability assessment and sustainability-oriented decision-making problems [14–16]. For example, Sanaei *et al.* [17] conducted a sustainability assessment by using the MCDM method. Jeong and González-Gómez [18–

20] have proposed sustainability-oriented decision-making models to optimize locations and construction of renewable energy facilities. These methods were also extended to investigate the hydrogen productions. For instance, Chung *et al.* [21] analyzed the hydrogen production selection problem in Korea based on the analytical hierarchy process (AHP) method. Ren *et al.* [22] used the decision making trial and evaluation laboratory (DEMATEL) method to enhance sustainability in hydrogen production, and they [23] combined extension theory and AHP method to prioritize the hydrogen production technologies. Ramazankhani *et al.* [24] analyzed the hydrogen production problem in Iran using the technique for order preference by similarity to an ideal solution (TOPSIS) and VIKOR methods. The studies employed different MCDM methods for prioritizing different hydrogen production pathways based on different situations. However, the data (information) in hydrogen production process may consist of not only the crisp numbers but also the interval numbers, fuzzy numbers, and linguistic terms. For instance, the cell temperature for polymer membrane (PEM) electrolyzers should be controlled within 50-80 ℃ [25], and it could be expressed as an interval number; and some qualitative criteria, such as the maturity and social acceptance, are usually expressed by using linguistic terms [26,27]. There are also some other studies considering not only the crisp numbers, but also other types of data. For instance, Heo *et al.* [28] used the fuzzy AHP method to provide a choice for selecting hydrogen production methods. Manzardo *et al.* [29] used the group grey relational analysis (GRA) method for comparison. Ren *et al.* [30] developed the fuzzy group goal programming method for sustainability assessment of biomass-based technologies for hydrogen production. Ren *et al.* [31] extended DEMATEL to interval DEMATEL for ranking hydrogen production pathways under uncertainties. Sustainability analysis of different hydrogen production options using hesitant fuzzy AHP was studied by Acar *et al.* [32]. An interval-valued intuitionistic fuzzy multi-attribute decision-making method was raised by Oztaysi [33] for hydrogen production technologies evaluation.

The methods mentioned above solved several decision-making problems in hydrogen production under uncertainty, but they are incapable to prioritize hydrogen production pathways based on the conditions of hybrid information which consists of crisp numbers, interval numbers, fuzzy numbers and linguistic terms. In the real case of hydrogen pathway selection, the data collected from different sources for decision making contains hybrid information. For example, the social acceptance of hydrogen production pathways is analyzed by using linguistic terms, while the economic performances of the hydrogen production pathways are evaluated by using interval numbers or fuzzy numbers. Therefore, it is necessary to propose as MCDM method to handle the decision-making matrix with hybrid information. Several MCDM methods to deal with hybrid information have been proposed. Among them, new MCDM methods were raised to handle hybrid information by extending traditional MCDM methods. For example, TOPSIS [34–41], VIKOR [42,43], and GRA [44,45] were extended to new MCDM methods to deal with the decision-making matrix hybrid information. In addition, some integrated methods were developed to solve decision-making problems. For instance, DEA method combining with the Dempster-Shafer theory [46–48] or Fuzzy Synthetic Assessment [49–51] were studied. However, these existing MCDM methods that can handle hybrid information did not consider the vagueness of the subjectivity existing in stakeholders' judgments. The decision makers express their preferences with ambiguity due to their hesitation, knowledge limitation, and linguistic expression.

Therefore, there are still two knowledge gaps in the MCDM method for hydrogen production technologies prioritization:

(1) It lacks a MCDM method that can deal with the decision-making matrix with hybrid information in the selection process of hydrogen production pathways.

(2) It lacks the method which can quantify the weights of criteria properly based on stakeholder's preference with vagueness.

To fill this gap, the objective of this study is to develop a systematic prioritization framework for hydrogen production pathways from a sustainability perspective, solving selection problems with hybrid information, and vagueness in the determination of the weights of criteria. In this work, the newly proposed MCDM method will be innovated in the following points:

(1) To solve decision-making problems with hybrid information, this framework proposed an extended method based on ELECTRE; and

(2) To deal with ambiguity existing in judgement of experts, Z-Number Best Worst Method (ZBWM) [52] is adopted to accurately quantify the decision maker's opinion.

Beside this section, the following parts of this study will be illustrated as below. The prioritization framework for hydrogen production methods is explained in section 2. An illustrated case study applied the proposed model in section 3. The results of case study er studied and the proposed model is evaluated in section 4. Finally, section 5 concludes this study.

2 Methodology

In this section, the prioritization framework of hydrogen production pathways is developed to rank sustainable performances of multiple hydrogen production pathways. As shown in **Fig.1**, this framework consists of three main stages: (i) establishing the criteria system; (ii) determining the weights of the criteria; and (iii) ranking. In the first step, the criteria are selected to describe the sustainability of the hydrogen production pathways. In the second step, ZBWM [52], is used to deal with the vagueness existing in the judgments of the decision makers. In the third step, the data with respect to criteria and the weights of criteria are aggregated to generate ranks for all alternatives. To handle the decision-making matrix with hybrid information, the ELECTRE method [53] has been improved to hybrid-information based ELECTRE (H-ELECTRE) for handling the decision-making matrix with hybrid information.

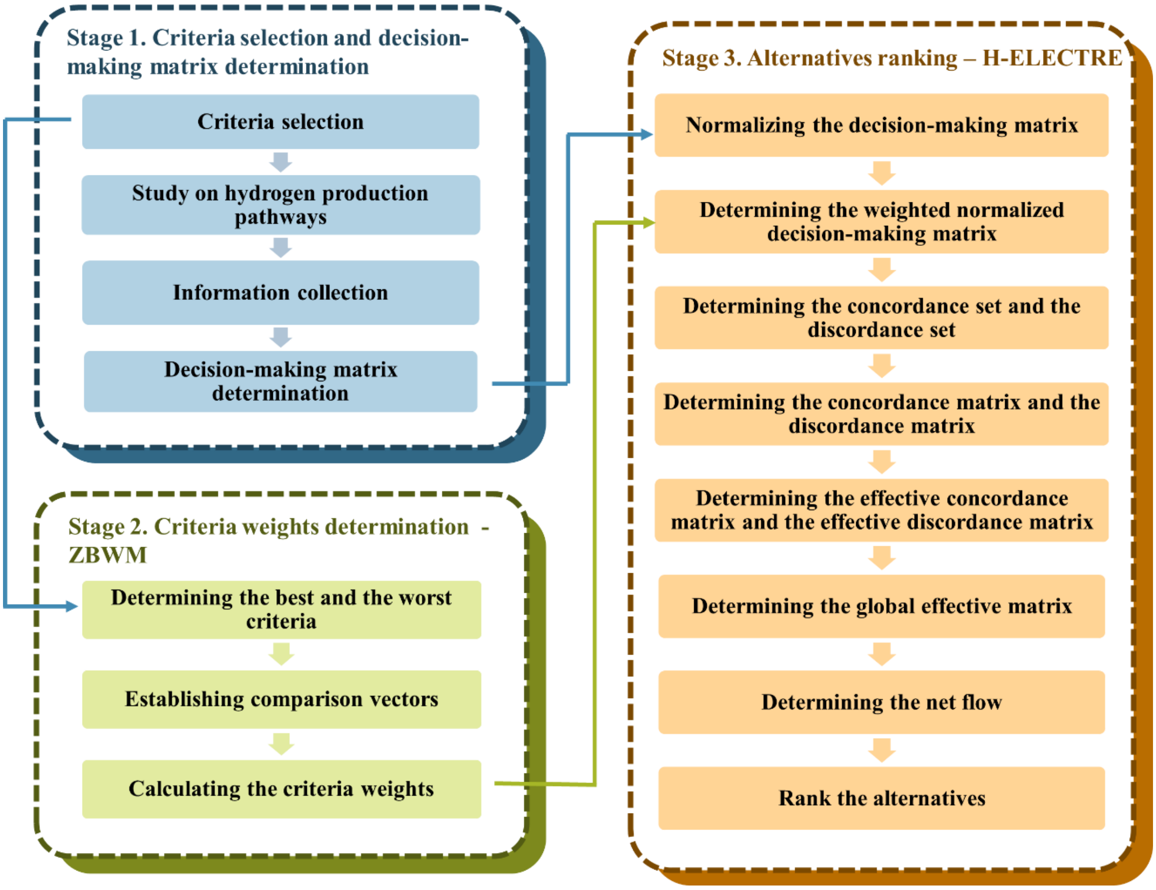

Fig. 1. Hydrogen production pathways prioritization framework

2.1 Criteria weights determination method – ZBWM

The best-worst method (BWM) method [54] is an efficient method to determine the weights of criteria, and it is less time-consuming than other traditional methods such as AHP [55,56]. To precisely express the priority of decision makers, Z-number is introduced and used to extend BWM as ZBWM [57].

