AIChE

Sustainability Decision Support Framework for Industrial System Prioritization

Jingzheng Ren
Dept. of Chemical Engineering, School of Chemistry and Chemical Engineering, Chongqing University, Chongqing 400044, China

Dept. of Technology and Innovation, University of Southern Denmark, Niels Bohrs Allé 1, 5230 Odense M, Denmark

Di Xu, Huan Cao, Shun'an Wei, and Lichun Dong
Dept. of Chemical Engineering, School of Chemistry and Chemical Engineering, Chongqing University, Chongqing 400044, China

Key Laboratory of Low-Grade Energy Utilization Technologies & Systems of the Ministry of Education, Chongqing University, Chongqing 400044, China

Michael Evan Goodsite
Dept. of Technology and Innovation, University of Southern Denmark, Niels Bohrs Allé 1, 5230 Odense M, Denmark

DOI 10.1002/aic.15039
Published online September 25, 2015 in Wiley Online Library (wileyonlinelibrary.com)

A multicriteria decision-making methodology for the sustainability prioritization of industrial systems is proposed. The methodology incorporates a fuzzy Analytic Hierarchy Process method that allows the users to assess the soft criteria using linguistic terms. A fuzzy Analytic Network Process method is used to calculate the weights of each criterion, which can tackle the interdependencies and interactions among the criteria. The Preference Ranking Organization Method for Enrichment Evaluation approach is used to prioritize the sustainability sequence of the alternative systems. Moreover, a sensitivity analysis method was developed to investigate the most critical and sensitive criteria. The developed methodology was illustrated by a case study to rank the sustainability of five alternative hydrogen production technologies. The advantages of the developed methodology over the previous approaches were demonstrated by comparing the results determined by the proposed framework with those determined using the pervious approaches. © 2015 American Institute of Chemical Engineers *AIChE J*, 62: 108–130, 2016

Keywords: sustainability assessment, multicriteria decision making, industrial systems, fuzzy analytic network process, PROMETHEE, fuzzy analytic hierarchy process

Introduction

Industrial systems, for example, chemical production systems, power generation systems, vehicle manufacturing systems, play a significant role in the national economy. However, industrial systems as double-edged swords can also cause various environmental and social problems like. water pollutions, haze-fog phenomena, health problems, and riots due to the risks of environmental contaminations,[1–3] the concept of sustainability should be incorporated in the industrial systems for achieving the sustainable development.[4] Taking hydrogen energy production systems as an example, hydrogen, a clean energy carrier without the emission of polluting gases during its oxidation process, has long been regarded as a promising way for alleviating the environmental and economic problems caused by the excessive use of fossil fuels.[5] However, although the processes to use hydrogen have little or zero negative impacts on the environment, the processes to produce hydrogen may have significant negative impacts on the environment. Moreover, different hydrogen production pathways have distinctive environmental impacts as well as different economic performance[6,7] and social concerns.[8,9] Recently, the sustainability assessment and prioritization of various hydrogen production pathways by considering all the three pillars (environmental impacts, economic performance, and social concerns) has received more and more attentions. Manzardo et al.[10] studied the economic, social, and environmental performances of various hydrogen production technologies in a life cycle perspective, and concluded that different pathways behave differently in term of sustainability. As the sustainability assessment of different industrial systems is a prerequisite for selecting the scenario that has the best integrated economic-environmental-social performance, an efficient methodology for prioritizing the different industrial

Correspondence concerning this article should be addressed to L. C. Dong at lcdong72@cqu.edu.cn.

© 2015 American Institute of Chemical Engineers

systems or technologies according to their sustainability is very helpful for the stakeholders/decision-makers to select the most sustainable pathway.

Othman et al.[11] pointed out that the criteria for the sustainability assessment can be categorized into two types: hard criteria and soft criteria. The hard criteria are usually objective factors that can be quantitatively evaluated using crisp numbers, while the soft criteria are usually subjective measures that can only be given a qualitative description according to the knowledge and experience of the stakeholders/decision-makers. Accordingly, previous methodologies that were developed for the sustainability assessment of industrial systems can also be divided into two types: quantitative assessment or qualitative evaluations. Afgan et al.[12] carried out a multicriteria evaluation of various hydrogen systems by incorporating multiple technological, environmental, and market indicators into a general sustainability index using different weight functions. Pilavachi et al.[13] integrated five criteria into a generic index as the overall evaluation of different hydrogen technologies in terms of weights calculated using the Analytic Hierarchy Process (AHP) method. Bozoglan et al.[14] used exergy-based environmental and sustainability parameters to analyze the sustainability of various solar hydrogen production techniques. Tugnol et al.[15] developed a sustainability "fingerprint" based on multiple key performance indicators to investigate the sustainability of a variety of hydrogen production technologies by the steam reforming of natural gas. Khoo et al.[16] carried out a relative life cycle assessment to investigate the sustainability of 2-MeTHF manufacture originating from different biomass resources. A novel sustainability assessment methodology for energy systems using life-cycle emission factors and sustainability indicators was developed by Hacatoglu et al.,[17] which was applied to a hybrid energy system with hydrogen-based storage to meet the energy needs of a small community in southern Ontario. A life cycle sustainability assessment methodology was employed for the analysis of biogas production systems in Kenya by linking the biogas energy with production infrastructures.[18] Gangadharan et al.,[19] compared two polygeneration systems, which use coal and natural gas as feed to produce di-methyl ether and power, using a comprehensive sustainability assessment methodology. All these methodologies belong to the type of quantitative assessment that can only consider the hard criteria.

For the importance of soft criteria in the sustainability assessment, there are also multiple qualitative methodologies for the sustainability assessment of industrial systems that can address the soft criteria. Ren et al.[20] proposed a fuzzy multiactor multicriteria decision-making methodology to assess the sustainability of four biomass-based hydrogen production technologies, in which, 15 criteria concerning the four aspects of economic, environmental, technological, and social-political performances were considered. The developed method allows decision-makers/stakeholders to evaluate the alternatives with respect to each criterion using linguistic terms. Chang et al.[21] used a fuzzy Delphi method to evaluate multiple hydrogen production technologies based on 14 criteria, and the relative performances of different pathways with respect to each criterion were also scored by linguistic terms. These two methods are essentially based on the qualitative evaluations, although they can incorporate both hard and soft criteria. In the methods,[20,21] the users first use linguistic terms to evaluate all the criteria according to the preferences of the decision-makers/stakeholders, which were, then, transformed to fuzzy numbers or crisp numbers. Accordingly, the data for the sustainability assessment used in these methods were mainly obtained according to the subjective judgments of the decision-makers/stakeholders. As the human's judgments usually involve subjectivities, vagueness, and uncertainties, the hard criteria, which can be directly quantified using crisp numbers, cannot be fully depicted in these methods. In other words, both the hard and soft criteria were evaluated qualitatively in these methods; the quantitative data of the alternatives with respect to the hard criteria were not be fully used. Consequently, the assessment accuracy using these methods can not be ensured due to the characteristics of the subjective judgments. The expected method for the sustainability assessment of various industrial systems should not only consider both the hard and soft criteria, but also handle the hard and soft criteria differently, that is, evaluating the hard criteria quantitatively and soft criteria qualitatively. Moreover, while the sustainability assessment usually concerns the three pillars, that is, economic, environmental, and social aspects,[11,22–27] the criteria regarding the technological and political aspects were also often included as the technological and political issues always affect the economic, environmental, and social performance.[20–22,28,29] Thus, the sustainability assessment and prioritization of various industrial systems or technologies is a typical multicriteria decision-making problem as it requires to score a finite number of alternatives (i.e., different industrial systems) with the considerations of multiple dimensional performances. These kinds of problems usually involve not only multiple alternatives and multiple criteria, but also the interdependencies and interactions among the criteria. Therefore, it is also necessary for the assessment methodology to be capable of tackling the interdependencies and interactions among the criteria.[23,30]

In the multicriteria decision-making problems, the determination of the criteria weights is of vital importance as it can reflect not only the relative importance of the criteria, but also the preferences of the decision-makers. Taking the sustainability performance of power generation based on different sources as an example, there are various energy sources for power generation, for example, hydropower, wind power, solar power, and nuclear power; however, the sustainability of electricity generation originating from different energy sources is distinctive due to the varied preference of the stakeholders and the different performance of various energy sources in different countries. Therefore, an effective sustainability assessment method should be object-oriented, meaning that the method should be capable of helping the stakeholders to select the most sustainable industrial system among multiple alternatives for achieving their objectives based on the preferences/willingness of the stakeholders/decision-makers and the actual conditions.

In this study, a novel Multi-Criteria Decision Making (MCDM) methodology for the sustainability assessment and prioritization of industrial systems was developed. The methodology adopts the fuzzy AHP method to quantify the soft criteria, which allows the stakeholders/decision-makers to evaluate the performances of various pathways with respect to soft criteria using linguistic terms. As the hard criteria, they are directly quantified according to the data collected from the literatures, for example, books, papers, technical reports, and so forth. Moreover, the method of fuzzy Analytic Network Process (ANP),[31] which can handle the interdependencies and interactions among the criteria by combing the thoughts of the fuzzy AHP and the conventional ANP method, is employed to determine the weights of the criteria for aggregating multiple criteria into a generic index. Finally, the Preference Ranking

Organization Method for Enrichment Evaluation (PROMETHEE) approach is used to prioritize the sustainability sequence of the alternative pathways by calculating the net outranking flow of each scenario. Consequently, the proposed methodology is not only capable of evaluating the hard and soft criteria with different approach, but also exploring the interdependencies and interactions among the criteria.[30] All in all, this study aims to develop a generic and object-oriented sustainability decision support framework for the prioritization of industrial systems that can handle both the hard criteria and soft criteria, and also the interdependencies and interactions among the criteria.

Mathematical Methods

In this section, the mathematical framework of the proposed methodology was introduced (Figure 1). In the methodology, the criteria system for the sustainability assessment was first established. Subsequently, the data of the alternatives with respect to each criterion were determined; the data corresponding to the hard criteria were collected from literatures, and those of the soft criteria were determined using the fuzzy AHP method.[32] Moreover, the fuzzy ANP method[31,33] was introduced to determine the weight of each criterion. Finally, the PROMETHEE approach[34,35] was used to prioritize the sustainability sequence of the various industrial systems, and a sensitivity analysis method was developed for identifying the most critical and sensitive criteria that have significant effects on the sustainability sequence of the alternative industrial systems.

Establishment of the criteria system

The three pillars, that is, economic prosperity, environmental protection, and social development, are a common ground of numerous sustainability standards, therefore, the criteria system for the sustainability assessment usually consists of the economic, environmental, and social factors. While the technological and political aspects can affect the economic, environmental, and social performances,[36] the technological and political issues are also usually incorporated in the criteria systems. In this study, a total of 14 criteria concerning the four aspects, that is, economic, environmental, technological, and social-political issues,[11,13,20,26,37–47] were used for the sustainability assessment of various industrial systems (Table 1).

- Criteria concerning the economic aspect
  1. Capital cost: it refers to the cost for the equipments, transportation, and construction of each unit.
  2. Operation and maintenance (O&M) cost: it measures the expenses related to the operation and maintenance of each unit.
  3. Feedstock cost: it refers to the cost of raw materials. Taking the production of bioethanol as an example, the feedstock cost refers to the cost for purchasing the raw materials like corn, wheat, cassava, crop residues, and so forth.
  4. Production cost: it accounts for the total cost for manufacturing the targeted products using different industrial systems/technologies.
  5. Resource availability: it measures the potential reserve of the key feedstocks used in various industrial systems, and it is an indicator of the development potential of each technology/system. For instance, the different reserves of the feed stocks, for example, *Jatropha*, soybean, palm oil, and rapeseed, will affect the development availability of the biodiesel production pathways using different feedstocks.
- Criteria concerning the environmental aspect
  1. Global warming potential: it measures the emissions of greenhouse gases, for example, CO_2, CH_4, and NO_x emitted by alternative industrial systems with the unit of g CO_2 eq.
  2. Acidification potential: it accounts for the emissions of acids deposited into the soil and water by different industrial systems with the unit of g SO_2 eq.
- Criteria concerning the technological aspect
  1. Maturity: it measures the maturity degree of the technology by referring how widespread it is used at both international and national levels.
  2. Energy efficiency: it refers to the ratio of the energy that can be generated by the product to the total energy required for producing the product, and therefore, it is a measure of the energy conversion efficiency.
  3. Exergy efficiency: it refers to the ratio of the exergy that can be output by the product to the total exergy that was input for producing the product.
  4. Technology innovation: it refers to the integrated innovation degree of each technology including the renewability, future prospect, and accessibility. It is a criterion to measure the innovation degree of each technology to substitute the conventional technologies, and can also measure the effect of each technology on the diversity of resources and pathways for manufacturing a specific product.
- Criteria concerning the social-political aspect
  1. Social acceptability: this criterion is to measure the overall opinions of the local people on different industrial systems or technologies, and it can reflect the impacts of the hypothesized project on the society.
  2. Effect for energy security: it measures the effect of each industrial system or technology on energy security and mitigating the dependence on energy import of a nation or region by introducing this technology as the increasing consumption of nonrenewable fossil fuels could deteriorate the energy security.
  3. Policy applicability: it is a measure of the accordance of the industrial systems or technologies with the governmental policies, regulations, and laws. This criterion can reflect the support of each project by the government.

