Industrial system prioritization using the sustainability-interval- index conceptual framework with life-cycle considerations

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Abstract

This study aims to develop a sustainability-interval-index (SII) conceptual framework with life-cycle considerations which can incorporate the opinions/preferences of multiple stakeholders in the complex decision-making processes and address the decision-making matrix composed by multiple types of data for multiactor life cycle ranking of industrial systems. The multiactor fuzzy best-worst method which allows multiple groups of stakeholders to use fuzzy numbers to express their opinions and preferences was developed for determining the weights of the indicators in life cycle sustainability assessment. A multicriteria decision-making method under hybrid information was developed for addressing the decision-making matrix composed by multiple types of data. Five hydrogen production pathways were studied, and the results reveal that the developed SII is feasible for sustainability ranking of industrial systems in life cycle perspective.

Keywords:

best-worst method, life cycle sustainability assessment, multicriteria decision-making, sustainability

1 INTRODUCTION

The concept of sustainability or sustainable development, which emphasizes the harmonious development of economy, environment, and society simultaneously, has drawn more and more attentions of the stakeholders of industrial systems. Life cycle analysis methods, which broaden the horizons from a single production process to the scale of the entire industry chain, greatly extend people's perception of the impact of industrial processes. In order to investigate the sustainability of industrial systems, the idea of combining sustainability and life cycle thinking was proposed and evolved into the life cycle sustainability assessment (LCSA) method. Sustainability assessment consists of three main pillars: economic, environmental and social. Kloepffer[1] suggested in a conceptual formula: LCSA = LCA + LCC + SLCA. LCSA has three separate life cycle based methods: life cycle assessment (LCA), life cycle costing (LCC) and social life cycle analysis (SLCA). LCSA is a transdisci- plinary integration framework of models rather than a model in itself,[2] wherein, (a) LCA is the compilation and evaluation of the inputs, out- puts and the potential environmental impacts of a product system throughout its life cycle[3]; (b) LCC is the logical counterpart of LCA for the economic assessment, LCC surpasses the purely economic cost calculation by taking into account the use- and end-of-life phases and hidden costs; and (c) the key point of SLCA is how to combine social indicators with functional units of product systems using qualitative and semi-quantitative approaches.[1]

Previous investigations about LCSA are usually the calculations and comparisons of single or multiple criteria for a product or technol- ogy under the same dimension. The three separate life cycle based methods are supported by various criteria, for example, LCA consists nearly 1,500 life cycle impact results, which usually include climate change, primary energy consumption, acidification, and eutrophica- tion, and so on.[4]

The wide applications of LCSA for decision-making face two severe challenges:

1. How to represent the life cycle sustainability of a technology, product or production pathway? There are few cases that can achieve the condition that all the criteria are the optimum, thus the contradictions usually happen when judging the superiority and inferiority of alternatives. This leads to the trade-off of multi- ple criteria.
2. How to deal with the opinions and preferences of the decision- makers that may be conflict with each other?

Multicriteria decision-making (MCDM) was introduced in life cycle tools and regarded as the best solution for dealing with sustainability conflicts at both micro and macro levels of analysis. Fuzzy approach was widely used for sustainability assessment or sustainability ranking, because it can effectively address the uncertainties and ambiguity. Phillis and Andriantiatsaholiniaina[5] proposed the use of fuzzy logic to assess sustainability. Conner et al.[6,7] presented the sustainability-interval-index (SII) for sustainability assessment employing fuzzy logic, interval analysis, and global optimization concepts. Phillis et al.[8] provided a review of this system of systems approach for sustainability assessment, within which there are numerous references about fuzzy logic based approaches for sustainability assessment.[9] MCDM coupled with LCSA can achieve the sustainability assessment of the alternatives from a life cycle perspective. For instance, Campos-Guzmán et al.[10] verified that the methodological framework integrated by the LCA and MCDM combination was the right tool for the sustainability evaluation of renewable energy systems. Tang and You[11] presented multicriteria environmental and economic analysis of municipal solid waste (MSW) grate incineration power plants without and with CO_2 capture and separation (CCS) technologies, the LCA and techno-economic analysis (TEA) are integrated with the AHP and TOPSIS approaches for systematic environmental and economic analysis. In the light of major characteristics of cellulosic ethanol supply chains, You et al.[12] developed multiobjective mixed-integer linear programming (mo-MILP) model and revealed the trade-off between the economic, environmental, and social dimensions of the sustainable biofuel supply chains. In order to handle the vagueness during the assessment and to eliminate the perceived hesitancy in the decision-makers' preferences, Acar et al.[13] proposed an innovative method, a hybrid hesitant fuzzy MCDM methodology com- posed of hesitant fuzzy analytic hierarchy process (HFAHP) and hesitant fuzzy technique for order preference by similarity to ideal solution (HFTOPSIS), was utilized to assess the sustainability of the energy storage systems. Ren et al.[14] determined the weights by fuzzy AHP and ANP (Analytic Network Process), PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) that was applied to determine the sustainability priority to rank the sustainability of five alternative hydrogen production technologies. Phillis and It is apparent that the combination of LCSA and MCDM was also widely used in chemical engineering.[15] All these studies demonstrated the feasibility of combining LCSA and MCDM for life cycle sustainability ranking of industrial systems. However, the selection of the most sustainable industrial systems among multiple alternatives usually involves the concerns and preferences of multiple different groups of stakeholders (i.e., investors, administrators, engineers, residents and environmental protectors, etc.), and this is a group decision-making problem. More- over, there are usually various uncertainties in LCSA,[16] the crisp numbers cannot be used to address these uncertainties. In addition, the performances of industrial systems with respect to some "soft" criteria such as social acceptability and working environment are usually difficult or even impossible to be quantified, but it is more suitable for the stakeholders to use linguistic terms to express their opinions and preferences. Accordingly, multiple types of information or data are usually used in LCSA. Therefore, there are still two knowledge gaps in the traditional MCDM method for sustainability prioritization:

1. It lacks the method which can incorporate the preferences and opinions of numerous stakeholders when prioritizing the alternative industrial systems. Different stakeholders may have different preferences when prioritizing the industrial systems according to their sustainability performances.
2. It lacks the MCDM method which can address the decision-making matrix composed by multiple types of data.

This study aims to develop an SII based on the work of Conner et al.,[7] and the developed method in this study can fill in the abovementioned two gaps. In other words, they can incorporate the preferences of numerous stakeholders and address the decision-making matrix composed by multiple types of data for multiactor life cycle sustainability ranking of industrial systems under hybrid information.