Z-number can present linguistic expression in a more accurate way than numerical expressions. Zadeh [58] states that a Z-number is an ordered pair of fuzzy numbers which are a fuzzy subset of the domain of the variable and a fuzzy subset of the unit interval. For example, if the production cost of a chemical product is approximately 2 dollars per kilogram usually, the Z-number of this example can be expressed as (approximately \$2, usually). The mathematic expression of Z-number can be shown as $\tilde{Z} = (\tilde{A}, \tilde{B})$, where

$\tilde{A}$ is the fuzzy subset of the domain of variable (l_A, m_A, u_A) and $\tilde{B}$ is the fuzzy subset of the unit interval (l_B, m_B, u_B). The l_A and l_B refer to the lower boundary of the variables, u_A and u_B refer to the upper boundary of the variables, and the m_A and m_B are the most possible values of each variable. The Z-number $\tilde{Z} = (\tilde{A}, \tilde{B})$ can be transformed into a triangular fuzzy number $\tilde{x} = (l, m, u)$ [59]. And the Z-number can better represent the vagueness in human's judgments. Therefore, the ZBWM is used to determine the weights of criteria in the sustainability prioritization framework. In this section, the steps of ZBWM developed by Aboutorab *et al.* [52] based on the work of Rezaei [54] are presented in the following three steps [52,54]:

Step 1. Determining the best and worst criteria

Before assigning the linguistic terms to the criteria in pairwise comparisons, the best and the worst criterion should be identified by the users. The best criterion (c_B) and the worst criterion (c_W) refer to the most important (e.g., most preferred and best) and the least important (e.g., least preferred and worst) criterion, respectively.

Step 2. Establishing comparison vectors

Then, the best-to-others (BO) vector by comparing the best criterion over other criteria and the other-to-worst (OW) vector by comparing all the other criteria over the worst criterion can be determined. Assume that there are *n* criteria, BO vector $\tilde{X}_B$ is shown as Eq.(1).

$$\tilde{X}_B = \left(\tilde{x}_{B1}, \tilde{x}_{B2}, ..., \tilde{x}_{Bn}\right) \tag{1}$$

where $\tilde{x}_{Bj}$ represents the fuzzy preference of the best criterion (c_B) over the *j*-th criterion ($j = 1, 2, ..., n$), the value of $\tilde{x}_{Bj}$ is determined based on linguistic terms and the corresponding transformation as shown in **Table 1**. Among them, the comparison of the best criterion over itself can be shown as $\tilde{x}_{BB} = (1,1,1)$.

The OW vector $\tilde{X}_W$ is determined as Eq.(2).

$$\tilde{X}_W = (\tilde{x}_{1W}, \tilde{x}_{2W}, ..., \tilde{x}_{nW}) \quad (2)$$

where $\tilde{x}_{iW}$ represents the fuzzy preference of the *i*-th criterion ($i = 1, 2, ..., n$) over the worst criterion (c_W),and the corresponding transformation as shown in **Table 1**. Among them, the comparison of the worst criterion over itself can be shown as $\tilde{x}_{WW} = (1,1,1)$.

Table 1. Transformation rules for Z-number linguistic variables to fuzzy numbers [52]

Linguistic terms	Membership function
(EI,VL)	(1,1,1)
(EI,L)	(1,1,1)
(EI,M)	(1,1,1)
(EI,H)	(1,1,1)
(EI,VH)	(1,1,1)
(WI,VL)	(0.21,0.32,0.47)
(WI,L)	(0.37,0.55,0.82)
(WI,M)	(0.47,0.71,0.82)
(WI,H)	(0.56,0.84,1.26)
(WI,VH)	(0.63,0.95,1.43)
(FI,VL)	(0.47,0.63,0.79)
(FI,L)	(0.82,1.10,1.37)
(FI,M)	(1.07,1.42,1.78)
(FI,H)	(1.26,1.68,2.10)
(FI,VH)	(1.43,1.90,2.38)

(VI,VL)	(0.79,0.95,1.11)
(VI,L)	(1.37,1.64,1.92)
(VI,M)	(1.78,2.13,2.49)
(VI,H)	(2.10,2.52,2.94)
(VI,VH)	(2.38,2.85,3.33)
(AI,VL)	(1.11,1.26,1.42)
(AI,L)	(1.92,2.19,2.47)
(AI,M)	(2.49,2.84,3.20)
(AI,H)	(2.94,3.36,3.78)
(AI,VH)	(3.33,3.80,4.28)

Notes: EI: Equally Important; WI: Weakly Important; FI: Fairly Important; VI: Very Important; AI: Absolutely Important; VL: Very Low; L: Low; M: Medium; H: High; VH: Very High.

Step 3. Calculating the criteria weights

The optimal fuzzy weight of the *j*-th criterion $\tilde{W}_j = (w_j^L, w_j^M, w_j^U)$ can be determined after solving Eq.(3).

$$\min \ \tilde{\xi}^* = (k^*, k^*, k^*)$$
$$\text{subject to} \begin{cases} \left| \dfrac{(w_B^L, w_B^M, w_B^U)}{(w_j^L, w_j^M, w_j^U)} - (x_{Bj}^L, x_{Bj}^M, x_{Bj}^U) \right| \le (k^*, k^*, k^*) \\ \left| \dfrac{(w_j^L, w_j^M, w_j^U)}{(w_W^L, w_W^M, w_W^U)} - (x_{jW}^L, x_{jW}^M, x_{jW}^U) \right| \le (k^*, k^*, k^*) \\ \sum_{j=1}^{n} \dfrac{w_j^L + 4 \times w_j^M + w_j^U}{6} = 1 \\ 0 \le w_j^L \le w_j^M \le w_j^U \\ j = 1, 2, ..., n \end{cases} \tag{3}$$

where $\left(x_{Bj}^L, x_{Bj}^M, x_{Bj}^U\right)$ refer to the pairwise comparison value of the best criterion over the

j-th criterion; $\tilde{W}_B = \left(w_B^L, w_B^M, w_B^U\right)$ and $\tilde{W}_W = \left(w_W^L, w_W^M, w_W^U\right)$ refer to the fuzzy weights of the best criterion and the worst criterion, respectively.

In order to have a consistency check, Eq.(4) can be used to determine the consistency ratio.

$$Consistency\ Ratio = \frac{k^*}{Consistency\ Index} \tag{4}$$

where consistency indices for all linguistic terms are shown in **Table 2** [52].

Table 2. Consistency index (CI) for ZBWM [52]

Linguistic terms	(EI, VL)	(EI, L)	(EI, M)	(EI, H)	(EI, VH)	(WI, VL)	(WI, L)	(WI, M)	(WI, H)
$\tilde{x}_{BW}$	1	1	1	1	1	0.47	0.82	1.07	1.26
CI	3	3	3	3	3	2.07	2.7	3.11	3.42
Linguistic terms	(WI, VH)	(FI, VL)	(FI, L)	(FI, M)	(FI, H)	(FI, VH)	(VI, VL)	(VI, L)	(VI, M)
$\tilde{x}_{BW}$	1.43	0.79	1.37	1.78	2.10	2.38	1.11	1.92	2.49
CI	3.68	2.64	3.6	4.22	4.71	5.11	3.17	4.44	5.27
Linguistic terms	(VI, H)	(VI, VH)	(AI, VL)	(AI, L)	(AI, M)	(AI, H)	(AI, VH)		
$\tilde{x}_{BW}$	2.94	3.33	1.42	2.47	3.20	3.78	4.28		
CI	5.92	6.45	3.68	5.24	6.27	7.07	7.74		

According to Ref. [52, 54], the smaller the consistency ratio is, the more consistent the judgments are. In this framework, when the consistency ratio is less than 0.1, the consistency level is acceptable. Otherwise, the users need to revise the BO or/and OW vectors.