In the established criteria system, eight criteria, that is, capital cost (C_1), O&M cost (C_2), feedstock cost (C_3), production cost (C_4), global warming potential (C_6), acidification potential (C_7), energy efficiency (C_9), and exergy efficiency (C_{10}), belong to the hard criteria. Six criteria, that is, resource availability (C_5), maturity (C_8), technology innovation (C_{11}), social acceptability (C_{12}), effect on energy security (C_{13}), and policy applicability (C_{14}) are soft criteria. The hard criteria can be directly scored according to the data collected from books, papers, technical reports, and survey from the manufacture or pilot plants, and so forth. Whearas the soft criteria are difficult to be directly quantified by the stakeholders/decision-makers, accordingly, this study employed a fuzzy AHP method to determine the relative priorities of the alternatives with respect to the soft criteria, in which, the stakeholders/decision-makers are allowed to evaluate each industrial system or technology

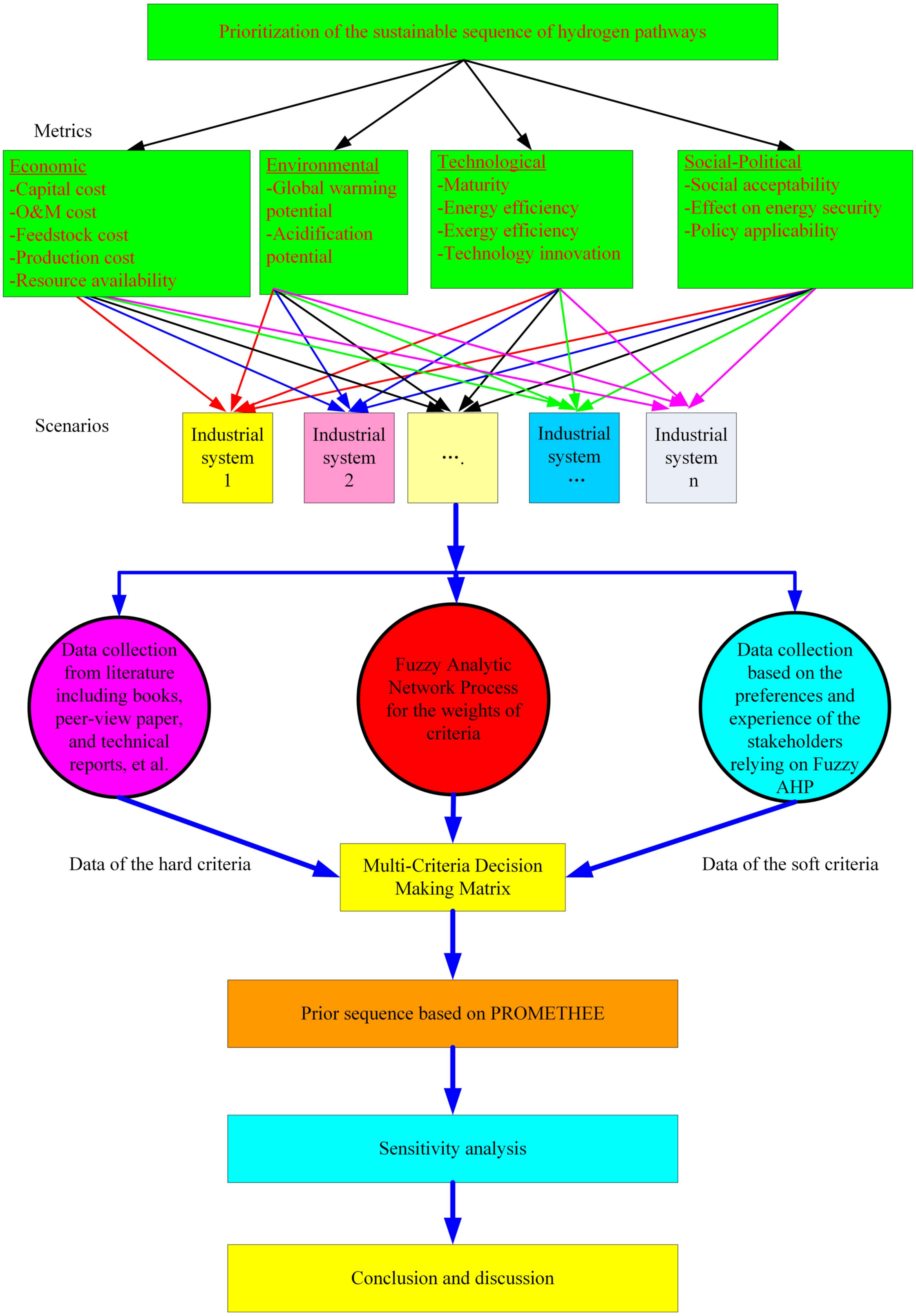


Figure 1. Framework of the developed sustainability decision support methodology for industrial system prioritization.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

using linguistic terms. Moreover, it is worth pointing out that the global warming potential and acidification potential are usually measured in the life cycle perspective, thus, it is important to use the same boundary to measure the other criteria. In other words, when the life cycle perspective was employed in measuring the global warming potential and acidification potential, the measure of the other criteria should not be limited on the production process.

Table 1. Criteria for the Sustainability Assessment of Industrial Systems

Aspect	Criteria	Type	Abbreviation
Economic	Capital cost[13]	Hard-cost	C_1
	O&M cost[13]	Hard-cost	C_2
	Feedstock cost[13]	Hard-cost	C_3
	Production cost[13]	Hard-cost	C_4
	Resource availability[20]	Soft-benefit	C_5
Environmental	Global warming potential[37]	Hard-cost	C_6
	Acidification potential[37]	Hard-cost	C_7
Technological	Maturity[20]	Soft-benefit	C_8
	Energy efficiency[37]	Hard-benefit	C_9
	Exergy efficiency[37]	Hard-benefit	C_{10}
	Technology innovation[37]	Soft-benefit	C_{11}
Social-political	Social acceptability[20]	Soft-benefit	C_{12}
	Effect for energy security[20]	Soft-benefit	C_{13}
	Policy applicability[20]	Soft-benefit	C_{14}

Among the 14 criteria, some are interactive and interdependent. For instance, the criterion of social acceptability (C_{12}) is affected by the global warming potential (C_6) and acidification potential (C_7), while the criterion of resources availability (C_5) influences the policy applicability (C_{14}). In this study, the interdependencies among the criteria were tackled using the fuzzy ANP method to determine the weights of each criterion with the consideration of feedbacks and interactions among the criteria.

The criteria selected in this study are the most important and also the most commonly used criteria for sustainability assessment of industrial systems. When the proposed object-oriented methodology is used to prioritize the sustainability of different industrial systems, the users should determine the suitable criteria system according to the actual conditions and their preference (e.g., data availability and information incompletion). The users can select parts of the 14 criteria, or add more criteria. For instance, the criteria of net present value, internal rate of return, payback period, and annual profit have also been widely used in the economic pillar of sustainability.[48] The metrics including land use change (occupied land area), water utilization, and some indicators in the life cycle assessment (e.g., climate change, ozone depletion, human toxicity, particular matter formation, and terrestrial acidification[49,50] are also widely used for measuring the environmental performances. The criteria of reliability, operability, and primary energy ratio are often adopted to measure the performances of industrial systems with respect to the technological aspect.[23,51,52] As for the social-political aspect, the number of added jobs, influence on the local culture, working conditions, health and safety, social benefits, contribution to economy development, food security, community engagement, and government support[52–54] could also be incorporated in the sustainability assessment according to the preferences of the decision-makers. However, it is worth pointing out that the accuracy of the sustainability assessment does not definitely increase with an increase in the criteria numbers as a large number of criteria may lead to the repeatability and overlaps in concepts.

Fuzzy AHP method for scoring the soft criteria

There are usually two ways for determining the relative priorities of the alternatives with respect to the soft criteria: the scaling system method[10,11] and the pair-wise comparison method.[55,56] The scaling method scores the alternatives using numbers (crisp numbers or gray numbers); while the pair-wise comparison method determines the relative priorities of the alternatives via the pair-wise comparison. The scaling method is simple and easy to be operated; however, it cannot assure the overall consistency among all the relative priorities of the alternatives with respect to each of the soft criteria. AHP is a widely used pair-wise comparison method for determining the relative priorities of the alternatives with respect to the soft criteria.[55,56] However, the conventional AHP method uses nice scales (1,2,. . .,9) and their reciprocals to determine the comparison matrix and the relative priorities of the criteria, which requires the users to describe their opinions using crisp numbers. As human's judgments are usually subjective, vague and ambiguous, this limitation could result in the inconvenience of the users and inaccuracy of the results.[57] Accordingly, this study adopted a fuzzy AHP method by combining the thoughts of the conventional AHP with the fuzzy set theory to quantify the relative priorities of the soft criteria. The fuzzy AHP method allows the stakeholders/decision-makers to describe their preferences using linguistic variables, that is, words or sentences in a natural or artificial languages, which is more suitable than the crisp numbers for depicting human's judgments. The linguistic variables are in turn connected to fuzzy numbers through the membership functions.[22,58]

For a universe set, X, the fuzzy set $\tilde{A}$ in X is characterized by a membership function $\mu\tilde{A}(x) \rightarrow [0,1]$, which quantifies the grade of membership of the element x to $\tilde{A}$.[59–61] The membership functions can be of different formulation, but in practice, triangular and trapezoidal membership functions are most frequently used in the fuzzy logic as showed in Eqs. 1 and 2,[61] in which, a, b, c, and d are parameters. For those unfamiliar to the fuzzy set theory, it also has been extensive used in some other literatures[59–61]

$$\mu_{\tilde{A}}(x)=\begin{cases} 0 & x \le a \\ \dfrac{x-a}{b-a} & a < x \le b \\ \dfrac{x-c}{b-c} & b < x \le c \\ 0 & x > c \end{cases} \tag{1}$$

$$\mu_{\tilde{A}}(x)=\begin{cases} 0 & x \le a \text{ or } x \ge d \\ \dfrac{x-a}{b-a} & a < x \le b \\ 1 & b < x \le c \\ \dfrac{x-d}{c-d} & x > c \end{cases} \tag{2}$$

In the fuzzy AHP method, the comparison matrix is first determined using the linguistic terms, which are then transformed into fuzzy numbers (Table 2).[62] Assuming $X=\{x_1, x_2, \cdots, x_n\}$ is an object set, and $U=\{g_1, g_2, \cdots, g_m\}$ is a goal set. Then, the performance of each object regarding each goal can be analyzed; the m-extent analysis values for each object can be obtained as Eq. 3

$$M_{gi}^1, M_{gi}^2, \cdots, M_{gi}^m, \quad i=1,2,\cdots,n \tag{3}$$

where $M_{gi}^j (j=1,2,\cdots,m) = \left(l_{gi}^j, m_{gi}^j, u_{gi}^j\right)$ are the triangular fuzzy numbers.