2 MULTICRITERIA DECISION ANALYSIS UNDER HYBRID INFORMATION

The SII conceptual framework for multiactor life cycle sustainability prioritization of industrial systems under hybrid information was illustrated in Figure 1. Life cycle tools including LCA, LCC, and SLCA were employed to obtain the data of the alternative industrial systems with respect to the criteria in economic, environmental and social aspects. The crisp numbers and the interval numbers were used for quantifying the data of the alternative industrial systems with respect to the "hard" criteria, and the fuzzy logic approach was employed to deter- mine the data of the alternative industrial systems with respect to the "soft" criteria. After this, the decision-making matrix under hybrid information which was composed by crisp numbers, interval numbers and fuzzy numbers can be determined. The multiactor fuzzy best- worst method which can incorporate the preferences of numerous stakeholders was developed for determining the weights of the criteria in economic, environmental and social aspects for sustainability assessment, and it also allows the stakeholders to use fuzzy numbers to describe the relative priority of a criterion over another. MCDM under hybrid information which can address the decision- making matrix which was composed by crisp numbers, interval numbers and fuzzy numbers ("hybrid data" or "hybrid information") was developed for prioritizing the alternative industrial systems.

In this section, the preliminary of fuzzy numbers and interval numbers was firstly introduced; the criteria system for sustainability assessment and the data collection were subsequently presented; then, the fuzzy logarithmic least squares method based multiactor fuzzy best- worst method for determining the weights of the criteria for sustainability assessment was developed; and finally, the multicriteria decision analysis method under hybrid data conditions was developed.

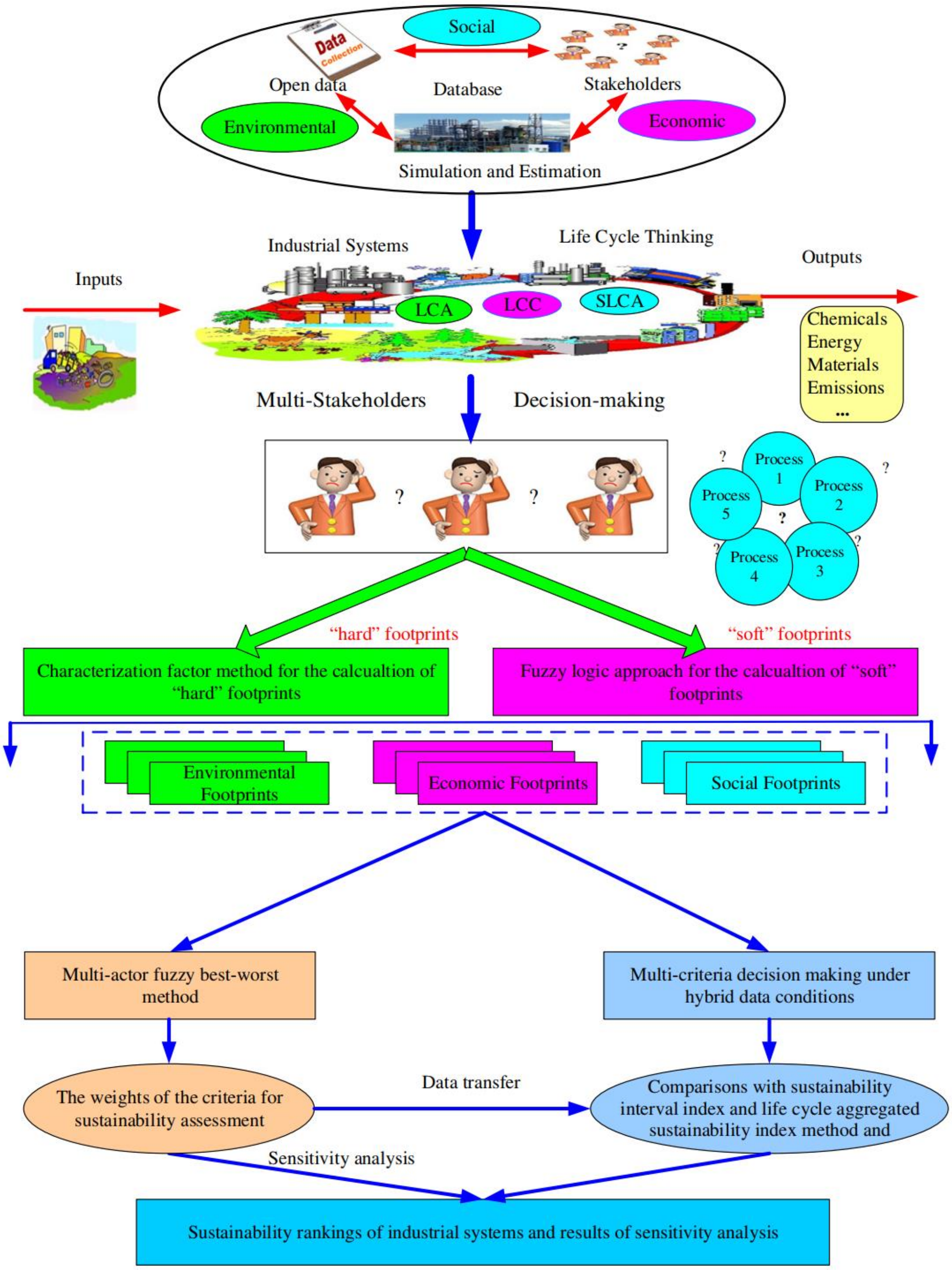

Figure 1 The framework for multiactor life cycle sustainability prioritization of

industrial systems under hybrid data conditions [Color figure can be viewed at wileyonlinelibrary.com]

2.1 Preliminary

The preliminary of fuzzy numbers and interval numbers were presented in the Supporting Information based on the works of Conner et al.,[7] Cheng and Lin,[17] Pedrycz and Gomide,[18] Zimmermann,[19] Junior et al.,[20] Zhang et al.,[21] Bohlender and Kulisch,[22] Liu and Huang[23] and Dymova et al.[24]