2.2 Alternative ranking method –ELECTRE under hybrid data types

The ELECTRE family are a series of classic MCDM methods used for ranking problems, and sorting problems [60]. However, they cannot deal with the decision-making matrix with hybrid information. In this study, the ELECTRE I [61] is extended to handle the decision-making matrix with hybrid information, and the proposed method (H-ELECTRE method) is specified as follows:

Assuming that there are *n* criteria to be assessed for the outranking of *m* alternatives, the data of alternatives with respect to the criteria consists of hybrid data types including crisp numbers, interval numbers, fuzzy numbers, and linguistic terms. The decision-making matrix *X* is presented in Eq.(5).

$$X = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{mn} \end{bmatrix} \tag{5}$$

where element a_{ij} represented the data of the *i*-th alternative with respect to the *j*-th criterion, as presented in Eq.(6).

$$a_{ij} = \begin{cases} x_{ij} & j \in N_1, i = 1,2,...,m \\ [x_{ij}^l, x_{ij}^u] & j \in N_2, i = 1,2,...,m \\ [x_{ij}^L, x_{ij}^M, x_{ij}^U] & j \in N_3, i = 1,2,...,m \end{cases} \tag{6}$$

where N_1 represents the crisp number. x_{ij} represents the element a_{ij} if a_{ij} is a crisp number. N_2 represents the interval number, x_{ij}^l and x_{ij}^u represent the lower and upper bounds of the element a_{ij} in the matrix *X* if a_{ij} is an interval number. N_3 represents fuzzy numbers. x_{ij}^L , x_{ij}^M and x_{ij}^U represent the lower bound, most possible number and the upper bound of the element a_{ij} in the matrix *X* if a_{ij} is a fuzzy number.

Step 1. Normalizing the decision-making matrix

The first step is to normalize the raw data a_{ij} (see Eq.(6)) in a decision-making matrix. There are two criteria types, which are cost-type and benefit-type. The benefit-type criteria represent a set of criteria which have the characteristic that the alternative will become better or more superior with the increase of the data with respect to the criteria. On the contrary, the cost-type criterion represents a set of criteria which have the characteristic that the alternative will become better or more superior with the decrease of the criterion value. The cost-type criterion can be normalized by using Eq.(7).

$$\tilde{Y}_{ij} = [y_{ij}^{l}, y_{ij}^{u}] = \begin{cases} [\frac{1/x_{ij}}{\sqrt{\sum_{i=1}^{n} 1/x_{ij}^{2}}}, \frac{1/x_{ij}}{\sqrt{\sum_{i=1}^{n} 1/x_{ij}^{2}}}], j \in N_1 \text{ and } i = 1,2,...,m \\ [\frac{1/x_{ij}^{u}}{\sqrt{\sum_{i=1}^{n} 1/x_{ij}^{l\,2}}}, \frac{1/x_{ij}^{l}}{\sqrt{\sum_{i=1}^{n} 1/x_{ij}^{u\,2}}}], j \in N_2 \text{ and } i = 1,2,...,m \\ [\frac{1/(x_{ij}^{M} + x_{ij}^{U})}{\sqrt{\sum_{i=1}^{n} 1/(x_{ij}^{L} + x_{ij}^{M})^{2}}}, \frac{1/(x_{ij}^{L} + x_{ij}^{M})}{\sqrt{\sum_{i=1}^{n} 1/(x_{ij}^{M} + x_{ij}^{U})^{2}}}], j \in N_3 \text{ and } i = 1,2,...,m \end{cases} \tag{7}$$

where N_1 represents the crisp number, N_2 represents the interval number, N_3 represents fuzzy numbers. $\tilde{Y}_{ij}$ represents the element of the *i*-th row and the *j*-th column of the normalized decision making matrix *Y*. y_{ij}^{l} and y_{ij}^{u} are the lower and the upper bounds of the element $\tilde{Y}_{ij}$.

Then, the benefit-type criterion can be normalized by using Eq.(8).

$$\tilde{Y}_{ij} = [y_{ij}^{l}, y_{ij}^{u}] = \begin{cases} [\frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^{2}}}, \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^{2}}}], j \in N_1 \text{ and } i = 1,2,...,m \\ [\frac{x_{ij}^{l}}{\sqrt{\sum_{i=1}^{n} x_{ij}^{u\,2}}}, \frac{x_{ij}^{u}}{\sqrt{\sum_{i=1}^{n} x_{ij}^{l\,2}}}], j \in N_2 \text{ and } i = 1,2,...,m \\ [\frac{x_{ij}^{L} + x_{ij}^{M}}{\sqrt{\sum_{i=1}^{n} (x_{ij}^{M} + x_{ij}^{U})^{2}}}, \frac{x_{ij}^{M} + x_{ij}^{U}}{\sqrt{\sum_{i=1}^{n} (x_{ij}^{L} + x_{ij}^{M})^{2}}}], j \in N_3 \text{ and } i = 1,2,...,m \end{cases} \tag{8}$$

where N_1 represents the crisp number, N_2 represents the interval number, N_3 represents fuzzy numbers. $\tilde{Y}_{ij}$ represents the element of the *i*-th row and the *j*-th column of the normalized decision making matrix *Y*. y_{ij}^l and y_{ij}^u are the lower and the upper bounds of the element $\tilde{Y}_{ij}$.

The crisp numbers and the fuzzy numbers in the decision-making matrix can be transformed into interval numbers. A crisp number can be treated as an interval number with equal upper bound and lower bound by Eq.(9).

$$X\left(x_{ij}\right)=\left[x_{ij},x_{ij}\right] \tag{9}$$

A fuzzy triangular number can be transformed into an interval number according to the method proposed by Wang *et al.* [62].

$$X\left(\left[x_{ij}^L,x_{ij}^M,x_{ij}^U\right]\right)=\left[x_{ij}^L+\alpha\left(x_{ij}^M-x_{ij}^L\right),x_{ij}^M+\alpha\left(x_{ij}^U-x_{ij}^M\right)\right] \tag{10}$$

where α is a real number which is set as 0.5 in this case study.

Therefore, the normalized decision making matrix *Y* is presented as Eq.(11).

$$Y=\begin{bmatrix} [y_{11}^l,y_{11}^u] & [y_{12}^l,y_{12}^u] & \cdots & [y_{1n}^l,y_{1n}^u] \\ [y_{21}^l,y_{21}^u] & [y_{22}^l,y_{22}^u] & \cdots & [y_{2n}^l,y_{2n}^u] \\ \vdots & \vdots & \ddots & \vdots \\ [y_{m1}^l,y_{m1}^u] & [y_{m2}^l,y_{m2}^u] & \cdots & [y_{mn}^l,y_{mn}^u] \end{bmatrix} \tag{11}$$

Step 2. Determining the weighted normalized decision-making matrix

After normalization, the normalized decision-making matrix should integrate the preference of criteria and determine the weighted normalized matrix as shown in Eq.(12).

$$\tilde{Z}_{ij}=[z_{ij}^l,z_{ij}^u]=[y_{ij}^l w_j^l,y_{ij}^u w_j^u] \quad i=1,2,...,m, \text{ and } j=1,2,...,n \tag{12}$$

where $\tilde{Z}_{ij}$ represents the element of the *i*-th row and the *j*-th column of the weighted normalized decision making matrix *Z*. z_{ij}^l and z_{ij}^u are the lower and the upper bounds of the element $\tilde{Z}_{ij}$. Then, the weighted normalized matrix Z can be presented in Eq.(13).

$$Z=\begin{bmatrix} [z_{11}^l, z_{11}^u] & [z_{12}^l, z_{12}^u] & \cdots & [z_{1n}^l, z_{1n}^u] \\ [z_{21}^l, z_{21}^u] & [z_{22}^l, z_{22}^u] & \cdots & [z_{2n}^l, z_{2n}^u] \\ \vdots & \vdots & \ddots & \vdots \\ [z_{m1}^l, z_{m1}^u] & [z_{m2}^l, z_{m2}^u] & \cdots & [z_{mn}^l, z_{mn}^u] \end{bmatrix} \tag{13}$$

Step 3. Determining the concordance set

The concordance set S_{ab} for the *a*-th alternative over the *b*-th alternative can be determined by Eq.(14).

$$S_{ab}=\{j \mid \tilde{Z}_{aj} \geq \tilde{Z}_{bj}\} \tag{14}$$

where $\tilde{Z}_{aj}$ and $\tilde{Z}_{bj}$ represent the weighted normalized elements of the *a*-th alternative and the *b*-th alternative with respect to the *j*-th criterion.