Subsequently, the fuzzy AHP method is conducted according to the followed four steps as developed by Chang[32,62–64]

Table 2. The Linguistic Terms and Corresponding Fuzzy Numbers for the Pairwise Comparison[62]

Linguistic Scales	Abbreviations	Fuzzy Scales
Equal importance	E	(1,1,1)
Weak importance	W	(2/3,1,3/2)
Moderate importance	M	(1,3/2,2)
Fairly strong importance	FS	(3/2,2,5/2)
Very strong importance	VS	(2,5/2,3)
Absolute importance	A	(5/2,3,7/2)
Reciprocals of these	RW, RM, RFS, RVS, RA	The reciprocals of these fuzzy numbers

Step 1: The value of the fuzzy synthetic extent with respect to the ith object is defined as Eq. 4

$$S_i=\sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} \tag{4}$$

where $\sum_{j=1}^{m} M_{gi}^{j}$ and $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1}$ can be determined according to Eqs. 5 and 6, respectively

$$\sum_{j=1}^{m} M_{gi}^{j}=\left(\sum_{j=1}^{m} l_{gi}^{j}, \sum_{j=1}^{m} m_{gi}^{j}, \sum_{j=1}^{m} u_{gi}^{j}\right), \quad i=1,2,\cdots,n \tag{5}$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1}=\left(\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} u_{gi}^{j}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} m_{gi}^{j}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} l_{gi}^{j}}\right) \tag{6}$$

Step 2: The degree of possibility of $S_2=(l_2,m_2,u_2) \geq S_1=(l_1,m_1,u_1)$ is defined as Eq. 7

$$V(S_2 \geq S_1)=\sup_{y>x}\left(\min\left\{\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(y)\right\}\right)$$
$$=\text{height}(S_2 \cap S_1)=\mu_{S_2}(d)=\begin{cases} 1 & \text{if } m_2 \geq m_1 \\ 0 & \text{if } l_1 \geq u_2 \\ \dfrac{l_1-u_2}{(m_2-u_2)-(m_1-l_1)} & \text{otherwise} \end{cases} \tag{7}$$

where d is the ordinate of the highest intersection point between μ_{M_1} and μ_{M_2} as illustrated in Figure 2. Both $V(S_2 \geq S_1)$ and $V(S_1 \geq S_2)$ are necessary for comparing S_1 and S_2.

Step 3: The degree of possibility for a convex fuzzy number to be greater than the convex fuzzy number $S_i\,(i=1,2,\cdots,k)$ is defined by Eq. 8

$$\begin{aligned} &V(S \geq S_1, S_2, \cdots, S_k) \\ &=V(S \geq S_1)\text{and}\,V(S \geq S_2)\ \text{and} \cdots \text{and}\ V(S \geq S_k) \\ &=\min V(S \geq S_i),\ i=1,2,\cdots,k \end{aligned} \tag{8}$$

Assuming that

$$d'(A_i)=\min V(S_i \geq S_k),\ k=1,2,\cdots,n \text{ and } k \neq i \tag{9}$$

Then, the weight vector of the n elements $A_i(i=1,2,\cdots,n)$ can be determined by Eq. 10

$$W'=(d'(A_1), d'(A_2), \cdots, d'(A_n))^T \tag{10}$$

where $d'(A_i)$ is the weight of the ith element A_i, and W' is the weight vector.

Step 4: The weight vector in Eq. 10 is normalized to obtain the weight of each element according to Eqs. 11 and 12, respectively. In Eq. 11, W is a nonfuzzy number

$$W=(d(A_1), d(A_2), \cdots, d(A_n))^T \tag{11}$$

$$d(A_i)=\frac{d'(A_i)}{\sum_{i=1}^{n} d'(A_i)} \tag{12}$$

After the normalization, the weights of the criteria satisfy Eq. 13

$$\sum_{i=1}^{n} d(A_i)=1 \tag{13}$$

where $d(A_i)$ is the normalized weight of the ith element A_i, and W is the normalized weight vector.

Fuzzy ANP method

ANP is a widely used MCDM technique that was derived from the AHP method.[33] The original AHP method was developed by Saaty in 1970s to rank the priority sequence associated with the alternatives of a specific problem in a ratio scale by combining the tangible and intangible aspects.[33,55,65] However, the method is unable to deal with any kinds of interdependence between the evaluation criteria, thus it cannot be used to solve the decision-making problems that involve the interactions between the assessment factors.[66] Accordingly, the ANP method was developed by extending the AHP technique to address the MCDM problems with interactions and interdependencies among the alternatives or criteria.[31,33,66,67] The structural difference between ANP and AHP (Figure 3) is that AHP represents a framework with a unidirectional hierarchical relationship, while ANP uses a hierarchical networks with feedback approaches among decision levels and attributes.[31,68] However, the conventional ANP method is based on the AHP method, it does not perform well when facing the subjectivity, vagueness, and ambiguity existed in human's judgments as discussed above. Thus, the fuzzy ANP method was employed for determining the weights of the criteria in

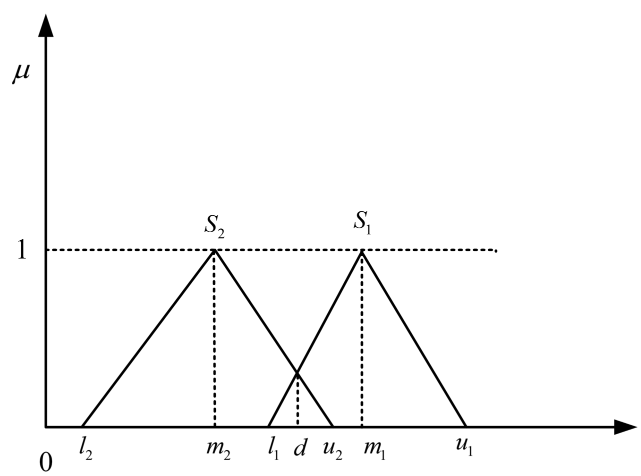


Figure 2. The intersection between S_1 and S_2.

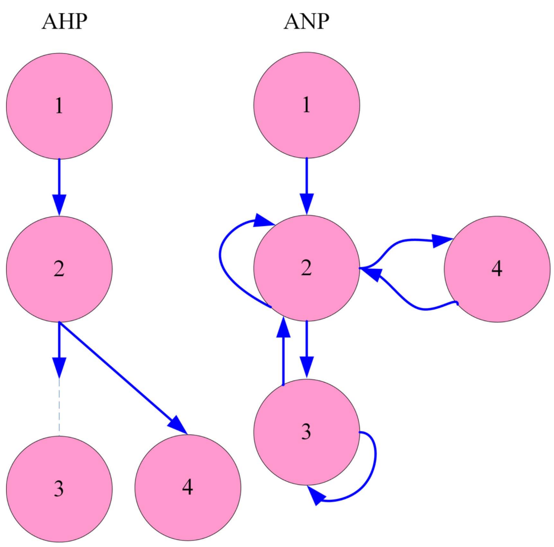


Figure 3. Structural difference between ANP and AHP.[69]

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

this study, and its procedure usually consists of four steps as showed in Figure 4.[66,68,69]

Step 1: Determining the evaluation network structure. According to the principle of ANP and the evaluation criteria, the evaluation network structure with the clarified relationships between the criteria or alternatives is to be established in this step.

Step 2: Establishing the fuzzy comparison matrices and calculating priority vectors. The fuzzy comparison matrices for pair-wisely comparing the elements of each cluster are to be established in this step. After the matrices are established, the local priority vectors for each pair-wise comparison matrix can be obtained using the fuzzy AHP method.[32] It is worth pointing out that the determination of the fuzzy comparison matrices should be based on a group decision-making, for example, a focus group, a seminar or a teleconference of the experts in the related areas including professors, senior engineers, government officials (investors and administrative executors), and so forth. During the group decision-making process, a consensus about the interdependencies and interactions among the criteria was achieved by exchanging opinions and discussion, which ensure the decision-making to incorporate the preferences/willingness of all the stakeholders and to avoid the inconsistencies existing in the opinions of the decision-makers.

Step 3: Calculating the supermatrix, weighted supermatrix formation, and limit supermatrix. In this step, the global priorities of a specific system with the interdependent factors are obtained by inputting the local priority vectors in the appropriate columns of a matrix. Assuming C_k to be the kth cluster ($k=1,2,\ldots\ldots,N$) that has n_k elements ($e_{k1}, e_{k2},\ldots\ldots, e_{knk}$), the standard form of a supermatrix is as Eq. 14. In the supermatrix, the segment, W_{ij}, represents the relationship between the ith cluster and the jth cluster; each column of W_{ij} is the local priority vector obtained from the corresponding pair-wise comparison matrix, indicating the relative importance of the elements in the ith cluster to an element in the jth cluster.[66]

Subsequently, the pair-wise comparisons are carried out between the clusters to determine the weight matrix, in which each column represents the relative effects between the other clusters on a specific cluster with respect to the corresponding criterion and the numerical sum of the elements in each column is 1. Then, according to the weight matrix, the supermatrix is normalized to obtain the weighted supermatrix, which is subsequently transformed into the limit supermatrix by raising it to powers for ensuring the convergence of the matrix[66]

$$
\begin{array}{cccccccc}
 & & C_1 & \cdots & C_k & \cdots & C_N \\
 & & e_{11}\cdots e_{1n_1} & \cdots & e_{k1}\cdots e_{kn_k} & \cdots & e_{n1}\cdots e_{nn_N} \\
 & e_{11} & & & & & \\
C_1 & \vdots & W_{11} & \cdots & W_{1k} & \cdots & W_{1N} \\
 & e_{1n_1} & & & & & \\
\vdots & & \vdots & \vdots & \vdots & \vdots & \vdots \\
 & e_{k1} & & & & & \\
C_k & \vdots & W_{k1} & \cdots & W_{kk} & \cdots & W_{kN} \\
 & e_{kn_1} & & & & & \\
\vdots & & \vdots & \vdots & \ddots & \vdots & \vdots \\
 & e_{n1} & & & & & \\
C_N & \vdots & W_{N1} & \cdots & W_{Nk} & \cdots & W_{NN} \\
 & e_{nn_N} & & & & &
\end{array}
\tag{14}
$$

Step 4: Obtaining the final weights of each elements.

The elements in each row of the limit supermatrix are same, and the value indicates the relative importance of each element. Then, the relative weights of the elements can be obtained by normalizing the limit supermatrix.

PROMETHEE method for the sustainability prioritization

The prioritization of alternative industrial systems is a typical MCDM problem, the stakeholders/decision-makers have to

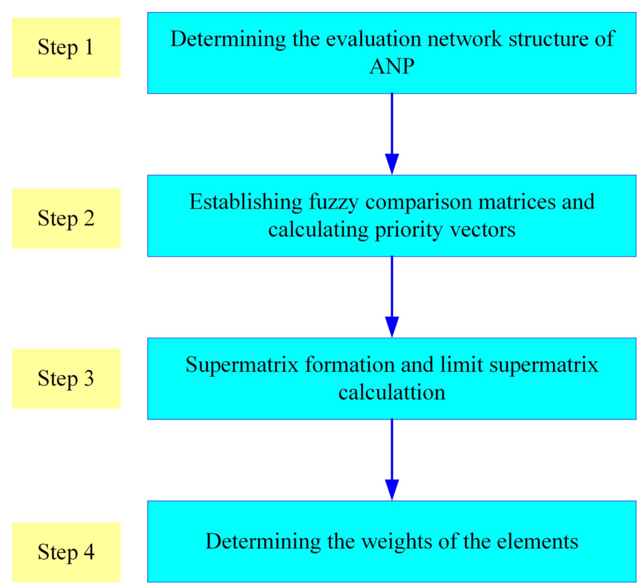


Figure 4. Procedure of the fuzzy ANP method.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

select the most sustainable scenario from a variety of pathways by considering multiple criteria. Among the various MCDM methods available in the literatures, for example, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS),[70] Data Envelopment Analysis (DEA),[71] Elimination Et Choix Traduisant la REalité (ELECTRE),[72] Grey Relational Analysis (GRA),[10] the method of Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) has the advantages of highly efficient and easy to be used and operated due to its lower level of complexity.[73,74]

PROMETHEE, developed by Brans and Vincke in 1980s to rank the alternatives using the outranking principle, is a collective name of the PROMETHEE family including PROMETHEE I (partial ranking), PROMETHEE II (complete ranking), PROMETHEE III (ranking based on intervals), PROMETHEE IV (continuous case), PROMETHEE V (PROMETHEE II and integer linear programming), PROMETHEE VI (weights of the criteria are intervals), and PROMETHEE GAIA (graphical representation of PROMETHEE).[35,75–78] One of the main advantages of PROMETHEE over other outranking methods is that the decision-makers can easily understand the concepts and parameters inherent in the method, which makes it simpler to be operated, and consequently increases the effectiveness.[79] In this study, PROMETHEE II (complete ranking) was selected as the decision making tool for prioritizing the sustainability sequence of alternative industrial systems.