2.2 Criteria system for sustainability assessment

There is no standard for selecting the indicators for sustainability assessment, and the indicators in three pillars including environmental, economic and social are usually considered for sustainability assessment, because sustainable development emphasizes economic prosperity, environmental cleanness and social responsibility.[23] Besides these, Ren et al.[10] held the view that the indicators in technological aspect (i.e., energy efficiency and exergy efficiency) usually have significant impacts on the indicators in the three main pillars of sustain- ability. Therefore, the indicators in environmental, economic, social, and technological aspects are considered for sustainability assessment based on literature reviews and focus group meetings, and they are atom economy, life cycle cost, capital cost, operation and maintenance cost, and social cost of carbon management in economic aspect[25,26]; global warming potential and acidification potential in environmental aspect[10]; energy efficiency, exergy efficiency), technology maturity and technology innovation in technological aspect[10]; social acceptability, added jobs and influences on the local culture (S_3) in social aspect.[10] See the Supporting Information for more details of these indicators. Note that the users should choose the most suitable indicators according to the concerns of the stakeholders, and they can delete or add some indicators for sustainability assessment of industrial systems according to the real conditions.[10,27] The data of the alternative chemical processes with respect to the hard criteria (i.e., atom economy, global warming potential, acidification potential, energy efficiency and exergy efficiency, etc.) can be obtained directly through calculations, simulations, literature reviews, and field survey. It is worth pointing out that the data can be either crisp numbers or interval numbers. However, the data with respect to some soft criteria (i.e., technology maturity, technology innovation and social acceptability) cannot be determined directly. The fuzzy scoring approach is employed to determine the relative performances of these alternative chemical processes with respect to the soft criteria suppose that there are a total of M alternatives to be assessed with respect to a soft criterion, and K experts are invited to participate in the evaluation process, each of the experts will be asked to use the linguistic terms including extremely poor (EP), very poor (VP), poor (P), fair (F), good (G), very good (VG), and extremely (EG) to rate these alternative chemical processes, and these linguistic terms correspond to (0,0,1), (1,1,3), (1,3,5), (3,5,7), (5,7,9), (7,9,10), and (9,10,10), respectively.[28] Assume that the score of the *i*-th alternative with respect to a criterion determined by the *k*-th expert is $\tilde{x}_{i,k}^{L,j} = (x_{i,k}^{L,j}, x_{i,k}^{M,j}, x_{i,k}^{U,j})$, then, the score of the *i*-th alternative with respect to a criterion can be determined by Equation (1).

$$\tilde{x}_i^j = \frac{\sum_{k=1}^{K} \tilde{x}_{i,k}^j}{K} = \left(\frac{\sum_{k=1}^{K} x_{i,k}^{L,j}}{K} \frac{\sum_{k=1}^{K} x_{i,k}^{M,j}}{K} \frac{\sum_{k=1}^{K} x_{i,k}^{U,j}}{K} \right) \tag{1}$$

where $\tilde{x}_i^j$ represents the performance of the i-th alternative with respect to the *j*-th criterion.

2.3 Fuzzy logarithmic least squares method based multiactor fuzzy best-worst method

The fuzzy logarithmic least squares method based multiactor best-worst method was developed based on the work of Wang et al.[29] and Rezaei.[30] There are five steps in the developed fuzzy best-worst method for determining the weights of the evaluation criteria:

Step 1: Determine the most important criterion (the best criterion) which plays the most important role in the evaluation process and the least important criterion (the worst criterion) which plans the least important role in the evaluation process.[30]

Step 2: Determine the best-to-others (BO) vector by using the linguistic expressions to comparing the most important criterion with each of all the evaluation criteria and the others-to-worst (OW) vector by comparing each of all the evaluation criteria with the worst criterion.[30,31].

Assuming that there are a total of N evaluation criteria, and they are C_1, C_2, …, C_N ($j = 1, 2, \ldots, N$), denotes the most important criterion by C_B, denotes the least important criterion by C_W, and denotes the k-th group of decision-makers by k, then, the BO vector and the OW vector determined by the k-th group of decision-makers can be firstly expressed by using linguistic terms, and these linguistic terms can be transformed into the corresponding fuzzy numbers (as presented in Equations (2) and (3), respectively) according to Figure 2. Five linguistic judgments including equally preferred (E), weakly preferred (W), fairly preferred (F), very preferred (V), and significantly preferred are employed to determine the *BO* and the *OW* vectors.[32]

$$BO_k = \left[\tilde{a}^k_{B1}\ \tilde{a}^k_{B2} \cdots \tilde{a}^k_{BN}\right] \quad (2)$$

where BO_k represents the best-to-other vector determined by the *k*-th group of decision-makers, and $\tilde{a}^k_{Bj} = (a^{k,L}_{Bj}, a^{k,M}_{Bj}, a^{k,U}_{Bj})\ (j = 1, 2, ..., N)$ represents the relative importance/priority of the most important criterion comparing with the *j*-th criterion.

$$OW_k = \left[\tilde{a}^k_{1W}\ \tilde{a}^k_{2W} \cdots \tilde{a}^k_{NW}\right] \quad (3)$$

where OW_k represents the other-to-worst vector determined by the k-th group of decision-makers, and $\tilde{a}^k_{jW} = (a^{k,L}_{jW}, a^{k,M}_{jW}, a^{k,U}_{jW})\ (j = 1, 2, ..., N)$ represents the relative importance/priority of the j-th criterion comparing with the least important criterion.

Step 3: Determine the fuzzy weights of the N criteria.[31]

The weights of the N criteria should satisfy the following two conditions (as presented in Equations 4 and 5), and it means that the optimum fuzzy weights should be a compromise solution based on the preferences of all the stakeholders.

$$\frac{\tilde{\omega}_B}{\tilde{\omega}_j} \approx \tilde{a}_{Bj}^{k} \, (j = 1, 2, \ldots, N) \tag{4}$$

$$\frac{\tilde{\omega}_j}{\tilde{\omega}_W} \approx \tilde{a}_{jW}^{k} \, (j = 1, 2, \ldots, N) \tag{5}$$

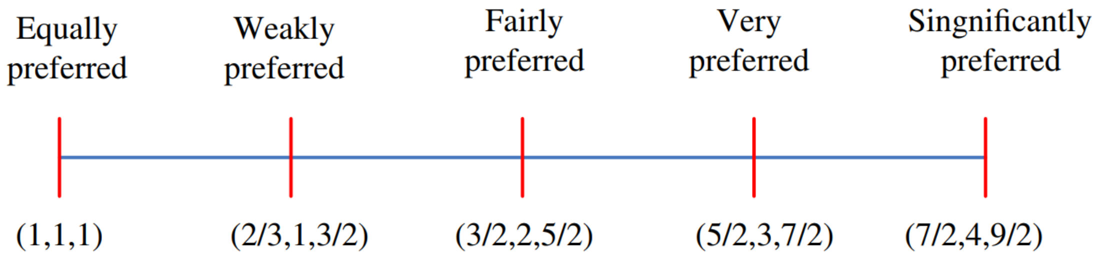

Figure 2 The linguistic expressions and the corresponding fuzzy numbers32 [Color figure can be viewed at wileyonlinelibrary.com]

where $\tilde{\omega}_B = (\tilde{\omega}_B^L \; \tilde{\omega}_B^M \; \tilde{\omega}_B^U)$ represents the weight of the most important criterion, $\tilde{\omega}_j = (\tilde{\omega}_j^L \; \tilde{\omega}_j^M \; \tilde{\omega}_j^U)$ represents the weight of the j-th criterion, and $\tilde{\omega}_W = (\tilde{\omega}_W^L \; \tilde{\omega}_W^M \; \tilde{\omega}_W^U)$ represents the weight of the most important criterion.