To deal with the interval comparison issues in the calculation, a reliability-based possibility degree of interval (RPDI) proposed by Jiang *et al.* [63] was used in this study. The RPDI for intervals $\tilde{A}=[a^l,a^u]$ and $\tilde{B}=[b^l,b^u]$ can be determined by Eq.(15).

$$\Pr(\tilde{A} \geq \tilde{B})=\frac{a^u-b^l}{a^u-a^l+b^u-b^l} \tag{15}$$

According to Jiang *et al.* [63], the comparison of intervals can be determined by Eq.(16).

$$\begin{cases} \Pr\left(\tilde{A} \geq \tilde{B}\right) \geq 1 & \tilde{A} \text{ absolutely outranks } \tilde{B} \\ 0.5 < \Pr\left(\tilde{A} \geq \tilde{B}\right) < 1 & \tilde{A} \text{ relatively outranks } \tilde{B} \\ \Pr\left(\tilde{A} \geq \tilde{B}\right) = 0.5 & \tilde{A} \text{ is indifferent to } \tilde{B} \\ 0 < \Pr\left(\tilde{A} \geq \tilde{B}\right) < 0.5 & \tilde{B} \text{ relatively outranks } \tilde{A} \\ \Pr\left(\tilde{A} \geq \tilde{B}\right) \leq 0 & \tilde{B} \text{ absolutely outranks } \tilde{A} \end{cases} \tag{16}$$

Therefore, the concordance set S_{ab} as presented in Eq.(14) can also be determined by Eq.(17).

$$S_{ab}=\left\{j \mid \Pr\left(\tilde{Z}_{aj} \geq \tilde{Z}_{bj}\right) \leq 0\right\} \tag{17}$$

where $\tilde{Z}_{aj}$ and $\tilde{Z}_{bj}$ represent the weighted normalized elements of the *a*-th alternative and the *b*-th alternative with respect to the *j*-th criterion.

Step 4. Determining the discordance set

Similarly, the discordance set P_{ab} for the *a*-th alternative over the *b*-th alternative can be determined by Eq.(18).

$$P_{ab} = \left\{ j \mid \Pr\left(\tilde{Z}_{aj} \geq \tilde{Z}_{bj}\right) \geq 1 \right\} \tag{18}$$

where $\tilde{Z}_{aj}$ and $\tilde{Z}_{bj}$ represent the weighted normalized elements of the *a*-th alternative and the *b*-th alternative with respect to the *j*-th criterion.

Step 5. Determining the concordance matrix

The element $C_{ab} = [c^l_{ab}, c^u_{ab}]$ in the concordance matrix C representing the concordance index of the *a*-th alternative over the *b*-th alternative can be determined by Eq.(19)

$$C_{ab} = \left[c^l_{ab}, c^u_{ab}\right] = \left[\sum_{j^* \in S_{ab}} w^l_{j^*}, \sum_{j^* \in S_{ab}} w^u_{j^*}\right] \tag{19}$$

Thereafter, the concordance matrix C can be presented in Eq.(20).

$$C = \begin{bmatrix} - & \left[c^l_{12}, c^u_{12}\right] & \cdots & \left[c^l_{1m}, c^u_{1m}\right] \\ \left[c^l_{21}, c^u_{21}\right] & - & \cdots & \left[c^l_{2m}, c^u_{2m}\right] \\ \vdots & \vdots & \ddots & \vdots \\ \left[c^l_{m1}, c^u_{m1}\right] & \left[c^l_{m2}, c^u_{m2}\right] & \cdots & - \end{bmatrix} \tag{20}$$

Step 6. Determining the discordance matrix

Similarly, the element d_{ab} in the discordance matrix $\vec{D}$ representing the concordance index of the *a*-th alternative over the *b*-th alternative can be determined by Eq.(21).

$$d_{ab} = \frac{\max_{j+ \in P_{ab}} \left| z^l_{aj+} - z^u_{bj+} \right|}{\max_{j=1,2,\ldots,n} \left| z^l_{aj} - z^u_{bj} \right|} \tag{21}$$

Thereafter, the discordance matrix D can be presented in Eq.(22).

$$D=\begin{bmatrix} - & d_{12} & \cdots & d_{1m} \\ d_{21} & - & \cdots & d_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ d_{m1} & d_{m2} & \cdots & - \end{bmatrix} \tag{22}$$

Step 7. Determining the effective concordance matrix

The threshold of concordance $\overline{C}$ can be firstly determined by Eq.(23).

$$\overline{C}=\left[\overline{c^l},\overline{c^u}\right]=\left[\frac{\sum_{k=1}^{m}\sum_{l=1}^{m}c_{kl}^{l}}{m(m-1)},\frac{\sum_{k=1}^{m}\sum_{l=1}^{m}c_{kl}^{u}}{m(m-1)}\right] \tag{23}$$

Then, the element f_{kl} of the *k*-th row and the *l*-th column of the effective concordance matrix F can be determined by Eq.(24).

$$f_{kl}=\begin{cases} 1 & \Pr\left(C_{kl}\geq\overline{C}\right)\leq 0 \\ 0 & \Pr\left(C_{kl}\geq\overline{C}\right)>0 \end{cases} \quad k=1,2,...,m \text{ and } l=1,2,...,m \tag{24}$$

The effective concordance matrix F can be obtained, as presented in Eq.(25).

$$F=\begin{bmatrix} - & f_{12} & \cdots & f_{1m} \\ f_{21} & - & \cdots & f_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ f_{m1} & f_{m2} & \cdots & - \end{bmatrix} \tag{25}$$

Step 8. Determining the effective discordance matrix

The threshold of discordance values $\overline{d}$ can be firstly determined by Eq.(26).

$$\overline{d}=\frac{\sum_{k=1}^{m}\sum_{l=1}^{m}d_{kl}}{m\left(m-1\right)} \tag{26}$$

The element g_{kl} in the cell of the *k*-th row and the *l*-th column of the effective discordance matrix G can be determined by Eq.(27).

$$g_{kl} = \begin{cases} 1 & d_{kl} \ge \bar{d} \\ 0 & d_{kl} < \bar{d} \end{cases} \quad k = 1, 2, ..., m \text{ and } l = 1, 2, ..., m \tag{27}$$

The effective discordance matrix G can be presented in Eq.(28).

$$G = \begin{bmatrix} - & g_{12} & \cdots & g_{1m} \\ g_{21} & - & \cdots & g_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ g_{m1} & g_{m2} & \cdots & - \end{bmatrix} \tag{28}$$

Step 9. Determining the global effective matrix

The global effective matrix can be then determined by integrating the effective concordance matrix and the effective discordance matrix. The element h_{kl} in the cell of the *k*-th row and the *l*-th column of the global effective matrix H can be determined by Eq.(29)[61].

$$h_{kl} = f_{kl} g_{kl}, \quad k = 1, 2, ..., m \text{ and } l = 1, 2, ..., m \tag{29}$$

The global effective matrix H can be determined by Eq.(30).

$$H = \begin{bmatrix} - & h_{12} & \cdots & h_{1m} \\ h_{21} & - & \cdots & h_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ h_{m1} & h_{m2} & \cdots & - \end{bmatrix} \tag{30}$$

Step 10. Determining the net flow and ranking the alternatives

To clearly illustrate the prioritization results, the net flow should be quantified. The net flow of the *i*-th alternative can be determined by Eq.(31).

$$NF_i = O_i - I_i, i = 1, 2, ..., m \tag{31}$$

where NF_i represents the net flow of the *i*-th alternative. O_i represents the number of outputs of the *i*-th alternative, which is determined by the sum of elements in the *i*-th column of global effective matrix *H*. I_i represents the number of inputs of the *i*-th alternative, which is determined by the sum of elements in the *i*-th row of global effective matrix H. To be specific, the output flow and the input flow of the i-th alternative can be determined by Eqs.(32)-(33) respectively.

$$O_i = \sum_{k=1,2,\ldots,m,\neq i} h_{ki} \tag{32}$$

$$I_i = \sum_{l=1,2,\ldots,m,\neq i} h_{il} \tag{33}$$

Then, all alternatives can be ranked by descending their net flows. If some alternatives are indifferent for their net flow, those alternatives should be selected to conduct an extra comparison by repeating step 1 to step 10 as shown in Eqs.(7)-(33).