In PROMETHEE II, a complete pre-order (complete ranking) of the alternatives is obtained according to the calculated net flow from each alternative. The analysis procedures include three steps: (1) establishment of the decision-making matrix with the data of the alternatives with respect to each criterion and the weights of the criteria; (2) selection of a preference function, by which, the difference between two alternatives regarding a criterion was transformed into a value between 0 and 1; (3) calculation of the net outranking flow of the alternatives with respect to each criterion as the preference index to prioritize the alternatives.[80] Among the three steps, the selection of the preference function is very critical, it can significantly affect the accuracy of the sustainability assessment. There are usually six types of preference functions corresponding to the six types of generalized criteria (see Table 3).[80] Among them, the Gaussian type preference function was selected in this study due to its advantages of sensitive to small variations of the PROMETHEE II input parameters[56] and containing continuity.[81] In the Gaussian-criterion as showed in Table 3, δ_j is defined as the threshold value and could be obtained by calculating the average variance of the jth criterion; and d_j represents the numerical difference of two alternatives regarding to each criterion.

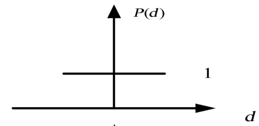
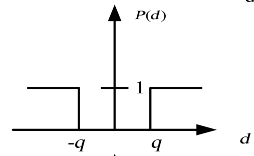
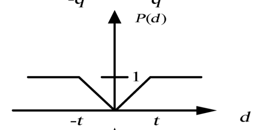
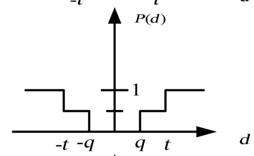
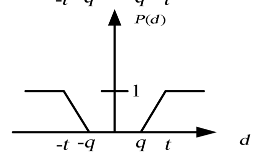
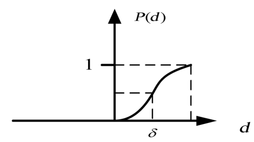
In the PROMETHEE II method, the multicriteria preference index for a pair of alternatives A_i and A_k is defined as Eq. 15

$$H(A_i, A_k) = \sum_{j=1}^{n} w_j P_j(A_i, A_k) \tag{15}$$

where $P_j(A_i, A_k)$ is the preference function, w_j is the weights of the jth criterion calculated using the ANP method. The positive outranking flow and negative outranking flow of an alternative can be calculated by Eqs. 16 and 17, respectively

$$\phi^+(A_i) = \sum_{k=1}^{m} H(A_i, A_k) \quad (i=1,2,\cdots,m) \tag{16}$$

Table 3. Shape of the Six Types of Generalized Criteria[80]

Generalized Criterion Type	Preference Function $P(d)$
Type I: Usual criteria $P_j(d_j)=\begin{cases}0 & d_j=0\\ 1 & \lvert d_j\rvert>0\end{cases}$	
Type II: U shape criterion $P_j(d_j)=\begin{cases}0 & \lvert d_j\rvert\le q\\ 1 & \lvert d_j\rvert>q\end{cases}$	
Type III: V shape criterion $P_j(d_j)=\begin{cases}\frac{\lvert d_j\rvert}{t} & \lvert d_j\rvert\le t\\ 1 & \lvert d_j\rvert>t\end{cases}$	
Type IV: Level criterion $P_j(d_j)=\begin{cases}0 & \lvert d_j\rvert\le q\\ \frac{1}{2} & q<\lvert d_j\rvert\le t\\ 1 & \lvert d_j\rvert>t\end{cases}$	
Type V: V-shape criterion with indifference criteria $P_j(d_j)=\begin{cases}0 & \lvert d_j\rvert\le q\\ \frac{\lvert d_j\rvert-q}{t-q} & q<\lvert d_j\rvert\le t\\ 1 & \lvert d_j\rvert>t\end{cases}$	
Type VI: Gaussian-criterion $P_j(d_j)=\begin{cases}0 & d_j\le 0\\ 1-e^{-\frac{d_j^2}{2\delta_j^2}} & d_j>0\end{cases}$	

$$\phi^-(A_i) = \sum_{k=1}^{m} H(A_k, A_i) \quad (i=1,2,\cdots,m) \tag{17}$$

Then, the net outranking flow of an alternative can be calculated by Eq. 18

$$\phi(A_i) = \phi^+(A_i) - \phi^-(A_i) \quad (i=1,2,\cdots,m) \tag{18}$$

As the net outranking flow indicates how much each alternative is preferred to the others, its value can be used to rank the alternatives, that is, a higher value of the net outranking flow corresponds to a better alternative.[74,81] The standards can be described as Eqs. 19 and 20

$$\text{if } \phi(A_i) \succ \phi(A_k) \quad \text{then } A_i \succ A_K \tag{19}$$

$$\text{if } \phi(A_i) \sim \phi(A_k) \quad \text{then } A_i \sim A_K \tag{20}$$

where "$\succ$" represents "superior to", "$\sim$" represents "no difference."

It is noteworthy that the values of the net outranking flow for the alternatives with respect to each criterion should be first transformed into dimensionless values, and the linear transformation method proposed by Hajkowicz and Higgins[82] was adopted in this study. Meanwhile, the 14 criteria can be divided into two categories according to their effects: benefit criteria and cost criteria. The greater the value of an industrial system with respect to a benefit criterion, the more superior the industrial system will be. On the contrary, the greater the value of an industrial system with respect to a cost criterion, the less superior the industrial system will be. Accordingly, resource availability, maturity, energy efficiency, exergy efficiency, technology innovation, social acceptability, effect on energy security, and policy applicability belong to the benefit criteria, and the other six criteria belong to the cost criteria. Both the benefit criteria and cost criteria can be normalized after the transformation. Moreover, the cost criteria can also be transformed into benefit criteria after this process.

Sensitivity analysis method

To identify the most critical and sensitive criteria that have a significant effect on the sustainability sequence and to investigate the influence of the interactions and interdependencies among the criteria on the results, a novel sensitivity analysis method was developed by extending the method proposed by Triantaphyllou and Sánchez.[83]

Assuming $A_j \succ A_i$ according to the PROMETHEE method, but the decision-makers want to alter the current ranking by modifying the weight of one criterion. With the tth criterion as an example, Eqs. 21 and 22 can be obtained

$$\begin{aligned}
\phi(A_i)-\phi(A_j) &= \left[\phi^+(A_i)-\phi^-(A_i)\right]-\left[\phi^+(A_j)-\phi^-(A_j)\right] \\
&= \left[\sum_{k=1}^{m}H(A_i,A_k)-\sum_{k=1}^{m}H(A_k,A_i)\right]-\left[\sum_{k=1}^{m}H(A_j,A_k)-\sum_{k=1}^{m}H(A_k,A_j)\right] \\
&= \left[\sum_{k=1}^{m}\sum_{d=1}^{n}w_dP_d(A_i,A_k)-\sum_{k=1}^{m}\sum_{d=1}^{n}w_dP_d(A_k,A_i)\right]-\left[\sum_{k=1}^{m}\sum_{d=1}^{n}w_dP_d(A_j,A_k)-\sum_{k=1}^{m}\sum_{d=1}^{n}w_dP_d(A_k,A_j)\right] \\
&= \left[\sum_{k=1}^{m}\left(\sum_{d=1,d\neq t}^{n}w_dP_d(A_i,A_k)+w_tP_t(A_i,A_k)\right)-\sum_{k=1}^{m}\left(\sum_{d=1,d\neq t}^{n}w_dP_d(A_k,A_i)+w_tP_t(A_k,A_i)\right)\right] \\
&\quad -\left[\sum_{k=1}^{m}\left(\sum_{d=1,d\neq t}^{n}w_dP_d(A_j,A_k)+w_tP_t(A_j,A_k)\right)-\sum_{k=1}^{m}\left(\sum_{d=1,d\neq t}^{n}w_dP_d(A_k,A_j)+w_tP_t(A_k,A_j)\right)\right] \\
&= \sum_{k=1}^{m}\left[\left(w_tP_t(A_i,A_k)+w_tP_t(A_k,A_j)\right)-\left(w_tP_t(A_j,A_k)+w_tP_t(A_k,A_i)\right)\right] \\
&\quad +\sum_{k=1}^{m}\left(\sum_{d=1,d\neq t}^{n}w_dP_d(A_i,A_k)+w_dP_d(A_k,A_j)-w_dP_d(A_k,A_i-w_dP_d(A_j,A_k)\right) \\
&= w_t\left[\sum_{k=1}^{m}\left(P_t(A_i,A_k)+P_t(A_k,A_j)\right)-\left(P_t(A_j,A_k)+P_t(A_k,A_i)\right)\right] \\
&\quad +\sum_{k=1}^{m}\left[\sum_{d=1,d\neq t}^{n}w_dP_d(A_i,A_k)+w_dP_d(A_k,A_j)-w_dP_d(A_k,A_i-w_dP_d(A_j,A_k)\right]\geq 0
\end{aligned} \tag{21}$$

$$\begin{aligned}
\sum_{k=1}^{m}\left[\sum_{d=1,d\neq t}^{n}w_dP_d(A_i,A_k)+w_dP_d(A_k,A_j)-w_dP_d(A_k,A_i-w_dP_d(A_j,A_k)\right] &= \phi(A_i)-\phi(A_j) \\
&\quad -w_t\left[\sum_{k=1}^{m}\left(P_t(A_i,A_k)+P_t(A_k,A_j)\right)-\left(P_t(A_j,A_k)+P_t(A_k,A_i)\right)\right]
\end{aligned} \tag{22}$$

Assuming that for reversing the current ranking of A_i and A_j, the minimum quantity of the weight of the tth criterion that has to be changed is $\delta_{t,i,j}$, then the modified weight of the tth criterion, w_t^*, is

$$w_t^*=w_t-\delta_{t,i,j}\geq 0 \tag{23}$$

To satisfy Eq. 13, the weight should be renormalized according to Eqs. 24 and 25

$$w_t'=\frac{w_t^*}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d} \tag{24}$$

$$w_d'=\frac{w_d}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d} \tag{25}$$

where w_t' represents the new normalized weight of the t-th criterion, and w_d' $(d=1,2,...,n, d\neq t)$ represents the new normalized weight of the dth criterion.

According to Eq. 21, the new relationship between the net outranking flow of the ith alternative and that of the jth alternative is as Eq. 26, in which, $\phi^*(A_i)$ and $\phi^*(A_j)$ represent the net flow of the ith alternative and the jth alternative, respectively.

To reverse the ranking of A_i and A_j, $\phi^*(A_i)-\phi^*(A_j)$ should be greater than 0 according to Eq. 19. Accordingly, Eq. 27 should be satisfied

$$\phi^*(A_i)-\phi^*(A_j)=\frac{w_t^*}{w_t^*+\sum_{d=1,d\neq t}^{n} w_d}\left[\sum_{k=1}^{m}\left(P_t(A_i,A_k)+P_t(A_k,A_j)\right)-\left(P_t(A_j,A_k)+P_t(A_k,A_i)\right)\right]+$$
$$\sum_{k=1}^{m}\left(\begin{array}{l}\sum_{d=1,d\neq t}^{n}\frac{w_d}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d}P_d(A_i,A_k)+\sum_{d=1,d\neq t}^{n}\frac{w_d}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d}P_d(A_k,A_j)-\\ \sum_{d=1,d\neq t}^{n}\frac{w_d}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d}P_d(A_k,A_i)-\sum_{d=1,d\neq t}^{n}\frac{w_d}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d}P_d(A_j,A_k)\end{array}\right)$$
$$=\frac{w_t^*}{w_t^*+\sum_{d=1,d\neq t}^{n} w_d}\left[\sum_{k=1}^{m}\left(P_t(A_i,A_k)+P_t(A_k,A_j)\right)-\left(P_t(A_j,A_k)+P_t(A_k,A_i)\right)\right]+$$
$$\sum_{k=1}^{m}\left(\begin{array}{l}\sum_{d=1,d\neq t}^{n}\frac{w_d}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d}P_d(A_i,A_k)+\sum_{d=1,d\neq t}^{n}\frac{w_d}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d}P_d(A_k,A_j)-\\ \sum_{d=1,d\neq t}^{n}\frac{w_d}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d}P_d(A_k,A_i)-\sum_{d=1,d\neq t}^{n}\frac{w_d}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d}P_d(A_j,A_k)\end{array}\right) \tag{26}$$

$$\phi^*(A_i)-\phi^*(A_j)==\frac{w_t^*}{w_t^*+\sum_{d=1,d\neq t}^{n} w_d}\left[\sum_{k=1}^{m}\left(P_t(A_i,A_k)+P_t(A_k,A_j)\right)-\left(P_t(A_j,A_k)+P_t(A_k,A_i)\right)\right]+$$
$$\sum_{k=1}^{m}\left(\begin{array}{l}\sum_{d=1,d\neq t}^{n}\frac{w_d}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d}P_d(A_i,A_k)+\sum_{d=1,d\neq t}^{n}\frac{w_d}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d}P_d(A_k,A_j)-\\ \sum_{d=1,d\neq t}^{n}\frac{w_d}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d}P_d(A_k,A_i)-\sum_{d=1,d\neq t}^{n}\frac{w_d}{w_t^*+\sum_{d=1,d\neq t}^{n}w_d}P_d(A_j,A_k)\end{array}\right)\geq 0 \tag{27}$$