Equations (4) and (5) can be rewritten as,

$$\frac{(\omega_B^L \; \omega_B^M \; \omega_B^U)}{(\omega_j^L \omega_j^M \omega_j^U)} \approx \left(a_{Bj}^{k,L} a_{Bj}^{k,M} a_{Bj}^{k,U}\right) \qquad (j = 1, 2, \ldots, N) \tag{6}$$

$$\frac{(\omega_j^L \omega_j^M \omega_j^U)}{(\omega_W^L \omega_W^M \omega_W^U)} \approx \left(a_{jW}^{k,L} a_{jW}^{k,M} a_{jW}^{k,U}\right) \qquad (j = 1, 2, \ldots, N) \tag{7}$$

In order to determine the optimum fuzzy weights of these N criteria, the following fuzzy logarithmic least square model was developed based on the work of Wang et al.[29]

$$MinJ=\sum_{j=1}^{N}\sum_{k=1}^{K}\left[\left(\ln\omega_B^L-\ln\omega_j^U-\ln a_{Bj}^{k,L}\right)^2+\left(\ln\omega_B^M-\ln\omega_j^M-\ln a_{Bj}^{k,M}\right)^2+\left(\ln\omega_B^U-\ln\omega_j^L-\ln a_{Bj}^{k,U}\right)^2\right]$$
$$+\sum_{j=1}^{N}\sum_{k=1}^{K}\left[\left(\ln\omega_j^L-\ln\omega_W^U-\ln a_{jW}^{k,L}\right)^2+\left(\ln\omega_j^M-\ln\omega_W^M-\ln a_{jW}^{k,M}\right)^2+\left(\ln\omega_j^U-\ln\omega_W^L-\ln a_{jW}^{k,U}\right)^2\right] \quad (8)$$

Meanwhile, the fuzzy weights should also satisfy the normalization constraints,[29,33] as presented in (9)–(11).

$$\omega_j^L+\sum_{i=1,i\neq j}^{N}\omega_i^U\geq 1, i=1,2,\ldots,N \quad (9)$$

$$\sum_{1}^{N}\omega_j^M=1 \quad (10)$$

$$\omega_j^U+\sum_{i=1,i\neq j}^{N}\omega_i^L\leq 1, i=1,2,\ldots,N \quad (11)$$

Moreover, the auxiliary constraint introduced by Jiménez et al.[34] should also be considered to normalize the interval weights.

$$\sum_{j}^{N}\left(\omega_j^L+\omega_j^U\right)=2 \quad (12)$$

The optimum fuzzy weights of these N criteria can be determined after solving the programming by integrating (8) to (12). It is worth pointing out that the criteria system contains two levels in this study, the first level is the four categories of sustainability including economic, environmental, technological and social aspects, and each category may also consists of several criteria, thus, the global weight of each criterion could be calculated after obtaining the weight of each category and the local weights of each criterion (see the Supporting Information for more details).

2.4 Multicriteria decision analysis under hybrid information

Step 1: determine the multiple-type-number based decision-making matrix. Assuming that there are a total of M alternatives A_1, A_2, …, A_M to be evaluated based on N evaluation criteria C_1, C_2, …, C_N, the data of the M alternatives with respect to these N evaluation criteria include crisp numbers, interval numbers and triangular numbers. Crisp numbers are used when the performances of the alternatives with respect to the evaluation criteria are deterministic, interval numbers are used when there are various uncertainties, and triangular fuzzy numbers are used to describe the data of the alternatives with respect to the "soft" criteria which cannot be quantified with dimensions directly. The decision-making matrix can be represented by Equation (13):

$$\begin{array}{cccccccccc} & C_1 & \cdots & C_S & C_{S+1} & \cdots & C_{S+L} & C_{S+L+1} & \cdots & C_{S+L+T} \\ & \tilde{\omega}_1 & \cdots & \tilde{\omega}_S & \tilde{\omega}_{S+1} & \cdots & \tilde{\omega}_{S+L} & \tilde{\omega}_{S+L+1} & \cdots & \tilde{\omega}_{S+L+T} \\ A_1 & x_{11} & \cdots & x_{1S} & x^{\pm}_{1(S+1)} & \cdots & x^{\pm}_{1(S+L)} & \tilde{x}_{1(S+L+1)} & \cdots & \tilde{x}_{1(S+L+T)} \\ A_2 & x_{21} & \cdots & x_{2S} & x^{\pm}_{2(S+1)} & \cdots & x^{\pm}_{2(S+L)} & \tilde{x}_{2(S+L+1)} & \cdots & \tilde{x}_{2(S+L+T)} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ A_M & x_{M1} & \cdots & x_{MS} & x^{\pm}_{M(S+1)} & \cdots & x^{\pm}_{M(S+L)} & \tilde{x}_{M(S+L+1)} & \cdots & \tilde{x}_{M(S+L+T)} \end{array} \qquad (13)$$

where $\tilde{\omega}_j\,(j=1,2,\ldots,N)$ represents the fuzzy weight of the j-th evaluation criterion, x_{ij} ($i = 1, 2, \ldots, M$; $j = 1, 2, \ldots, S$) which is a crisp number represents the data of the i-th alternative with respect to the j-th criterion, $x^{\pm}_{ij}\,(i=1,2,\ldots,M;\ j=S+1, S+2,\ldots,S+L)$ which is an interval number represents the data of the i-th alternative with respect to the j-th criterion, and $x_{ij}^{\pm}(i=1,2,...,M; j=S+L+1, S+L+2,..., S+L+T)$ which is a triangular fuzzy number represents the data of the i-th alternative with respect to the j-th criterion.