3 Case study

In this section, five hydrogen production pathways, including the steam methane reforming (A_1), the coal gasification (A_2), the biomass gasification (A_3), the dark fermentation (A_4), and the wind electrolysis (A_5) (see **Fig.2**), are ranked by the proposed model.

Steam methane reforming is a hydrogen production technology that produces hydrogen by reacting steam at high temperature and pressure with methane in the presence of a nickel catalyst. Since this technology has been studied for years and now exhibits relatively excellent industrial performance, the steam methane reformer is well-developed and is widely used in industry to make hydrogen. However, there is greenhouse gas produced during this hydrogen production process which causes negative impacts on the environment. In this case, researchers are working on more sustainable hydrogen production technologies.

Coal gasification produces hydrogen from coal, water, and air under special conditions and treatments [64]. This technology is cheap, and the supply of raw materials is easily accessed. However, the outputs of this process include not only hydrogen, but also carbon monoxide and carbon dioxide [64,65]. Those byproducts bring negative environmental influence, which is the main concern of adopting this technology.

Biomass gasification is a process of converting solid biomass fuel into a gaseous combustible gas through a sequence of thermo-chemical reactions [13]. The biomass gasification uses CO_2-neutral, abundant and cheap feedstock, but it forms tar, and it is difficult to control the purity due to seasonal availability and feedstock impurity [66].

Dark fermentation is the fermentative conversion of organic substrate to biohydrogen, which is a complex process manifested by diverse groups of bacteria, involving a series of biochemical reactions in three steps which are similar to anaerobic conversion [67]. Although this technology is relatively new and feasible, the production process is difficult to control and production cost is relatively high [68].

The wind-based water electrolysis produces hydrogen by electrolyzing water while adapting wind as an energy source [69]. Wind-based water electrolysis is a viable approach to producing greener hydrogen, holding promise to better utilize domestic renewable energy sources for the energy needs of the transportation sector. A wind-based electrolysis system can reduce greenhouse gas emissions from the transportation sector while integrating larger percentages of renewable energy into the electric grid. However, the production price of this technology is relatively high, and this technology requires some more mature technology supports [7].

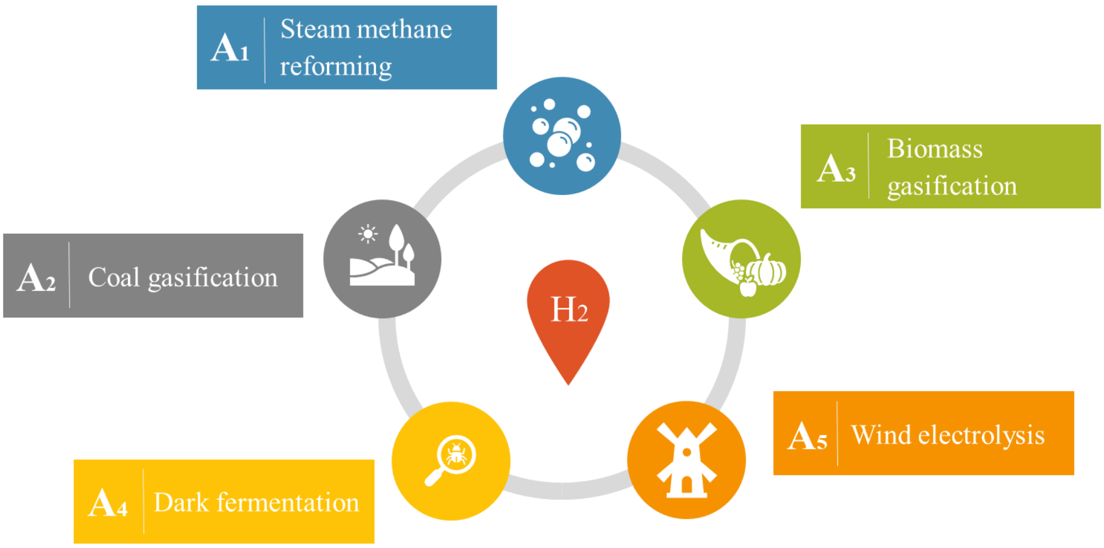

Fig. 2. Hydrogen production alternatives in the case study

The hydrogen production pathways are evaluated in environmental, economic, technical, and social aspects for their sustainability performances. In the environmental aspect, three indicators including global warming potential, water consumption potential and fossil resource scarcity were used for hydrogen production pathways selection. In the economic aspect, the capital cost and the hydrogen production cost were adopted. In the social aspect, social acceptance and human toxicity potential were considered. The data of alternatives with regards to responding criteria is presented in **Table 3**.

Table 3. Decision matrix for hydrogen production pathway selection

		Units	SMR	CG	BG	DF	WE	Ref
Environmental	GWP	kg $CO_{2\text{-eq}}$	12.13	24.2	2.67	[6.6, 16.29]	[2.21, 5.1]	[70]
	WCP	m^3 consumed	5.77	13.1	4.94	[23.98, 84.9]	[8.82, 16.4]	[70]
	FRS	kg $oil_{\text{-eq}}$	4.45	4.914	0.655	[1.68, 4.38]	[0.62, 1.72]	[70]
Economic	CC	M$	[180.7, 226.4]	[435.9, 545.6]	149.3	593	504.8	[8,71]
	HC	$/kg	[2.08, 2.27]	[1.34, 1.63]	[1.77, 2.05]	2.57	[5.1, 10.49]	[8]
Social	SA	-	Low	Low	Medium	High	Very high	[70]
	HTP-C	kg 1,4-$DCB_{\text{-eq}}$	0.008272	0.64	0.00433	[0.16, 0.565]	[0.356, 0.43]	[70]
	HTP-NC	kg 1,4-$DCB_{\text{-eq}}$	21.36	277.6	19.69	[82.1, 272.6]	[102.26, 157.25]	[70]

Note: SMR: Steam methane reforming; CG: Coal gasification; BG: Biomass gasification; DF: Dark fermentation; WE: Wind electrolysis; GWP: Global warming potential; WCP: Water consumption potential; FRS: Fossil resource scarcity; CC: Capital cost; HC: Hydrogen cost; SA: Social acceptance; HTP-C: Human toxicity potential-cancer; HTP-NC: Human toxicity potential-non-cancer.

After the criteria selection and the establishment of the decision-making matrix, the weights of the criteria should be determined by the ZBWM method according to Eqs.(1)-(3). Taking the comparisons among the three aspects as an example, the economic aspect was recognized as the most important aspect among three aspects and the social aspect was selected as the least important aspect, as shown in **Tables 4** and **Table 5**.

Table 4. The BO vector for aspect comparison

	Environment	Economic	Social
Economic	(VI, H)	(EI, VH)	(AI, M)
	(2.10,2.52,2.94)	(1,1,1)	(2.49,2.84,3.20)

Table 5. The OW vector for aspect comparison

	Social	
Environment	(WI, L)	(0.37,0.55,0.82)
Economic	(AI, M)	(2.49,2.84,3.20)
Social	(EI, VH)	(1,1,1)

According to Eq.(3), the weights of the three aspects can be determined by solving the programming model presented in Eq.(34).

$$
\min k^*
$$

$$
\text{subject to} \begin{cases}
-k^* \times w_1^U \le w_2^L - 2.10 \times w_1^U \le k^* \times w_1^U \\
-k^* \times w_1^M \le w_2^M - 2.52 \times w_1^M \le k^* \times w_1^M \\
-k^* \times w_1^L \le w_2^U - 2.94 \times w_1^L \le k^* \times w_1^L \\
-k^* \times w_3^U \le w_2^L - 2.49 \times w_3^U \le k^* \times w_3^U \\
-k^* \times w_3^M \le w_2^M - 2.84 \times w_3^M \le k^* \times w_3^M \\
-k^* \times w_3^L \le w_2^U - 3.20 \times w_3^L \le k^* \times w_3^L \\
-k^* \times w_3^U \le w_1^L - 0.37 \times w_3^U \le k^* \times w_3^U \\
-k^* \times w_3^M \le w_1^M - 0.55 \times w_3^M \le k^* \times w_3^M \\
-k^* \times w_3^L \le w_1^U - 0.82 \times w_3^L \le k^* \times w_3^L \\
-k^* \times w_3^U \le w_2^L - 2.49 \times w_3^U \le k^* \times w_3^U \\
-k^* \times w_3^M \le w_2^M - 2.84 \times w_3^M \le k^* \times w_3^M \\
-k^* \times w_3^L \le w_2^U - 3.20 \times w_3^L \le k^* \times w_3^L \\
\sum_{j=1}^{3} \frac{w_j^L + 4 \times w_j^M + w_j^U}{6} = 1 \\
0 \le w_j^L \le w_j^M \le w_j^U \\
j = 1, 2, \ldots, 3
\end{cases} \tag{34}
$$

The weights of the environmental aspect, economic aspect and the social aspect are [0.182,0.199,0.232], [0.561,0.567,0.590], [0.205,0.226,0.260], respectively. Since the data proceeded in this model is required to be in interval form, the aspect weights are transformed into interval numbers by Eq.(10). Therefore, the weights of environmental aspect, economic aspect and the social aspect are [0.191, 0.215], [0.564, 0.579], [0.216, 0.243], respectively.