Multiply Eq. 27 by $w_t^*+\sum_{d=1,d\neq t}^{n} w_d$, we could obtain Eq. 28

$$\begin{aligned}&\phi^*(A_i)-\phi^*(A_j)\\&=w_t^*\left[\sum_{k=1}^{m}\left(P_t(A_i,A_k)+P_t(A_k,A_j)\right)-\left(P_t(A_j,A_k)+P_t(A_k,A_i)\right)\right]\\&+\sum_{k=1}^{m}\left(\sum_{d=1,d\neq t}^{n} w_dP_d(A_i,A_k)+w_dP_d(A_k,A_j)-w_dP_d(A_k,A_i)-w_dP_d(A_j,A_k)\right)\geq 0\end{aligned} \tag{28}$$

By integrating Eq. 28 with Eq. 22, Eq. 29 can be obtained

$$\phi^*(A_i)-\phi^*(A_j)=\phi(A_i)-\phi(A_j)-\left(w_t-w_t^*\right)\left[\sum_{k=1}^{m}\left(P_t(A_i,A_k)+P_t(A_k,A_j)\right)-\left(P_t(A_j,A_k)+P_t(A_k,A_i)\right)\right] \tag{29}$$

Similarly, Eq. 30 can be obtained by integrating Eqs. 29 and 23

$$\phi^*(A_i)-\phi^*(A_j)=\phi(A_i)-\phi(A_j)-\delta_{t,i,j}\left[\sum_{k=1}^{m}\left(P_t(A_i,A_k)+P_t(A_k,A_j)\right)-\left(P_t(A_j,A_k)+P_t(A_k,A_i)\right)\right] \tag{30}$$

Finally, Eq. 31 can be obtained

$$\delta_{t,i,j}\left[\sum_{k=1}^{m}\left(P_t(A_i,A_k)+P_t(A_k,A_j)\right)-\left(P_t(A_j,A_k)+P_t(A_k,A_i)\right)\right]\leq \phi(A_i)-\phi(A_j) \tag{31}$$

According to Eq. 31, if $\sum_{k=1}^{m}\left[\left(P_t(A_i,A_k)+P_t(A_k,A_j)\right)-\left(P_t(A_j,A_k)+P_t(A_k,A_i)\right)\right]>0$, Eq. 32 should be satisfied

$$\delta_{t,i,j}\leq\frac{\phi(A_i)-\phi(A_j)}{\sum_{k=1}^{m}\left[\left(P_t(A_i,A_k)+P_t(A_k,A_j)\right)-\left(P_t(A_j,A_k)+P_t(A_k,A_i)\right)\right]} \tag{32}$$

While if $\sum_{k=1}^{m}\left[\left(P_t(A_i,A_k)+P_t(A_k,A_j)\right)-\left(P_t(A_j,A_k)+P_t(A_k,A_i)\right)\right]<0$, Eq. 33 should be satisfied

$$\delta_{t,i,j}\geq\frac{\phi(A_i)-\phi(A_j)}{\sum_{k=1}^{m}\left[\left(P_t(A_i,A_k)+P_t(A_k,A_j)\right)-\left(P_t(A_j,A_k)+P_t(A_k,A_i)\right)\right]} \tag{33}$$

It is worth pointing out that it is impossible to reverse the ranking of A_i and A_j by changing the weights of the criteria if

Eq. 34 is satisfied, which indicates that A_j dominates A_i. Meanwhile, Eq. 23 should be non-negative, implying that $\delta_{t,i,j} \le w_t$. A criterion is considered to be robust if any change of its weight cannot alter the ranking of each pair of alternatives, in another word, the tth criterion is considered to be robust if all the $\delta_{t,i,j}$ associated to it will all satisfy Eq. 34

$$\sum_{k=1}^{m} \left[\left(P_t(A_i, A_k) + P_t(A_k, A_j) \right) - \left(P_t(A_j, A_k) + P_t(A_k, A_i) \right) \right] \le 0 \text{ for all } t = 1, 2, \cdots, n \tag{34}$$

Divided $\delta_{t,i,j}$ by w_t, we can get the minimum percentage, $\delta'_{t,i,j}$, to change the weight of the ith criterion for reversing the ranking of A_i and A_j

$$\delta'_{t,i,j} = \frac{\delta_{t,i,j}}{w_t} \tag{35}$$

Subsequently, the following four definitions were introduced to investigate the criticality degree (CD) and the sensitivity coefficient (SC) of the assessment criteria according to Triantaphyllou and Sánchez[83] and Triantaphyllou et al.[84]

Definition. The percentage-top (PT) critical criterion is the criterion corresponding to the smallest $|\delta'_{t,i,J}|$ value (A_J is the best alternative, $i = 1, 2, \cdots, m$ and $t = 1, 2, \cdots, n$).

Definition. The percentage-any (PA) critical criterion is the criterion corresponding to the smallest $|\delta'_{t,i,j}|$ value ($i = 1, 2, \cdots, m$, $j = 1, 2, \cdots, m, j \ne i$, and $t = 1, 2, \cdots, n$).

Definition. The CD of the tth criterion, D'_t, is the smallest $|\delta'_{t,i,j}|$ ($i = 1, 2, \cdots, m$, and $j = 1, 2, \cdots, m, j \ne i$)

$$D'_t = \min_{i=1,2,\cdots,m, j=1,2,\cdots,m, j \ne i} \left\{ |\delta'_{t,i,j}| \right\}, \text{ for all } t = 1, 2, \cdots, n \tag{36}$$

Definition. The SC of the tth criterion, S_t, is the reciprocal of the CD

$$S_t = \frac{1}{D'_t} = \frac{1}{\min_{i=1,2,\cdots,m, j=1,2,\cdots,m, j \ne i} \left\{ |\delta'_{t,i,j}| \right\}}, \text{ for all } t = 1, 2, \cdots, n \tag{37}$$

After determining the most critical criteria and the criteria that have the greatest SC, the sensitivity analysis of the interactions and interdependencies among the criteria on the ranking sequence can be conducted by changing the weights of the columns with respect to the specific criterion. For instance, for the weighted supermatrix determined by the ANP method for calculating the weights of n criteria, as presented in Eq. 38, the analysis of the interactions and interdependencies associated with the tth criterion on the final ranking of the alternatives can be carried out by three steps

$$\text{WS} = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_n \end{array} \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \\ \omega_{11} & \omega_{12} & \cdots & \omega_{1n} \\ \omega_{21} & \omega_{22} & \cdots & \omega_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \omega_{n1} & \omega_{n2} & \cdots & \omega_{nn} \end{array} \tag{38}$$

where WS represents the weighted matrix, and ω_{ij} represents the relative effects of the ith criterion on the jth criterion.

Step 1: Changing the weights of the tth column in the weighted supermatrix (the relative effects of other criteria on the tth criterion) to recalculate the final weight of each criterion.

Step 2: Running the PROMETHEE method using the weights of the criteria determined in Step 1.

Step 3: Comparing the final rankings under different interactions and interdependencies associated to the tth criterion.

Case Study

To illustrate the proposed method, the sustainability of the industrial systems of hydrogen production with five alternative pathways, that is, coal gasification (CG), stream reforming of methane (SMR), biomass gasification (BG), photovoltaic electrolysis (PVEL), and wind turbine electrolysis (WEL) was prioritized (Figure 5) with the intention to compare the conventional technologies (CG, SMR) with the renewable source based technologies (BG) and the renewable energy based technologies (PVEL and WEL).

Among the 14 criteria concerning the four aspects of the sustainability, the data of each pathway regarding the eight hard criteria were obtained from the literatures (Table 4)[13,37,85] with some data being deduced from the reference.[37] It is worth pointing out that all the obtained data focus on the production process. As for the six soft criteria, the representative experts in the areas of renewable energies, sustainability engineering and energy planning were invited to fill a survey and their views on different production technologies regarding the six criteria were collected using linguistic terms. The comparison matrices were then obtained by incorporating the experts' views with the information from the supporting materials like papers, books and technological reports about the different hydrogen production technologies. Subsequently, the fuzzy AHP method was used to determine the priority of the five technologies with respect to each qualitative criterion. As an example, the priority of the five scenarios regarding the criterion of "resource availability" was determined according to the followed procedure. The comparison matrix for evaluating the five pathways regarding the criterion using linguistic terms was first established (Table 5). Then, the linguistic terms were transformed into fuzzy numbers according to Table 2 to achieve the corresponding comparison matrix using fuzzy numbers (Table 6). Taking the cell (1, 2) in Table 5 as an example, the element "*W*" can be transformed into "(2/3, 1, 3/2)." The values of the fuzzy synthetic extent of the five pathways with respect to the goal (resource availability) were then calculated according to Eqs. 4–6.

$$S(\text{CG}) = (2.571, 3.067, 3.800) \otimes (1/38.600, 1/32.133, 1/26.810) = (0.0667, 0.0954, 0.1417)$$

$$S(\text{SMR}) = (2.571, 3.067, 3.800) \otimes (1/38.600, 1/32.133, 1/26.810) = (0.0667, 0.0954, 0.1417)$$

$$S(\text{BG}) = (6.333, 8.000, 10.000) \otimes (1/38.600, 1/32.133, 1/26.810) = (0.1641, 0.2490, 0.3730)$$

$$S(\text{PVEL}) = (7.667, 9.000, 10.500) \otimes (1/38.600, 1/32.133, 1/26.810) = (0.1986, 0.2801, 0.3917)$$

$$S(\text{WEL}) = (7.667, 9.000, 10.500) \otimes (1/38.600, 1/32.133, 1/26.810) = (0.1986, 0.2801, 0.3917)$$

The degree of possibility (V values) for $S_i \ge S_j$ was subsequently determined according to Eq. 7 as presented in Table 7.

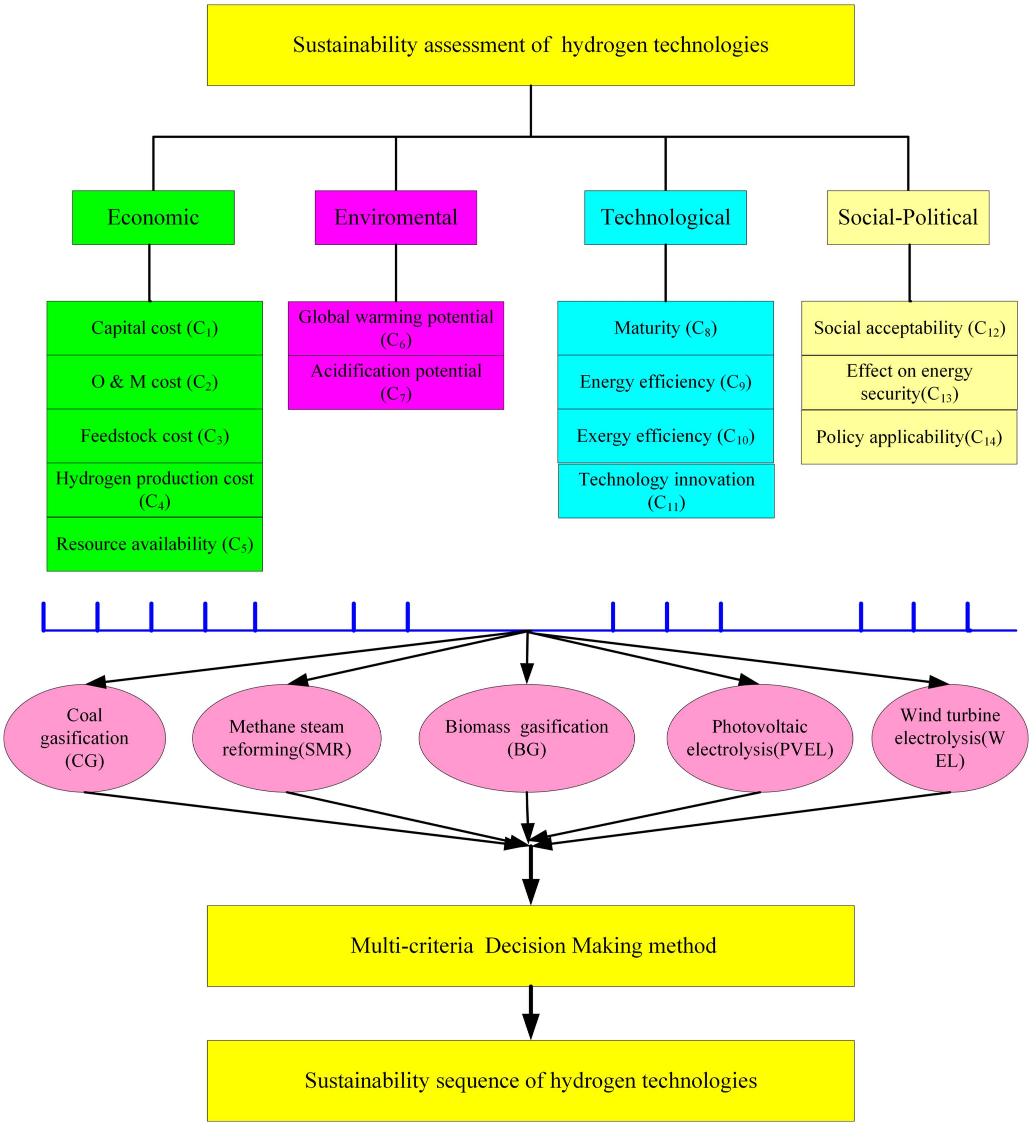


Figure 5. Framework of sustainability assessment of hydrogen production pathways.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Thereafter, the minimum degree of possibility was determined according to Eqs. 8–10