It is worth pointing out that six linguistic terms including extremely poor (EP), very poor (VP), poor (P), fair (F), good (G), very good (VG), and extremely good (EG) are used to describe the relative performances of the alternatives with respect to the soft criteria, and they correspond to the triangular fuzzy numbers (0,0,1), (1,1,3), (1,3,5), (3,5,7), (5,7,9), (7,9,10), and (9,10,10), respectively.35 There are a total of K decision-makers, denotes the data of the i-th alternative with respect to the j-th criterion which is a soft criterion by $\tilde{x}_{ij}^{k}(i=1,2,...,M; j=S+L+1, S+L+2,..., S+L+T; k=1,2,...,K)$, then, the average fuzzy score of the i-th alternative with respect to the j-th criterion can be determined by Equation (14).

$$\tilde{x}_{ij} = \frac{\sum_{k=1}^{K} \tilde{x}_{ij}^{k}}{K} \; (i=1,2,...,M; j=S+L+1, S+L+2,..., S+L+T) \qquad (14)$$

Step 2: determine the interval number based decision-making matrix.

The crisp numbers and triangular fuzzy numbers presented in Equation (13) can be transformed into interval numbers by Equations (15) and (16), respectively.

As for the crisp numbers x_{ij} (i = 1, 2, …, M; j = 1, 2, …, S), it can be transformed into interval numbers according to the preliminary presented in the Supporting Information.

$$x_{ij} = x_{ij}^{\pm} = \left[x_{ij}\, x_{ij}\right] \; (i=1,2,...,M; j=1,2,...,S) \qquad (15)$$

As for the triangular fuzzy numbers $\tilde{x}_{ij}(i=1,2,...,M; j=S+L+1, S+L+2,..., S+L+T)$, it can be transformed into interval numbers by the α-cut method (see Equation 16).[36] α can take the value from the interval [0 1], and the larger the value, the more confident the users to their judgments, and 0.50 was usually used to imply that the confidence level is "moderate."

$$x_{ij}^{\pm} = \left[x_{ij}^{L} + \alpha\left(x_{ij}^{M} - x_{ij}^{L}\right)\ x_{ij}^{U} - \alpha\left(x_{ij}^{U} - x_{ij}^{M}\right)\right] \quad (i = 1,2,\ldots,M; j = S+L+1, S+L+2,\ldots,S+L+T) \tag{16}$$

where $\tilde{x}_{ij} = (x_{ij}^{L}\ x_{ij}^{M}\ x_{ij}^{U})(i = 1, 2, \ldots, M; j = S+L+1, S+L+2, \ldots, S+L+T)$ represents the data of the i-th alternative with respect to the j-th criterion.

In a similar way, the fuzzy weights of the evaluation criteria can also be transformed into interval numbers by using the α-cut method according to Equation (17).

$$\omega_{ij}^{\pm} = \left[\omega_{ij}^{-}\ \omega_{ij}^{+}\right] = \left[\omega_{ij}^{L} + \alpha\left(\omega_{ij}^{M} - \omega_{ij}^{L}\right)\ \omega_{ij}^{U} - \alpha\left(\omega_{ij}^{U} - \omega_{ij}^{M}\right)\right] \ (j = 1,2,\ldots,N) \tag{17}$$

where $\tilde{\omega}_j = (\omega_j^L \omega_j^M \omega_j^U)\ (j = 1, 2, \ldots, N)$ represents the fuzzy weight of the *j*-th criterion.

The decision-making matrix with hybrid information presented in Equation (13) can be transformed into decision-making matrix with interval number, as presented in Equation (18).

$$\begin{array}{ccccccccc}
 & C_1 & \cdots & C_S & C_{S+1} & \cdots & C_{S+L} & C_{S+L+1} & \cdots & C_{S+L+T} \\
 & \omega_1^{\pm} & \cdots & \omega_S^{\pm} & \omega_{S+1}^{\pm} & \cdots & \omega_{S+L}^{\pm} & \omega_{S+L+1}^{\pm} & \cdots & \omega_{S+L+T}^{\pm} \\
A_1 & x_{11}^{\pm} & \cdots & x_{1S}^{\pm} & x_{1(S+1)}^{\pm} & \cdots & x_{1(S+L)}^{\pm} & x_{1(S+L+1)}^{\pm} & \cdots & x_{1(S+L+T)}^{\pm} \\
A_2 & x_{21}^{\pm} & \cdots & x_{2S}^{\pm} & x_{2(S+1)}^{\pm} & \cdots & x_{2(S+L)}^{\pm} & x_{2(S+L+1)}^{\pm} & \cdots & x_{2(S+L+T)}^{\pm} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
A_M & x_{M1}^{\pm} & \cdots & x_{MS}^{\pm} & x_{M(S+1)}^{\pm} & \cdots & x_{M(S+L)}^{\pm} & x_{M(S+L+1)}^{\pm} & \cdots & x_{M(S+L+T)}^{\pm}
\end{array} \tag{18}$$

where $\omega_j^{\pm} = [\omega_j^{-}\ \omega_j^{+}]$ ($j = 1, 2, \ldots, N$) which is an interval number represents the interval weights of the j-th criterion, and $x_{ij}^{\pm} = [x_{ij}^{-}\ x_{ij}^{+}]$ ($i = 1, 2, \ldots, M; j = 1, 2, \ldots, N$) which is an interval number represents the interval data of the i-th alternative with respect to the j-th criterion.

Step 3: Normalize the data in the decision-making matrix.

The interval decision-making matrix presented in Equation (18) should be normalized because the criteria consist of both the benefit- type criteria and the cost-type criteria. Benefit-type criterion (i.e., added jobs, social acceptability and technology maturity, etc.) is the criterion which can benefit the priority of the alternatives with the increase of the data with respect to this criterion. On the contrary, cost-type criterion (i.e., global warming potential, acidification potential and life cycle cost, etc.) will have negative impacts on the priority of the alternatives with the increase of the data with respect to this criterion. The data of the alternatives with respect to the benefit-type criteria and the cost- type criteria can be normalized by Equations (19) and (20), respectively.