Similarly, the local weights of the criteria in each aspect can be calculated by using ZBWM. The BO vectors and OW vectors for determining the local weights of the criteria in each of these three aspects are presented in the **Supplementary Materials**, and the results are shown in **Table 6**.

Table 6. The global weights and the local weights of the criteria determined by ZBWM for sustainability prioritization of hydrogen production technologies

Aspect	Aspect weight	Criteria	Local weight	Global weight
Environment	[0.191, 0.215]	GWP	[0.502, 0.537]	[0.096, 0.116]
		WCP	[0.279, 0.318]	[0.053, 0.069]
		FRS	[0.166, 0.178]	[0.032, 0.038]
Economic	[0.564, 0.579]	CC	[0.327, 0.366]	[0.184, 0.212]
		HC	[0.556, 0.721]	[0.313, 0.417]
Social	[0.216, 0.243]	SA	[0.153, 0.182]	[0.033, 0.044]
		HTP-C	[0.417, 0.417]	[0.09, 0.101]
		HTP-NC	[0.417, 0.417]	[0.09, 0.101]

After determination of the global weights of criteria, the ranking of alternatives need to be determined by H-ELECTRE model. The decision-making matrix presented in **Table 3** need to be normalized by using Eqs.(7)-(8). Taking the first element in the fourth row as an example, the GWP is a cost-type criterion and this element is an interval number. Therefore, the element $\tilde{Y}_{41}$ in normalized decision making matrix can be determined by Eq.(35).

$$\tilde{Y}_{41}=[y_{41}^{l}, y_{41}^{u}]=[\frac{1/16.29}{\sqrt{(\frac{1}{12.13^2}+\frac{1}{24.2^2}+\ldots+\frac{1}{2.21^2})}}, \frac{1/6.6}{\sqrt{(\frac{1}{12.13^2}+\frac{1}{24.2^2}+\ldots+\frac{1}{5.1^2})}}]=[0.1, 0.347] \quad (35)$$

Similarly, other elements in the normalized decision-making matrix can be determined as presented in the **Supplementary Materials**.

Then, the elements in the weighted normalized decision-making matrix Z can be determined by Eq.(12). Taking the first element in the fourth row as an example, the weight of the criterion GWP is [0.096,0.116] according to **Table 6**. The element $\tilde{Z}_{41}$ in the weighted normalized decision making matrix can be determined by Eq.(36).

$$\tilde{Z}_{41}=[z_{41}^{l}, z_{41}^{u}]=[y_{41}^{l}w_{1}^{l}, y_{41}^{u}w_{1}^{u}]=[0.1\times 0.096, 0.347\times 0.116]=[0.01, 0.04] \quad (36)$$

Similarly, other elements in the weighted normalized decision-making matrix can be determined as presented in the **Supplementary Materials**.

To determine the concordance and the discordance sets for the *a*-th alternative over the *b*-th alternative, the RPDI for intervals can firstly be determined by Eq.(15). Taking the RPDI for weighted normalized intervals of the first alternative (SMR) over the second alternative (CG) regarding the first criterion (GWP) as an example, the $\Pr\left(\tilde{Z}_{11}\geq\tilde{Z}_{21}\right)$ can be determined by Eq.(37).

$$\Pr\left(\tilde{Z}_{11}\geq\tilde{Z}_{21}\right)=\frac{z_{11}^{u}-z_{21}^{l}}{z_{11}^{u}-z_{11}^{l}+z_{21}^{u}-z_{21}^{l}}=\frac{0.022-0.006}{0.022-0.013+0.011-0.006}=1.142 \quad (37)$$

The RPDIs between each pair of these five alternatives with respect to each criterion are presented in the **Supplementary Materials**. Then, the concordance and discordance sets can be determined by Eqs.(17)-(18). For example, the concordance set and the discordance set for the first alternative (SMR) over the second alternative (CG) are presented in Eqs.(38)-(39).

$$S_{12}=\varnothing \tag{38}$$

$$P_{12}=\{\text{GWP, WCP, CC, HTP-C, HTP-NC}\} \tag{39}$$

Thereafter, the concordance index C_{ab} representing the of the *a*-th alternative over the *b*-th alternative can be determined by Eq.(19). Taking the concordance index for the first alternative (SMR) over the second alternative (CG) as an example, the concordance index C_{12} can be determined by Eq.(40)

$$C_{12}=[c_{12}^{l},c_{12}^{u}]=[0,0] \tag{40}$$

The concordance matrix *C* is presented in the **Supplementary Materials**.

The discordance index d_{ab} of the *a*-th alternative over the *b*-th alternative can be determined by Eq.(21). Taking the discordance index for the first alternative (SMR) over the second alternative (CG) as an example, the concordance index d_{12} can be determined by Eq.(41).

$$d_{12}=\frac{\max\limits_{j+\in P_{12}}\left|z_{1j+}^{l}-z_{2j+}^{u}\right|}{\max\limits_{j=1,2,\ldots,8}\left|z_{1j}^{l}-z_{2j}^{u}\right|}=\frac{\max(|0.013-0.011|,|0.031-0.018|\ldots,|0.059-0.005|)}{\max(|0.013-0.011|,|0.031-0.018|\ldots,|0.059-0.005|)}=0.186 \tag{41}$$

The discordance matrix *D* is presented in the **Supplementary Materials**.

Thereafter, the effective concordance matrix can be determined by Eqs.(23)-(24). The threshold of concordance $\overline{C}$ can be firstly determined by Eq.(42).

$$\overline{C}=\left[\overline{c^{l}},\overline{c^{u}}\right]=[\frac{0+0.217\ldots+0.313}{5\times4},\frac{0+0.255\ldots+0.417}{5\times4}]=[0.267,0.325] \tag{42}$$

Then, the element f_{kl} in the *k*-th row and the *l*-th column of the effective concordance matrix F can be determined by Eq.(24). Taking the second element in the first row as an example, the RPDI of the concordance index over the threshold of concordance can be determined by Eq.(43).

$$\Pr\left(C_{12} \geq \overline{C}\right) = \frac{c_{12}^{u} - \overline{c}^{l}}{c_{12}^{u} - c_{12}^{l} + \overline{c}^{u} - \overline{c}^{l}} = \frac{0 - 0.267}{0 - 0 + 0.325 - 0.267} = -4.585 < 0 \tag{43}$$

Therefore, the element f_{12}=1. Similarly, the effective concordance matrix is presented in Eq.(44).

$$f = \begin{bmatrix} - & 1 & 1 & 1 & 1 \\ 0 & - & 0 & 1 & 0 \\ 1 & 1 & - & 1 & 1 \\ 0 & 0 & 0 & - & 1 \\ 0 & 0 & 0 & 0 & - \end{bmatrix} \tag{44}$$

Then, the effective discordance matrix can be determined by Eqs.(26)-(27). The threshold of discordance values $\overline{d}$ can be firstly determined by Eq.(45).

$$\overline{d} = \frac{0.186+0+...+0.002}{5 \times 4} = 0.098 \tag{45}$$

Then, all the elements in effective discordance matrix can be determined. Taking the second element in the first row as an example, the element in effective discordance matrix $g_{12} = 1$ because the concordance index d_{12}=0.186 > 0.098. Therefore, the effective discordance matrix is shown in Eq.(46).

$$g = \begin{bmatrix} - & 1 & 0 & 1 & 1 \\ 0 & - & 0 & 0 & 1 \\ 1 & 1 & - & 1 & 1 \\ 0 & 0 & 0 & - & 0 \\ 0 & 0 & 0 & 0 & - \end{bmatrix} \tag{46}$$

Hence, the elements in the global effective matrix can be determined by Eq.(29). Taking the second element in the first row as an example, the element can be determined by Eq.(47).

$$h_{12} = f_{12} g_{12} = 1 \times 1 = 1 \tag{47}$$

Therefore, the elements in global effective matrix can be determined and presented in Eq.(48).

$$h = \begin{bmatrix} - & 1 & 0 & 1 & 1 \\ 0 & - & 0 & 0 & 0 \\ 1 & 1 & - & 1 & 1 \\ 0 & 0 & 0 & - & 0 \\ 0 & 0 & 0 & 0 & - \end{bmatrix} \tag{48}$$

According to the effective concordance matrix and the effective discordance matrix, the results can be determined, as shown in **Fig.3**.