$$d'(A_{CG})=\min V(S_{CG}\geq S_k),\ k=\text{SMR, BG, PVEL, WEL}$$
$$=\min\{1.0000,0,0,0\}$$
$$=0$$
$$d'(A_{SM})=0$$
$$d'(A_{BG})=0.8486$$
$$d'(A_{PVEL})=1.0000$$
$$d'(A_{WEL})=1.0000$$

Afterward, the weight vector is determined according to Eqs. 11 and 12

$$W=(0.0000,0.0000,0.2979,0.3511,0.3511)^T$$

The weight vector indicates that the priorities of the five pathways with respect to the criterion of "resource

Table 4. Values of the Hard Criteria for Each Hydrogen Production Pathway[13,37,85]

	Unit	CG	SMR	BG	PVEL	WEL
C_1	US\$.day^{-1} kg^{-1}	1637.19	284.77	104.82	10,448.56	3170.86
C_2	US\$.day^{-1} kg^{-1}	54.9	14.51	52.56	15.71	15.71
C_3	US\$.day^{-1} kg^{-1}	120.15	154.32	194.88	0	0
C_4	US\$.day^{-1} kg^{-1}	22.37	32.75	23.78	17.36	36.75
C_6	g CO_2 eq. kg^{-1}	17,000	12,000	2992	2000	1200
C_7	g SO_2 eq. kg^{-1}	30.69	14.516	29.03	8.07	2.58
C_9	–	0.35	0.375	0.65	0.05	0.31
C_{10}	–	0.315	0.315	0.60	0.04	0.30

Table 5. Comparison Matrix for the Evaluation of Five Hydrogen Production Pathways with Respect to the Criterion of "Resource Availability" Using Linguistic Terms

Resource Availability	CG	SMR	BG	PVEL	WEL
CG	E	W	RVS	RA	RA
SMR	RW	E	RVS	RA	RA
BG	VS	VS	E	RW	RW
PVEL	A	A	W	E	E
WEL	A	A	W	E	E

Table 6. Comparison Matrix for the Evaluation of Five Hydrogen Production Pathways with Respect to the Criterion of "Resource Availability" Using Fuzzy Numbers

Resource Availability	CG	SMR	BG	PVEL	WEL
CG	(1,1,1)	(2/3,1,3/2)	(1/3,2/5,1/2)	(2/7,1/3,2/5)	(2/7,1/3,2/5)
SMR	(2/3,1,3/2)	(1,1,1)	(1/3,2/5,1/2)	(2/7,1/3,2/5)	(2/7,1/3,2/5)
BG	(2,5/2,3)	(2,5/2,3)	(1,1,1)	(2/3,1,3/2)	(2/3,1,3/2)
PVEL	(5/2,3,7/2)	(5/2,3,7/2)	(2/3,1,3/2)	(1,1,1)	(1,1,1)
WEL	(5/2,3,7/2)	(5/2,3,7/2)	(2/3,1,3/2)	(1,1,1)	(1,1,1)

availability" are 0, 0, 0.2979, 0.3511, and 0.3511, respectively. This results agree well with the fact that both coal and natural gas are fossil resources that are gradually exhausted,[86] while biomass, solar power, and wind power are renewable resources. It is also reasonable that the relative performance of CG and stream reforming of methane in term of resource availability is 0, indicating the nonrenewability of hydrogen production from coal and natural gas. This result demonstrated, to some extent, that the priority sequence of the five pathways determined using the fuzzy AHP method can fairly reflect their performances with respect to the soft criteria. By following the same procedure, the priorities of these five pathways with respect to the other five soft criteria were also determined and presented in Tables 8–12.

Subsequently, the fuzzy ANP method was used to calculate the weights of the criteria in each aspect, whose evaluation network structure was illustrated in Figure 6. In this study, the interactive and interdependent relationships among the criteria are based on a focus group meeting carried out in Chongqing University in China, and a total of seven experts including three processors in Chemical Engineering, two chemical engineers who has abundant experience in cleaner production, and two PhD students whose research focuses on Sustainability Engineering. The relationships among the criteria were presented in Table 13. If the element of cell (i, j) in Table 13 is 1, it means that the jth criterion affects the ith criterion, while 0 means that the jth criterion does not affect the ith criterion. For instance, the elements of cell (8, 1) and cell (11, 1) in Table 13 are equal to 1, indicating that the criteria of C_8 (maturity) and C_{11} (technology innovation) affect C_1 (capital cost). The interactions and interdependencies among the criteria as well as their intensity vary with the preferences of the users and the actual conditions of the studied industrial system as they are incorporated in the developed method.

Afterward, the local priority vectors were obtained by executing the fuzzy pair-wise comparisons and entered in the appropriate column of the supermatrix. Taking the criterion of O&M cost (C_2) in the economic aspect as an example, four criteria (C_8, C_9, C_{10}, and C_{11}) in the technological aspect affect the O&M cost, the pair-wise comparison can be established as showed in Table 14. The local priorities of C_8, C_9, C_{10}, and C_{11} in the first cluster (economic aspect) were obtained to be 0.4437, 0.2973, 0.1846, and 0.0744, respectively, which were entered in the appropriate place of the second column of the unweighted supermatrix (Table 15). Similarly, the other elements in the unweighted supermatrix could also be determined and the corresponding element is equal to 0 if the two criteria do not affect each other.

Meanwhile, it was assumed that the four aspects of the sustainability assessment are interactive and interdependent, the influences of each corresponding cluster on the other clusters with respect to the evaluation criteria were hence determined. Taking the "economic" cluster as an example, by assuming that the four clusters of economic, environmental, technological, and social-political aspects affect the "economic" cluster, the comparison matrix for calculating the weights of the four aspects affecting the economic aspect can be calculated according to the fuzzy AHP method (Table 16). Then, the weights of these four clusters in term of their effect on the "economic" cluster can be determined according to Chang's fuzzy AHP method (also see Table 16).[32] By following a similar procedure, the weights representing the influences of the other clusters on the "environmental," "technological," and "social-political" clusters can also be obtained (Table 17).

If the sum of the elements of any column in the composed supermatrix is greater than 1, the column will be normalized according to the relative weights in the weighted matrix determined by using the ANP method (see Table 18).[31,33] Taking the third column (toward the criterion of "feedstock cost (C_3)" in the economic cluster) in Table 15 as an example, the sum of the elements of the column is greater than 1, and five criteria including one criterion in the "economic" cluster and four criteria in the "technological" cluster affect the criterion. The weight of the "economic" cluster and "technological" cluster on the "economic" cluster is 0.2203 and 0.5121 according to Table 16, thus the relative weights of the two clusters can be determined: $0.2203/(0.2203 + 0.5121) = 0.3008$ and $0.5121/(0.2203 + 0.5121) = 0.6992$. Then, the studied column can be weighted by multiplying the elements and the corresponding relative weights of the cluster to which these elements belong. Thus, cell (5, 3) in Table 5 should multiply by 0.3008, cell (8, 3), cell (10, 3), and cell (11, 3) should multiply by 0.6992. Similarly, all the columns in the unweighted supermatrix can be weighted, and the weighted supermatrix was obtained as showed in Table 18. Subsequently, the limit supermatrix was calculated as showed in Table 19. After the normalization, the weights of the 14 criteria are $W = [0.0196, 0.0122, 0.0065, 0.0163, 0.0310, 0.0436, 0.0401, 0.1045, 0.0667, 0.0564, 0.2511, 0.0432, 0.0505, 0.2583]$.

Table 7. The Degree of Possibility (V Values) for $S_i \geq S_j$

	S_{CG}	S_{SMR}	S_{BG}	S_{PVEL}	S_{WEL}
S_{CG}	–	1.0000	0.0000	0.0000	0.0000
S_{SMR}	1.0000	–	0.0000	0.0000	0.0000
S_{BG}	1.0000	1.0000	–	0.8486	0.8486
S_{PVEL}	1.0000	1.0000	1.0000	–	1.0000
S_{WEL}	1.0000	1.0000	1.0000	1.0000	–

Table 8. Comparison Matrix for the Evaluation of Five Pathways with Respect to the Criterion of "Maturity" Using Fuzzy Numbers

Maturity	CG	SMR	BG	PVEL	WEL	Weights
CG	E	W	M	FS	FS	0.3188
SMR	RW	E	M	FS	FS	0.3188
BG	RM	RM	E	W	W	0.1583
PVEL	RFS	RFS	RW	E	E	0.1021
WEL	RFS	RFS	RW	E	E	0.1021

Table 9. Comparison Matrix for the Evaluation of Five Pathways with Respect to the Criterion of "Technology Innovation" Using Fuzzy Numbers

Technology Innovation	CG	SMR	BG	PVEL	WEL	Weights
CG	E	E	RFS	RVS	RVS	0
SMR	E	E	RFS	RVS	RVS	0
BG	FS	FS	E	RW	RW	0.2952
PVEL	VS	VS	W	E	E	0.3524
WEL	VS	VS	W	E	E	0.3524

Table 11. Comparison Matrix for the Evaluation of Five Pathways with Respect to the Criterion of "Effect on Energy Security" Using Fuzzy Numbers

Energy Security	CG	SMR	BG	PVEL	WEL	Weights
CG	E	E	RFS	RFS	RFS	0
SMR	E	E	RFS	RFS	RFS	0
BG	FS	FS	E	RM	RM	0.2859
PVEL	FS	FS	M	E	E	0.3571
WEL	FS	FS	M	E	E	0.3571

After the decision-making matrix of the five technologies regarding all the 14 criteria was obtained (Table 20), the PROMETHEE method was used to determine the sustainability sequence of the five scenarios by calculating the positive flow, the negative flow, and the net flow according to Eqs. 15–18. The obtained priority sequence in Table 21 shows that the pathway of BG was assessed as the most sustainable technology for hydrogen production, followed by wind turbine electrolysis, PVEL, stream reforming of methane, and CG. This result agrees well with the actual conditions. The pathway of BG has the highest energy efficiency and exergy efficiency, and the second best performance on "policy applicability," which is the most important criterion according to its weight. Meanwhile, it also has a medium performance on the other criteria. Wind turbine electrolysis was regarded as the second best pathways as its corresponding net flow is close to that with respect to BG. On the other side, although the technology of "photovoltaic electrolysis" emerges as an innovative technology for hydrogen production due to its excellent environmental and social performance, its development in large scales is still being dragged by the problems of low energy efficiency, low exergy efficiency, and high capital cost. As for the conventional hydrogen production pathways of stream reforming of methane and CG, the negative values of the net flows clearly demonstrate the low sustainability of the two technologies.