As for the benefit-type criteria,

$$y_{ij}^{\pm} = \left[y_{ij}^{-} y_{ij}^{+}\right] = \left[\frac{x_{ij}^{-}}{\max_i\left\{x_{ij}^{+}\right\}} \frac{x_{ij}^{+}}{\max_i\left\{x_{ij}^{+}\right\}}\right] \tag{19}$$

As for the cost-type criteria,

$$y_{ij}^{\pm} = \left[y_{ij}^{-} y_{ij}^{+}\right] = \left[\frac{1/x_{ij}^{+}}{1/\min_i\left\{x_{ij}^{-}\right\}} \frac{1/x_{ij}^{-}}{1/\min_i\left\{x_{ij}^{-}\right\}}\right] \tag{20}$$

where, $y_{ij}^{\pm}$ represents the normalized data of the i-th alternative with respect to the j-

th criterion, and y_{ij}^{-} and y_{ij}^{+} represent the lower and upper bounds of the interval number $y_{ij}^{\pm}$, respectively.

Step 4: Determine the global priorities (*GP*s) of the alternatives.

The method for determining the *GP* of each alternative was developed in this study based on the work of Conner et al.[7] and Wang et al.[29] The lower bound of the *i*-th alternative can be determined by solving the following linear programming model.[29]

$$GP_i^L = \underset{s.t.}{\text{Min}} \sum_{j-1}^{N} y_{ij}^{-} \omega_j \; i = 1,2,\ldots,M$$
$$\omega_j^{-} \leq \omega_j \leq \omega_j^{+} \qquad (21)$$
$$\sum_{j=1}^{N} \omega_j = 1$$

where GP_i^L represents the lower bound of the GP of the *i*-th alternative.

The upper bound of the *i*-th alternative can be determined by solving the following linear programming model.[29]

$$GP_i^U = \underset{s.t.}{\text{Max}} \sum_{j-1}^{N} y_{ij}^{+} \omega_j \; i = 1,2,\ldots,M$$
$$\omega_j^{-} \leq \omega_j \leq \omega_j^{+} \qquad (22)$$
$$\sum_{j=1}^{N} \omega_j = 1$$

where GP_i^U represents the upper bound of the GP of the *i*-th alternative.

After determining GP_i^L and GP_i^U after solving programming (21) and (22), the *GP* of each alternative can be determined, as presented in Equation (23),

$$GP_i^{\pm} = \left[GP_i^L \; GP_i^U\right] \qquad (23)$$

where $GP_i^{\pm}$ is an interval number represents the *GP* of the *i*-th alternative.

Step 5: Determine the priority sequence of the alternatives.[37]

The degree of possibility of the *GP* of the *a*-th alternative $GP_a^{\pm} = [GP_a^L \; GP_a^U]$ to be greater than that of the *b*-th alternative $GP_b^{\pm} = [GP_b^L \; GP_b^U]$ can be determined by Equation (24).

$$p_{ab} = \frac{1}{2}\left[1 + \frac{\left(GP_a^U - GP_b^U\right) + \left(GP_a^L - GP_b^L\right)}{\left|GP_a^U - GP_b^U\right| + \left|GP_a^L - GP_b^L\right| + L}\right] \qquad (24)$$

where p_{ab} represents the degree of possibility of the *GP* of the *a*-th alternative to be greater than that of the *b*-th alternative, and *L* represents the distance between $GP_a^{\pm} = [GP_a^L \; GP_a^U]$ and $GP_b^{\pm} = [GP_b^L \; GP_b^U]$.

Then, the possibility coefficient matrix can be determined by comparing the *GP*s of each pair of alternatives, as presented in Equation (25).

$$P = \begin{array}{c|cccc} & A_1 & A_2 & \cdots & A_m \\ A_1 & p_{11} & p_{12} & \cdots & p_{1m} \\ A_2 & p_{21} & p_{22} & \cdots & p_{2m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & p_{m1} & p_{m1} & \cdots & p_{mm} \end{array} \qquad (25)$$

The alternatives can be ranked according to the following rules:

1. A_a is superior to A_b if and only if $p_{ab} > p_{ba}$;

2. A_a is equivalent to A_b if and only if $p_{ab} = p_{ba}$; and

3. A_a is inferior to A_b if and only if $p_{ab} < p_{ba}$.

3 CASE STUDY

In order to illustrate the developed method for prioritizing the industrial systems in life cycle sustainability perspective, five pathways for hydrogen production have been studied in this work, and they are coal gasification (CG), steam methane reforming (SMR), biomass gasification (BG), photovoltaic-based electrolysis (PVEL), and wind-based electrolysis (WEL). Ten criteria in four categories including capital cost (EC_1), production cost (EC_2) and atom economy (EC_3) in economic (EC) category, GWP (EN_1) and AP (EN_2) in environmental (EN) category, energy efficiency (T_1), exergy efficiency (T_2), technology maturity (T_3), and technology innovation (T_4) in technological (T) category, and social acceptability (S_1) in social (S) aspect are employed to measure the life cycle sustainability of the five chemical processes for hydrogen production. The data of the five hydrogen production pathways with respect to the seven hard criteria including capital cost, production cost, atom economy, GWP, AP, energy efficiency, and exergy efficiency are obtained from literatures.25,26,38,39 As for the data of these five chemical processes for hydrogen production with respect to the three soft criteria including technology maturity, technology innovation and social acceptability, they are scored by using the fuzzy approach, and the six linguistic terms including extremely poor (EP), very poor (VP), poor (P), fair (F), good (G), very good (VG), and extremely good (EG) corresponding to (0,0,1), (1,1,3), (1,3,5), (3,5,7), (5,7,9), (7,9,10), and (9,10,10) are used to rate the five hydrogen production pathways with respect to technology maturity, technology innovation and social acceptability. The life cycle sustainability performances of the five hydrogen production pathways were presented in Table 1.

Three groups of decision-makers including scholar and researcher group (DM#1), manager and administrator group (DM#2), and engineer group (DM#3). There are two professors whose research focuses on cleaner hydrogen production, one postdoctoral researcher and two PhD researchers in chemical engineering from two Chinese universities in the scholar and researcher group. There are three senior managers who directed the state-owned chemical factories for more than 10 years and three administrators from the local government of China in the manager and administrator group. There are six senior engineers who are skilled in hydrogen production processes from the state-owned chemical factories in the engineering group. One of the authors in this study worked as the coordinator to coordinate the focus group meeting of each decision-making group, the coordinator used the Delphi method to achieve that the best (the most important) criterion and the worst (the least important) criterion determined by the three decision making groups are the same. Taking the calculation weights of the four categories of sustainability, the technological category and the social category were recognized as the most sustainable and the least sustainable, respectively. The BO and the OW vectors determined by these groups of decision-makers were presented in Table 2.