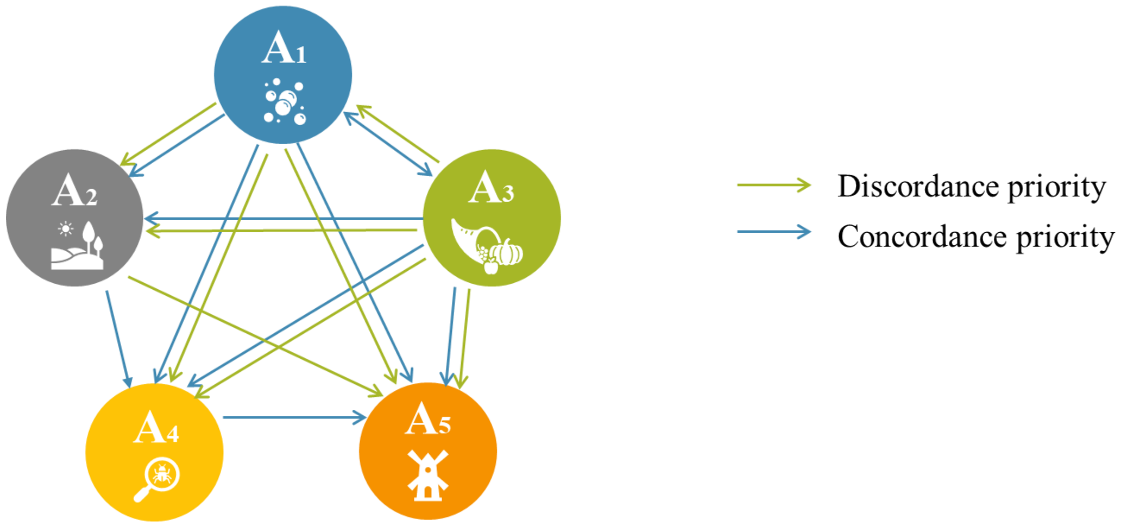

Fig. 3. The priority graph based on the effective concordance matrix and effective discordance matrix

After integrating the relationship flows, the priority is shown in **Fig.4**.

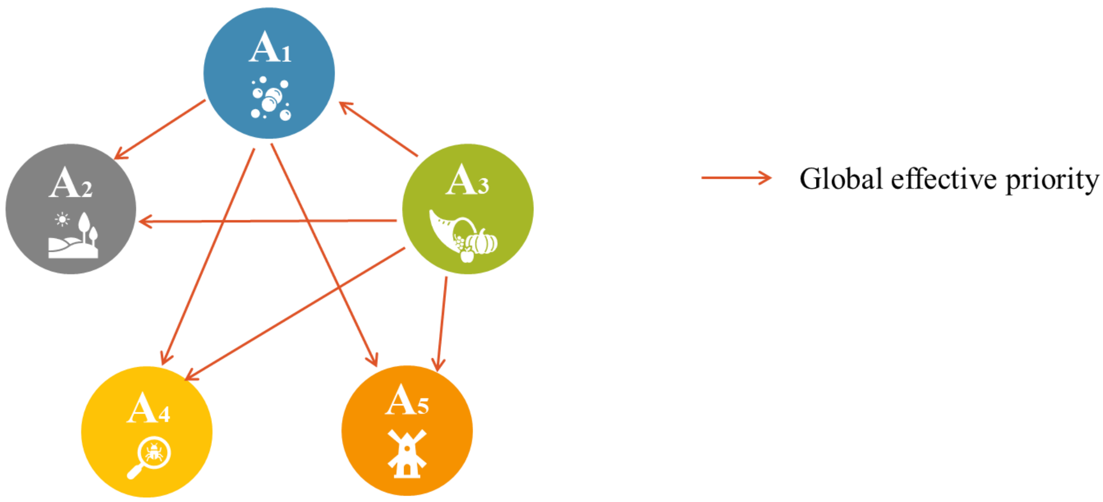

Fig. 4. The priority graph for the global effective matrix

According to Eqs.(31)-(33), the numbers of outputs, inputs and the net flow of each alternative can be determined (as presented in **Table 7).**

Table 7. Summary of the global effective matrix

Node	No. of outputs (O)	No. of inputs (I)	Net flow (NF)	Ranking
A_1 (SMR)	3	1	2	2nd
A_2 (CG)	0	2	-2	3rd
A_3 (BG)	4	0	4	1st
A_4 (DF)	0	2	-2	3rd
A_5 (WE)	0	2	-2	3rd

According to **Table 7**, the biomass gasification is ranked as the best pathway, following by the steam methane reforming. The coal gasification, the dark fermentation, and the wind electrolysis are indifferent in terms of priority according to the results presented in Table 7. Therefore, the developed ELECTRE method should be used to re-rank these three alternatives that are indifferent. The data of the coal gasification, the dark fermentation, and the wind electrolysis with respect to all criteria are selected to repeat the decision-making process. The global effective matrix for the second round processing is shown in Eq.(49).

$$h = \begin{bmatrix} - & 0 & 0 \\ 0 & - & 0 \\ 1 & 0 & - \end{bmatrix} \tag{49}$$

According to Eq.(49), the ranking of those three alternatives is presented in **Table 8**.

Table 8. Summary of the global effective matrix

Node	No. of outputs (O)	No. of inputs (I)	Net flow (NF)	Ranking
A_2 (CG)	0	1	-1	3rd
A_4 (DF)	0	0	0	2nd
A_5 (WE)	1	0	1	1st

According to **Table 7** and **Table 8**, the final prioritization result is presented in **Table 9**.

Table 9. Prioritization results of the hydrogen production selection

Alternative	A_1 (SMR)	A_2 (CG)	A_3 (BG)	A_4 (DF)	A_5 (WE)
Ranking	2nd	5th	1st	4th	3rd

4 Discussion

In this section, the proposed MCDM model and the results of the hydrogen production methods prioritization are discussed. The sensitivity analysis was conducted to check the robustness of the proposed model. In addition, the results determined by the proposed method has been validated by the result determined by combining BWM [54] and the hybrid TOPSIS method [72].

4.1 Sensitivity analysis

Sensitivity analysis is designed to analyze the impacts of the weights of the criteria on the sustainability rankings in this model. Also, the robustness of the model can also be evaluated through sensitivity analysis.

In the sensitivity analysis, eight scenarios are evaluated. The weights of the criteria in each scenario are presented in follows:

- **Scenario 1:** The weight of GWP is [0.3, 0.3], while the weights of other criteria are [0.1, 0.1].
- **Scenario 2:** The weight of WCP is [0.3, 0.3], while the weights of other criteria are [0.1, 0.1].
- **Scenario 3:** The weight of FRS is [0.3, 0.3], while the weights of other criteria are [0.1, 0.1].
- **Scenario 4:** The weight of CC is [0.3, 0.3], while the weights of other criteria are [0.1, 0.1].
- **Scenario 5:** The weight of HC is [0.3, 0.3], while the weights of other criteria are [0.1, 0.1].
- **Scenario 6:** The weight of SA is [0.3, 0.3], while the weights of other criteria are [0.1, 0.1].
- **Scenario 7:** The weight of HTP-C is [0.3, 0.3], while the weights of other criteria are [0.1, 0.1].
- **Scenario 8:** The weight of HTP-NC is [0.3, 0.3], while the weights of other criteria are [0.1, 0.1].