It needs to be clarified that the result of this case study is based on the current status of these technologies, the priority sequence would surely change with the technological development as well as the variation of resource reserves.[87] Moreover, the relative priorities (performances) of the soft criteria determined using the fuzzy AHP method and the weights of the criteria determined using the fuzzy ANP method were only based on the knowledge and preferences of the authors and a limited amount of experts, the users of this methodology can calculate them via a more thorough investigation of the preference/willingness of the decision makers/stakeholder and experts.

To investigate the robustness of the prioritization results, especially the effect of the interactions and interdependencies among the criterion on the final ranking, the sensitivity analysis method presented in aforementioned section was employed to determine the most critical criterion. The results were presented in Tables 22 and 23, in which, the alternative pathways of CG, stream reforming of methane (SMR), BG, PVEL, and wind turbine electrolysis (WEL) were denoted as A_1, A_2, A_3, A_4, and A_5, respectively. Tables 22 and 23 demonstrate the change of the criteria weights for achieving the rank reversal of each pair of alternatives in absolute and percentage values, respectively. According to Definitions 1 and 2, Feedstock cost (C_3) was recognized as both the PT critical criterion and the PA critical criterion. Table 24 presents the CD and the SC of each criterion determined according to Definitions 3 and 4. It is apparent that the 14 criteria can be categorized into three groups according to their relative criticality and sensitivity: most critical and sensitive group, moderately critical and sensitive group, and less critical and sensitive group. The most critical and sensitive group consists of feedstock cost (C_3), acidification potential (C_7), and O&M cost (C_2). The criteria of production cost (C_4), energy efficiency (C_9), and exergy efficiency (C_{10}) belong to the moderately critical and sensitive group. The other criteria belong to the less critical and sensitive group. Consequently, the accurate determination of the weights of feedstock cost (C_3), acidification potential (C_7), and O&M cost (C_2) is crucial for ranking the alternatives correctly and accurately. Thus, the sensitivity analysis of the interactions and interdependencies associated to these three criteria was conducted by changing the corresponding weights in the weighted supermatrix (see Table 18). Moreover, it is worth pointing out that the high criticality and sensitivity does not mean high importance as the importance of the criteria can only be reflected by their weights.

Taking C_3 as an example, it can be affected by four criteria, that is, C_5, C_8, C_{10}, and C_{11}, and the corresponding weights are 0.3008, 0.3143, 0.1449, and 0.2400, respectively (see Table 18). When applying sensitivity analysis, the weight of the investigated criterion is varied while the relative ratio between the weights of the other criteria remains constant. Then, when the sensitivity of ω_{53} that represents the effect of C_5 on C_3 is investigated, we changed ω_{53} from 0 to 1 with a step size of 0.1, while keeping the relative ratio between ω_{83},

Table 10. Comparison Matrix for the Evaluation of Five Pathways with Respect to the Criterion of "Social Acceptability" Using Fuzzy Numbers

Social Acceptability	CG	SMR	BG	PVEL	WEL	Weights
CG	E	W	RFS	RVS	RVS	0
SMR	RW	E	RFS	RFS	RFS	0.0186
BG	FS	FS	E	RM	RM	0.2631
PVEL	VS	FS	M	E	E	0.3591
WEL	VS	FS	M	E	E	0.3591

Table 12. Comparison Matrix for the Evaluation of Five Pathways with Respect to the Criterion of "Policy Applicability" Using Fuzzy Numbers

Policy Applicability	CG	SMR	BG	PVEL	WEL	Weights
CG	E	RM	RFS	RFS	RFS	0.0329
SMR	M	E	RM	RFS	RFS	0.1249
BG	FS	M	E	RW	RW	0.2663
PVEL	FS	FS	W	E	E	0.2880
WEL	FS	FS	W	E	E	0.2880

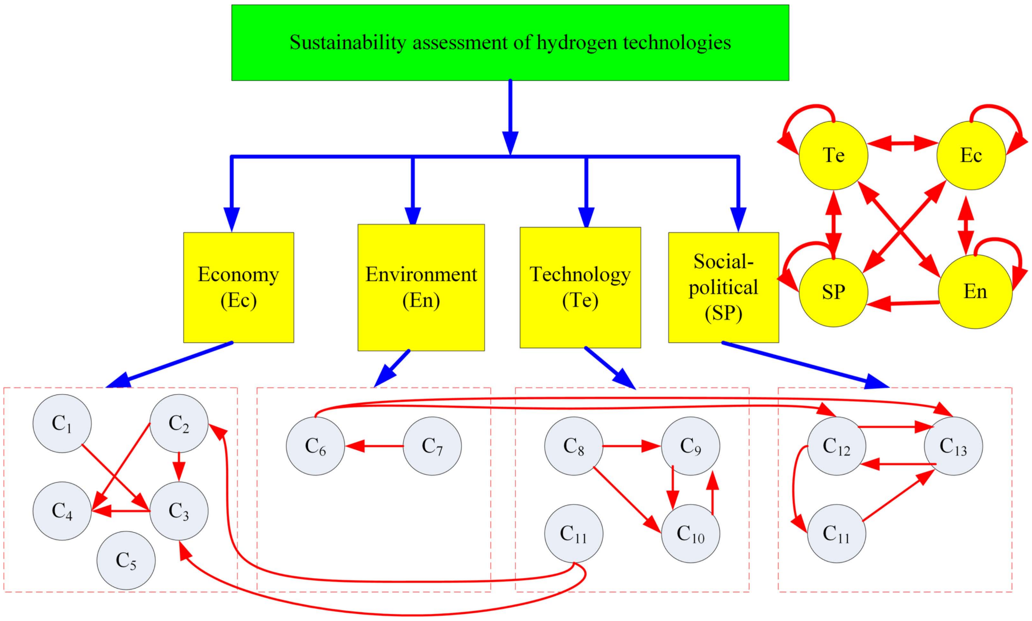


Figure 6. Evaluation network structure of the fuzzy ANP method (parts of the relationships).

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

ω_{103}, and ω_{113} to be constant. When $\omega_{53}=0.1$, we could obtain

$$\omega_{83}=\frac{(1-0.1)\times 0.3143}{(0.3143+0.1449+0.2400)}=0.4046$$

$$\omega_{103}=\frac{(1-0.1)\times 0.1449}{(0.3143+0.1449+0.2400)}=0.1865,$$

$$\omega_{113}=\frac{(1-0.1)\times 0.2400}{(0.3143+0.1449+0.2400)}=0.3089$$

Then, the new weighted supermatrix can be obtained by replacing the corresponding elements in the original weighted supermatrix (Table 18) with the four new weights. The net flows and the ranking of the five alternative pathways was then recalculated by running PROMETHEE with the new weights. Consequently, the net flow of the alternative hydrogen production pathways at different ω_{53} values can be determined as presented in Table 25.

The results of the sensitivity analysis by changing the weights of C_5, C_8, C_{10}, and C_{11} with respect to C_3 on the final ranking of the alternative hydrogen production pathways were summarized in Figure 7 by varying the values of ω_{53}, ω_{83}, $\omega_{10,3}$, and $\omega_{11,3}$ from 0 to 1 with a step size of 0.1, respectively. Figure 7 clearly shows that the net flow of each alternative pathway changes slightly with the variation of the weights of C_5, C_8, C_{10}, and C_{11} with respect to C_3 (Table 18), while the priority sequence keeps invariant. Therefore, the final ranking is not sensitive to the interactions and interdependencies between the other criteria with C_3 although it is the most critical and sensitive criterion in the decision-making. The sensitivity analysis of the weight of C_8, C_9, C_{10}, and C_{11} with respect to C_2 on the final ranking was also employed, and a similar conclusion was drawn according to the results presented in Figure 8.

However, the sensitivity analysis of the weights of C_8, C_9, C_{10}, and C_{11} with respect to C_7 demonstrated a different conclusion. The results of the sensitivity analysis in Figure 9 show that the variation of the weights of C_8 and C_{11} with respect to C_7 can alter the priority order between BG and WEL. Therefore, the final ranking is sensitive to the interactions and interdependencies between the other criteria with C_7. Therefore, it can be concluded that only the interactions and

Table 13. Relationships Among the Criteria

		Ec					En		Te				SP		
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}
Ec	C_1	0	0	0	0	0	0	0	0	0	0	0	1	0	1
	C_2	0	0	0	0	0	0	0	0	0	0	0	1	0	1
	C_3	0	0	0	0	0	0	0	0	0	0	0	1	0	1
	C_4	0	0	0	0	0	0	0	0	0	0	0	1	0	1
	C_5	0	0	1	0	0	0	0	0	0	0	0	1	1	1
En	C_6	0	0	0	0	0	0	0	0	0	0	0	1	1	1
	C_7	0	0	0	0	0	0	0	0	0	0	0	1	1	1
Te	C_8	1	1	1	1	0	1	1	0	1	1	0	1	0	1
	C_9	0	1	0	1	0	1	1	0	0	0	0	1	1	1
	C_{10}	0	1	1	1	0	1	1	0	0	0	0	1	1	1
	C_{11}	1	1	1	1	1	1	1	1	1	1	0	1	0	1
SP	C_{12}	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	C_{13}	0	0	0	0	0	0	0	0	0	0	0	1	0	1
	C_{14}	0	0	0	0	0	0	0	0	0	0	1	1	0	0

Table 14. Comparison Matrix for Calculating the Weights of the Criteria in the Technological Aspect Affecting the Criterion of "O&M Cost"

	C_8	C_9	C_{10}	C_{11}	Weight
Maturity (C_8)	(1,1,1)	(1,3/2,2)	(3/2,2,5/2)	(3/2,2,5/2)	0.4437
Energy efficiency (C_9)	(1/2,2/3,1)	(1,1,1)	(1,3/2,2)	(1,3/2,2)	0.2973
Exergy efficiency (C_{10})	(2/5,1/2,2/3)	(1/2,2/3,1)	(1,1,1)	(1,3/2,2)	0.1846
Technology innovation (C_{11})	(2/5,1/2,2/3))	(1/2,2/3,1)	(1/2,2/3,1)	(1,1,1)	0.0744
λ_{max} =4.0104, CI=0.0035, CR=0.0038 < 0.1					

Table 15. Unweighted Supermatrix

		Ec					En		Te				SP		
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}
Ec	C_1	0	0	0	0	0	0	0	0	0	0	0	0.2934	0	0.2934
	C_2	0	0	0	0	0	0	0	0	0	0	0	0.1831	0	0.1831
	C_3	0	0	0	0	0	0	0	0	0	0	0	0.0976	0	0.0976
	C_4	0	0	0	0	0	0	0	0	0	0	0	0.2429	0	0.2429
	C_5	0	0	1	0	0	0	0	0	0	0	0	0.1831	1	0.1831
En	C_6	0	0	0	0	0	0	0	0	0	0	0	0.6842	0.5	0.5
	C_7	0	0	0	0	0	0	0	0	0	0	0	0.3158	0.5	0.5
Te	C_8	0.6842	0.4437	0.4495	0.3427	0	0.0250	0.0250	0	0.5	0.5	0	0.4388	0	0.1778
	C_9	0	0.2973	0	0.0903	0	0.4505	0.4505	0	0	0	0	0.2109	0.3158	0.2896
	C_{10}	0	0.1846	0.2072	0.2242	0	0.3427	0.3427	0	0	0	0	0.0556	0.6842	0.1532
	C_{11}	0.3158	0.0744	0.3433	0.3427	1	0.1817	0.1817	1	0.5	0.5	0	0.2947	0	0.3794
SP	C_{12}	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5
	C_{13}	0	0	0	0	0	0	0	0	0	0	0	0.50	0	0.5
	C_{14}	0	0	0	0	0	0	0	0	0	0	1	0.50	0	0

Table 16. Comparison Matrix for Calculating the Weights of the Four Aspects Affecting the Economic Aspect

Economic	Ec	En	Te	SP	Weights
Ec	(1,1,1)	(1,3/2,2)	(2/5,1/2,2/3)	(2/3,1,3/2)	0.2203
En	(1/2,2/3,1)	(1,1,1)	(2/5,1/2,2/3)	(2/3,1,3/2)	0.1051
Te	(3/2,2,5/2)	(3/2,2,5/2)	(1,1,1)	(3/2,2,5/2)	0.5121
SP	(2/3,1,3/2)	(2/3,1,3/2)	(2/5,1/2,2/3)	(1,1,1)	0.1625

interdependencies between the other criteria with C_7 have a significant impact on the final ranking.