According to Equations (8)–(12), the programming for determining the fuzzy weights of the four categories of sustainability can be determined.

$$
\begin{aligned}
&Min\,J=\sum_{j=1}^{4}\sum_{k=1}^{3}\left[\left(\ln\omega_3^L-\ln\omega_j^U-\ln a_{3j}^{k,L}\right)^2+\left(\ln\omega_3^M-\ln\omega_j^M-\ln a_{3j}^{k,M}\right)^2+\left(\ln\omega_3^U-\ln\omega_j^L-\ln a_{3j}^{k,U}\right)^2\right]\\
&\quad+\sum_{j=1}^{4}\sum_{k=1}^{3}\left[\left(\ln\omega_j^L-\ln\omega_4^U-\ln a_{j4}^{k,L}\right)^2+\left(\ln\omega_j^M-\ln\omega_4^M-\ln a_{j4}^{k,M}\right)^2+\left(\ln\omega_j^U-\ln\omega_4^L-\ln a_{j4}^{k,U}\right)^2\right]\\
&\omega_1^L+\omega_2^U+\omega_3^U+\omega_4^U\ge 1\\
&\omega_2^L+\omega_1^U+\omega_3^U+\omega_4^U\ge 1\\
&\omega_3^L+\omega_1^U+\omega_2^U+\omega_4^U\ge 1\\
&\omega_4^L+\omega_1^U+\omega_2^U+\omega_3^U\ge 1\\
&\omega_1^M+\omega_2^M+\omega_3^M+\omega_4^M=1\\
&\omega_1^U+\omega_2^L+\omega_3^L+\omega_4^L\le 1\\
&\omega_2^U+\omega_1^L+\omega_3^L+\omega_4^L\le 1\\
&\omega_3^U+\omega_1^L+\omega_2^L+\omega_4^L\le 1\\
&\omega_4^U+\omega_1^L+\omega_2^L+\omega_3^L\le 1\\
&\sum_{j=1}^{4}\left(\omega_j^L+\omega_j^U\right)=2
\end{aligned}
\tag{26}
$$

where $j=1,2,3,4$ represents the economic, environmental, technological and social aspect, respectively. $\omega_j=(\omega_j^L\ \omega_j^M\ \omega_j^U)$ $j=1,2,3,4$ represents the weights of economic, environmental, technological and social aspect, respectively. $a_{3j}^k=(a_{3j}^{k,L}\ a_{3j}^{k,M}\ a_{3j}^{k,U})$ represents the relative importance of the most important aspect (technological aspect) comparing with the j-th aspect. $a_{j4}^k=(a_{j4}^{k,L}\ a_{j4}^{k,M}\ a_{j4}^{k,U})$ represents the relative importance of the j-th aspect comparing with the least important aspect (social aspect). The fuzzy weights of the four categories can be then determined, and the results were also presented in Table 2. In a similar way, the local weights of capital cost (EC_1), production cost (EC_2) and atom economy (EC_3) in economic aspect, the local weights of GWP (EN_1) and AP (EN_2) in environmental aspect, energy efficiency (EN_1), exergy efficiency (EN_2), technology maturity (EN_3) and technology innovation (EN_4) in technological aspect, and social acceptability in social aspect can also be determined. The results were presented in the Supporting Information. Note that there is only one indicator in social pillar, thus, the global weight of social acceptability is (0.1109,0.1139,0.1182). After these, the global weights of the 10 indicators can be deter- mined, and the results were presented in the Supporting Information. After transforming the linguistic terms into triangular fuzzy numbers, the decision-making matrix by using hybrid information (including crisp numbers, interval numbers and fuzzy numbers) can be deter- mined (see the Supporting Information). The α-cut method was used to transform the triangular fuzzy numbers into interval numbers and α was taken the value of 0.50. The decision-making matrix based on interval numbers was presented in the Supporting Information. The normalized interval decision-making matrix can be determined by Equations (19) and (20). The results were presented in the Supporting Information. The *GP* of each of the five industrial systems can be determined by programming (21) and programming (22), and the results were presented in Table 3.

After this, the possibility coefficient matrix can be determined by Equations (24) and (25), and the results were presented in Equation (27).

$$\begin{array}{cccccc} & CG & SMR & BG & PVEL & WEL \\ CG & / & 0.3896 & 0.1315 & 0.5444 & 0.1312 \\ SMR & 0.6104 & / & 0.1308 & 0.8641 & 0.1308 \\ BG & 0.8685 & 0.8692 & / & 0.8691 & 0.1309 \\ PVEL & 0.4556 & 0.1359 & 0.1309 & / & 0.1309 \\ WEL & 0.8688 & 0.8692 & 0.8691 & 0.8691 & / \end{array} \quad (27)$$

Table 1 The life cycle sustainability performances of the five hydrogen production pathways

		CG	*SMR*	*BG*	*PVEL*	*WEL*	Reference
Capital cost	US$ day kg^{-1}	1,637.19	284.77	104.82	10,448.56	3,170.86	38
Production cost	US$ day kg^{-1}	0.4–1.8	2.3–3.2	1.4–2.8	2.8–7.5	2.3–6.8	25
Atom economy	/	7	4	3	1	1	25
GWP	gCO_2 eq kg^{-1}	17,000	12,000	2,992	2,000	1,200	26, 39
AP	gSO_2 eq kg^{-1}	30.69	14.516	29.03	8.07	2.58	26, 39
Energy efficiency	/	0.35	0.375	0.65	0.05	0.31	26
Exergy efficiency	/	0.315	0.315	0.60	0.04	0.30	26
Technology maturity	/	EG, VG,G	VG, VG, EG	F, P, P	VP,VP,VP	P,P,VP	Fuzzy approach
Technology innovation	/	VP,P,F	F,G,G	EG,EG,EG	VG,VG,G	G,VG,VG	Fuzzy approach
Social acceptability	/	VP,P,VP	F,F,P	VG,G,G	EG,EG,VG	EG,VG,EG	Fuzzy approach

Table 2 The BO and the OW vectors determined by these three groups of decision-makers

	The most important: Technological		The least important: Social	
	Economic	Environmental	Technological	Social
BO by DM#1	F	W	E	V
OW by DM#1	F	F	V	E
BO by DM#2	W	E	E	S
OW by DM#2	F	V	S	E
BO by DM#3	F	W	E	V
OW by DM#3	F	V	F	E
Fuzzy weights	(0.1731,0.2221,0.2787)	(0.2603,0.3203,0.3819)	(0.3207,0.3437,0.3561)	(0.1109,0.1139,0.1182)