The five hydrogen production pathways in the 8 scenarios are ranked respectively according to Eqs.(7)-(30). The results of sensitivity analysis are presented in **Fig.5**.

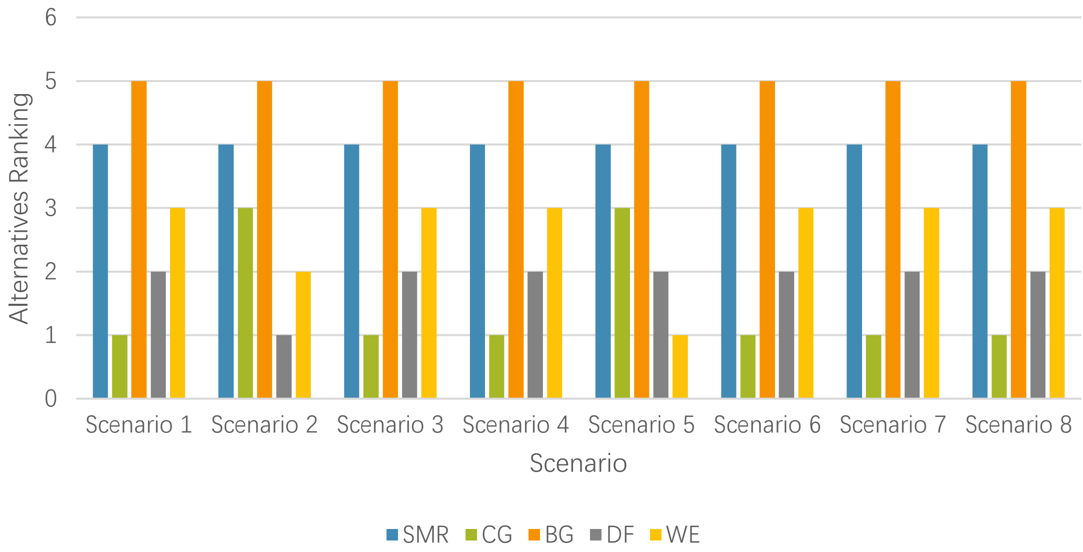

Fig. 5. The results of sensitivity analysis

By analyzing the sensitivity analysis results, it is apparent that the weights of the criteria play significant roles in sustainability rankings of the alternatives. According to **Fig. 5**, biomass gasification is the best hydrogen production pathway and the steam methane reforming ranks at the second among these five hydrogen production pathways. The remainder of the alternatives including the coal gasification, the dark fermentation, and the wind electrolysis have different ranking results when assigning different weights to the criteria.

4.2 Validation

In order to confirm the feasibility and to discover the advantages of the proposed method, validation is conducted by comparing the proposed framework with the crisp BWM [54] and the hybrid TOPSIS [72] respectively. The BWM is first compared with the ZBWM and the results are shown in **Table 10**. The pairwise comparison vectors used in the BWM for determining the weights of the criteria are presented in **Part III of Supplementary Materials**.

Table 10. The global weights and the local weights of the criteria determined by BWM

for sustainability prioritization of hydrogen production technologies

Aspect	Aspect weight	Criteria	Local weight	Global weight
Environment	0.167	GWP	0.571	0.095
		WCP	0.286	0.048
		FRS	0.143	0.024
Economic	0.667	CC	0.5	0.333
		HC	0.5	0.333
Social	0.167	SA	0.143	0.024
		HTP-C	0.429	0.071
		HTP-NC	0.429	0.071

According to **Table 6** and **Table 10**, the ZBWM is more suitable in the decision-making framework under hybrid information. Firstly, the results generated from the two models are similar, which indicates that the ZBMW is feasible for problem-solving. Secondly, ZBWM can provides a more precise result in capturing the vagueness of opinions of decision maker, because the interval results determined by BWM showed less information loss. Lastly, the slight differences between criteria can be presented in ZBWM. For example, the criteria weights for two criteria in the economic aspect are the same in the results determined by BWM, but they are slightly different in the result determined by ZBWM. Therefore, ZBWM is suitable and efficient in capturing the hesitation and vagueness in judgement of decision makers.

Thereafter, three combined methods for prioritizing the hydrogen production pathways were used to evaluate the results of the H-ELECTRE method. The hybrid TOPSIS [72] proposed by Gao and Zhu was used as the other option of alternative ranking method. Because the hybrid TOPSIS method can handle crisp numbers and interval numbers but it cannot deal with fuzzy numbers and linguistic terms, the data of fuzzy numbers and linguistic terms was processed in normalization process to interval numbers as well. The following combined models are evaluated and compared.

M1: ZBWM+ H-ELECTRE (The proposed method)

M2: ZBWM+ Hybrid TOPSIS

M3: BWM+ H-ELECTRE

M4: BWM+ Hybrid TOPSIS

Because data types required in different methods are different, the weights of criteria should be transformed into corresponding data types. The weight of the *j*-th criterion generated by ZBWM will be transformed into crisp numbers by using Eq.(50) in **M2**, and the weights of criteria determined by BWM should be transformed into interval numbers by using Eq.(51) in **M3**.

$$w_j = \frac{w_j^L + 4w_j^M + w_j^U}{6}, j = 1, 2, ..., n \tag{50}$$

$$\left[w_j^l, w_j^u\right] = \left[w_j, w_j\right], j = 1, 2, ..., n \tag{51}$$

The comparative results between different combined models are presented in **Table 11**. The calculation processes and the results are presented in **Part IV of Supplementary Materials**.

Table 11. Comparative rankings determined by the proposed method and the validation methods

	M1	**M2**	**M3**	**M4**
A_3 (BG)	1st	1st	1st	1st
A_1 (SMR)	2nd	4th	2nd	4th
A_5 (WE)	3rd	3rd	5th	3rd
A_2 (CG)	5th	2nd	3rd	2nd
A_4 (DF)	4th	5th	4th	5th

According to **Table 11**, the ranking results determined by different ranking methods are different. The H-ELECTRE ranks those options by considering concordance and discordance, while the hybrid TOPSIS measures the distances from each alternative to the ideal alternative. According to the results, it is obvious that the results determined by H-ELECTRE are more sensitive to the criteria weights, which also indicates that ZBWM is a suitable method to determine the weights of criteria, because the results remain less information loss and it can capture the hesitation and vagueness in the preference of decision makers. Compared with the hybrid TOPSIS method, the proposed method can handle the fuzzy numbers and linguistic terms as well, which is superior to the evaluation method. Furthermore, the biomass gasification (A_3) is the best option based on the considered criteria in this study.

5 Conclusion

This study has developed a novel multi-criteria sustainability prioritization framework for sustainability prioritization of hydrogen production pathways under the context of hybrid information. Two challenges have been overcome in the decision-making process: (1) quantifying the weights of the criteria properly and accurately based on the preferences of stakeholders with hesitation and vagueness in their judgments; and (2) handling decision-making matrix with hybrid information (multiple types of data). The ZBWM was applied to determine the weights of the criteria accurately by using Z numbers to capture the vagueness and ambiguity in human's judgments. Then, an extended ELECTRE model was developed for sustainability prioritization of hydrogen production pathways based in the decision-making matrix with hybrid information. In order to illustrate the proposed sustainability prioritization framework, a case study including five hydrogen production pathways were studied. Sensitivity analysis was conducted for testing the influences of the weights of the criteria on the sustainability rankings and checking the robustness of the proposed model. The results determined by the proposed method has been validated by comparing with that determined by BWM and hybrid TOPTSIS method. The H-ELECTRE is validated to be feasible to handle the decision-making matrix with hybrid information.

Although the proposed framework is feasible in dealing with hybrid information and vagueness in judgement of decision makers, there is still a limitation-the preferences/opinions of different decision makers were not allowed to be incorporated in the decision-making process simultaneously. Therefore, the H-ELECTRE method will be improved in the further to incorporate the preferences/opinions of different decision makers in the decision-making process.

Acknowledgments

The work described in this paper was supported by the grant from the Research Committee of The Hong Kong Polytechnic University under student account code RK22 and was also supported by the Hong Kong Research Grants Council for Early Career Scheme (Grand No. 25208118) and the Joint Supervision Scheme with the Chinese Mainland, Taiwan and Macao Universities - Other Chinese Mainland, Taiwan and Macao Universities (Grant No. SB2S).

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