Table 3 The global priority of each industrial system

	CG	*SMR*	*BG*	*PVEL*	*WEL*
The global priority	[0.2788, 0.4533]	[0.3363, 0.4225]	[0.5367, 0.6491]	[0.3234, 0.3965]	[0.5646, 0.6820]
Ranking	4	3	2	5	1

Table 4 Life cycle aggregated sustainability index and the rankings of these five industrial systems

	CG	*SMR*	*BG*	*PVEL*	*WEL*
Sustainability index	[0.0756 0.1302]	[0.0921 0.1223]	[0.1675 0.2169]	[0.1213 0.1546]	[0.2179 0.2776]
Ranking by Ren[40]	5	4	2	3	1
Sustainability interval index (SII)	[0.6802 0.6802]	[0.6611 0.7131]	[0.5941 0.5941]	[0.7920 0.7920]	[0.8613 0.8614]
Ranking by Conner et al.[7]	4	3	5	2	1
Ranking by this study	4	3	2	5	1

It is apparent that *WEL* was recognized as the most sustainable, following by *BG*, *SMR*, *CG*, and *PVEL* in the descending order. The ranking of *WEL* as the most sustainable hydrogen production pathway is reasonable, because it has the least global warming potential, the least acidification potential, the best technology innovation and the best social acceptability.

4 VALIDATION AND SENSITIVITY ANALYSIS

The SII conceptual framework with life-cycle considerations presented in this study was developed based on the work developed by Conner et al.,[7] and the developed SII in this study can effectively incorporate the preferences/opinions of different stakeholders and address the decision-making matrix with multiple types of data (especially crisp numbers, interval numbers and fuzzy numbers). In order to validate the developed SII conceptual framework for multiactor life cycle sustainability ranking of alternative industrial systems, the life cycle aggregated sustainability index method developed by Ren[40] and the SII method proposed by Conner et al.[7] were employed to validate the results determined in this study (see the Supporting Information for more details).

Life cycle aggregated sustainability index of each of the five industrial systems can be determined, and the results were presented in Table 4. It is apparent that *WEL* and *BG* were recognized as the first two most sustainable pathways for hydrogen production. The SII of each of the five industrial systems can also be calculated as shown in the Supporting Information, and the results were also presented in Table 4. The result shows that WEL and PVEL were recognized as the first two most sustainable pathways for hydrogen production.

Therefore, to some extent, it could be concluded that *WEL* is the most sustainable industrial system among these five alternatives. However, the rankings of the other three industrial systems (including *CG*, *SMR*, and *PVEL*) determined by these two methods are different.

In order to investigate the influences of the weights of these indicators for sustainability assessment on the rankings of these five industrial systems, a sensitivity analysis was carried out by studying the following 11 scenarios based on the normalized interval decision- making matrix:

Scenario 1: an equal weight (0.1000) was assigned to each indicator as the weight;

Scenario 2–11 (*i* = 2, 3, …, 11): a dominant weight [0.1000 0.5500] was assigned to the (*i*–1)-th indicator, and [0.0500 0.1000] was assigned to the other nine indicators.

The results of sensitivity analysis were presented in the Supporting Information, and it is apparent that the rankings of these five industrial systems may change with the change of the weights of these 10 indicators. To some extent, it reveals that it is necessary to incorporate the preferences of different stakeholders to determine the weights of the indicators for sustainability assessment accurately.

5 CONCLUSIONS

This study aims to develop an SII for multiactor life cycle sustainability ranking of industrial systems under hybrid information based on the work of Conner et al.,[7] and it provides an effective approach for sustain- ability prioritization of alternative industrial systems after life cycle sustainability assessment which includes LCA, LCC, and SLCA. The multiactor fuzzy best-worst method was developed for determining the weights of the indicators for sustainability assessment, it allows numerous groups of stakeholders to use fuzzy numbers to express their opinions and preferences when participating in the decision-making process. This method can not only incorporate the preferences of different stakeholders in the complex decision-making process, but also success- fully solve the hesitations and ambiguity existing in human judgments. A multicriteria decision analysis method under hybrid information was developed for ranking alternative industrial systems after LCSA, it can address the decision-making matrix composed by hybrid information with multiple types of data (i.e., crisp numbers, interval numbers and tri- angular fuzzy numbers). Comparing with the traditional multicriteria decision analysis method, the developed method in this study can adapt the results of LCSA better, because there are usually various uncertainties and difficulties in quantifying the social life cycle indicators when using LCSA to investigate the environmental impacts, economic performances and social influences of different industrial systems.

Five pathways for hydrogen production including *CG*, *SMR*, *BG*, *PVEL*, and *WEL* were studied, and the results revealed that the sustainability sequence from the most sustainable to the least is *WEL*, *BG*, *SMR*, *CG*, and *PVEL*. The results determined by the SII conceptual framework proposed in this study were compared with that deter- mined by the life cycle aggregated sustainability index method developed by Ren[40] and the SII method proposed by Conner et al.[13] Sensitivity analysis was also carried to investigate the influences of the weights of the indicators on the sustainability rankings of different industrial systems, and the results of sensitivity analysis revealed that the weights of the indicators for sustainability assessment have signif- icant impacts on the final sustainability rankings and the accurate determination of the weights is prerequisite.

All in all, the developed SII for life cycle sustainability ranking of industrial systems has the following two most important advantages:

1. It can incorporate the opinions and preferences of numerous groups of stakeholders when determining the weights of the indicators for sustainability assessment, and the ambiguity and hesitations existing in human judgments can also be addressed by using fuzzy approach;

2. The users can use hybrid information (multiple types of data, i.e., crisp numbers, interval numbers and triangular fuzzy numbers) to describe the life cycle environmental, economic and social performances of different industrial systems, and the developed multicriteria decision analysis method can be used for prioritizing the alternative industrial systems under hybrid information.

Besides these advantages, there is also a weak point-the developed multicriteria decision analysis method under hybrid information transforms the triangular fuzzy numbers into interval numbers, and this may cause the loss of some useful information. In addition, the game relations among different groups of stakeholders were not incorporated in the decision-making though all their preferences have been considered.[41,42] The future work is to develop a multicriteria decision analysis method, which can use all types of data directly without any loss of information and incorporate the game relation- ships among the stakeholders.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.