To verify the advantages of the developed method, including the significance of employing the fuzzy ANP method to determine the weights of the criteria, the advantages of using the fuzzy AHP method to quantify the performances of the alternatives with respect to the soft criteria, and the accuracy of PROMETHEE for decision-making, the following three cases were studied to compare the final ranking of the alternative hydrogen production pathways determined using the developed method with that by using the previous methods.

Case 1: PROMETHEE was used to rank the hydrogen production alternatives based on the obtained decision-making matrix, in which the weights of the criteria for sustainability assessment were determined using the conventional AHP method instead of the fuzzy ANP method and the performance of the alternative pathways with respect to the soft criteria were quantified using the fuzzy AHP method. This case aims to prove the necessity for considering the interactions and interdependencies among the criteria when calculating the weights of the criteria. The weight of the four macroaspects was first determined (Table 26). Similarly, the local weight of the criteria in each of the four aspects was also determined, and the results were presented in Table 27. Then, the global weight of each criterion (Table 27) can be determined by calculating the product of the local weight of the criterion and the weight of the aspect to which the criterion belongs to. For instance, the global weight of "capital cost (C_1)" is the product of its local weight (0.1443) and the weight of the economic aspect (0.4717) as $0.1443 \times 0.4717 = 0.0681$. Figure 10 compared the weights determined by using the fuzzy ANP method with those determined using the conventional AHP method. It is apparent that the weights of the criteria determined using the two methods are different; the conventional AHP method gives high priorities to the criteria of "feedstock cost (C_3)" and "production cost (C_4)," while the fuzzy ANP method gives high priorities to the criteria of "technology innovation (C_{11})" and "policy applicability (C_{14})." The results obtained using the fuzzy ANP method with the consideration of the interactions and interdependencies among the criteria are considered to be more accurate than those determined using the conventional AHP method as "technology innovation (C_{11})" and "policy applicability (C_{14})" can significantly affect some other criteria or be affected by some other criteria, and therefore, both of them play a key role in the complex cause-effect

Table 17. Weight Matrix of the Four Aspects Affecting the Economic Aspect

	Ec	En	Te	SP
Ec	0.2203	0.3251	0.2779	0.2218
En	0.1051	0.0122	0.0296	0.2218
Te	0.5121	0.3847	0.5276	0.2218
SP	0.1625	0.2780	0.1649	0.3347

Table 18. Weighted Supermatrix

		Ec					En		Te				SP		
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}
Ec	C_1	0	0	0	0	0	0	0	0	0	0	0	0.0651	0	0.0651
	C_2	0	0	0	0	0	0	0	0	0	0	0	0.0406	0	0.0406
	C_3	0	0	0	0	0	0	0	0	0	0	0	0.0216	0	0.0216
	C_4	0	0	0	0	0	0	0	0	0	0	0	0.0539	0	0.0539
	C_5	0	0	0.3008	0	0	0	0	0	0	0	0	0.0406	0.3333	0.0406
En	C_6	0	0	0	0	0	0	0	0	0	0	0	0.1518	0.1667	0.1109
	C_7	0	0	0	0	0	0	0	0	0	0	0	0.0700	0.1667	0.1109
Te	C_8	0.6842	0.4437	0.3143	0.3427	0	0.0250	0.0250	0	0.5	0.5	0	0.0973	0	0.0394
	C_9	0	0.2973	0	0.0903	0	0.4505	0.4505	0	0	0	0	0.0468	0.1053	0.0642
	C_{10}	0	0.1846	0.1449	0.2242	0	0.3427	0.3427	0	0	0	0	0.0123	0.2280	0.0340
	C_{11}	0.3158	0.0744	0.2400	0.3427	1	0.1817	0.1817	1	0.5	0.5	0	0.0654	0	0.0842
SP	C_{12}	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1674
	C_{13}	0	0	0	0	0	0	0	0	0	0	0	0.1674	0	0.1674
	C_{14}	0	0	0	0	0	0	0	0	0	0	1	0.1674	0	0

Table 19. Limit Supermatrix

		Ec					En		Te				SP		
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}
Ec	C_1	0.0198	0.0198	0.0198	0.0198	0.0198	0.0198	0.0198	0.0198	0.0198	0.0198	0.0198	0.0198	0.0198	0.0198
	C_2	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123
	C_3	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066	0.0066
	C_4	0.0164	0.0164	0.0164	0.0164	0.0164	0.0164	0.0164	0.0164	0.0164	0.0164	0.0164	0.0164	0.0164	0.0164
	C_5	0.0313	0.0313	0.0313	0.0313	0.0313	0.0313	0.0313	0.0313	0.0313	0.0313	0.0313	0.0313	0.0313	0.0313
En	C_6	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439	0.0439
	C_7	0.0404	0.0404	0.0404	0.0404	0.0404	0.0404	0.0404	0.0404	0.0404	0.0404	0.0404	0.0404	0.0404	0.0404
Te	C_8	0.1053	0.1053	0.1053	0.1053	0.1053	0.1053	0.1053	0.1053	0.1053	0.1053	0.1053	0.1053	0.1053	0.1053
	C_9	0.0672	0.0672	0.0672	0.0672	0.0672	0.0672	0.0672	0.0672	0.0672	0.0672	0.0672	0.0672	0.0672	0.0672
	C_{10}	0.0568	0.0568	0.0568	0.0568	0.0568	0.0568	0.0568	0.0568	0.0568	0.0568	0.0568	0.0568	0.0568	0.0568
	C_{11}	0.2530	0.2530	0.2530	0.2530	0.2530	0.2530	0.2530	0.2530	0.2530	0.2530	0.2530	0.2530	0.2530	0.2530
SP	C_{12}	0.0436	0.0436	0.0436	0.0436	0.0436	0.0436	0.0436	0.0436	0.0436	0.0436	0.0436	0.0436	0.0436	0.0436
	C_{13}	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509	0.0509
	C_{14}	0.2062	0.2062	0.2062	0.2062	0.2062	0.2062	0.2062	0.2062	0.2062	0.2062	0.2062	0.2062	0.2062	0.2062

Table 20. Decision-Making Matrix Based on the Weights of the Criteria Determine Using the Fuzzy ANP Method and the Data with Respect to the Soft Criterion Determined Using the Fuzzy AHP Method

			CG	SMR	BG	PVEL	WEL
Type	Criteria	Weights					
Benefit	C_5	0.0310	0	0	0.2979	0.3511	0.3511
	C_8	0.1045	0.3188	0.3188	0.1583	0.1021	0.1021
	C_9	0.0667	0.35	0.375	0.65	0.05	0.31
	C_{10}	0.0564	0.315	0.315	0.60	0.04	0.30
	C_{11}	0.2511	0	0	0.2952	0.3524	0.3524
	C_{12}	0.0432	0	0.0186	0.2631	0.3591	0.3591
	C_{13}	0.0505	0	0	0.2859	0.3571	0.3571
	C_{14}	0.2583	0.0329	0.1249	0.2663	0.2880	0.2880
Cost	C_1	0.0196	1637.19	284.77	104.82	10448.56	3170.86
	C_2	0.0122	54.9	14.51	52.56	15.71	15.71
	C_3	0.0065	120.15	154.32	194.88	0	0
	C_4	0.0163	22.37	32.75	23.78	17.36	36.75
	C_6	0.0436	17000	12000	2992	2000	1200
	C_7	0.0401	30.69	14.516	29.03	8.07	2.58

relationships among the 14 criteria. On the contrary, the users of the conventional AHP method consider that the criteria of "feedstock cost (C_3)" and "production cost (C_4)" have significant direct effects on people's preferences to the alternative hydrogen production pathways, while the indirect effects due to he interactions and interdependencies among the criteria cannot been incorporated. Therefore, it is natural that higher weights were assigned to the criteria of "feedstock

Table 21. Sustainable Sequence Determined Using the PROMETHEE Method

Scenarios	CG	SMR	BG	PVEL	WEL
Positive flow	0.4024	0.5564	1.5247	1.3639	1.4465
Negative flow	2.1601	1.7411	0.3682	0.6601	0.3645
Net flow	−1.7577	−1.1847	1.1565	0.7039	1.0820
Ranks	5	4	1	3	2

Table 22. Absolute Value Change of the Criteria Weights for Achieving the Pair-Wise Rank Reversal

	A_2-A_1	A_4-A_2	A_4-A_1	A_5-A_4	A_5-A_2	A_5-A_1	A_3-A_5	A_3-A_4	A_3-A_2	A_3-A_1
C_5	N-F	N-F	N-F	N-F	N-F	N-F	−0·2218	−1·3476	N-F	N-F
C_8	N-F	−0·4186	−0·5456	N-F	−0·5024	−0·6294	N-F	N-F	−0·6309	−0.7853
C_9	N-F	−0·5800	−0·7979	N-F	−5·0008	−10·0687	0.0218	N-F	N-F	N-F
C_{10}	N-F	−0·6233	−0·8124	N-F	−25·937	−32·4941	0.0225	N-F	N-F	N-F
C_{11}	N-F	N-F	N-F	N-F	N-F	N-F	−0·1991	−1·2098	N-F	N-F
C_{12}	N-F	N-F	N-F	N-F	N-F	N-F	−0·0846	−0·5142	N-F	N-F
C_{13}	N-F	N-F	N-F	N-F	N-F	N-F	−0·1433	−0·8704	N-F	N-F
C_{14}	N-F	N-F	N-F	N-F	N-F	N-F	−0·372	−2·2597	N-F	N-F
C_1	N-F	−0·3784	−0·5373	N-F	−2·1748	−4·4857	N-F	N-F	N-F	N-F
C_2	N-F	−49·5584	N-F	N-F	−59·480	N-F	−0·0173	−0·1052	−0·5394	N-F
C_3	−0·7716	N-F	N-F	N-F	N-F	N-F	−0·0154	−0·0937	−3·2741	−1·9992
C_4	−0·1741	N-F	N-F	−0·0721	−2·6938	−0·6871	0.0195	−0·3164	N-F	−9·0819
C_6	NF	N-F	N-F	N-F	N-F	N-F	−0·2752	−2·8649	N-F	N-F
C_7	N-F	N-F	N-F	N-F	N-F	N-F	−0·0156	−0·1115	−0·7926	N-F

N-F (nonfeasible) due to the dominating relations between some pairs of alternatives or the dissatisfaction of Eq. 22.

Table 23. Percentage Change of the Criteria Weights for Achieving the Pair-Wise Rank Reversal (%)

	A_2-A_1	A_4-A_2	A_4-A_1	A_5-A_4	A_5-A_2	A_5-A_1	A_3-A_5	A_3-A_4	A_3-A_2	A_3-A_1
C_5	N-F	N-F	N-F	N-F	N-F	N-F	−393.3	−2020.3	N-F	N-F
C_8	N-F	−2135.6	−211.2	N-F	−1162.9	−250.6	N-F	N-F	−603.7	−2533.3
C_9	N-F	−2959	−309	N-F	−11576	−4010	39.0	N-F	N-F	N-F
C_{10}	N-F	−3180	−315	N-F	−60040	−12941	40.0	N-F	N-F	N-F
C_{11}	N-F	N-F	N-F	N-F	N-F	N-F	−353.1	−1813.8	N-F	N-F
C_{12}	N-F	N-F	N-F	N-F	N-F	N-F	−150.1	−770.9	N-F	N-F
C_{13}	N-F	N-F	N-F	N-F	N-F	N-F	−254.0	−1304.9	N-F	N-F
C_{14}	N-F	N-F	N-F	N-F	N-F	N-F	−659.5	−3387.8	N-F	N-F
C_1	N-F	−1930.8	−208.0	N-F	−5034.3	−1786.4	N-F	N-F	N-F	N-F
C_2	N-F	−252850	N-F	N-F	−137690	N-F	−30.0	−160	−520	N-F
C_3	−6324.4	N-F	N-F	N-F	N-F	N-F	−27.3	−140.4	−3133.1	−6448.9
C_4	−1427.0	N-F	N-F	−143.0	−6236	−274	35.0	−474	N-F	−29297
C_6	NF	N-F	N-F	N-F	N-F	N-F	−487.9	−4295.2	N-F	N-F
C_7	N-F	N-F	N-F	N-F	N-F	N-F	−27.7	−167.1	−758.4	N-F

N-F refers to "nonfeasible."

Table 24. The Criticality Degree (CD) and the Sensitivity Coefficient (SC) of Each Criterion

	C_5	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_1	C_2	C_3	C_4	C_6	C_7
CD (%)	393.3	211.2	39	40	353.1	150.1	254.0	659.5	208.0	30.0	27.3	35.0	487.9	27.7
SC	0.2543	0.4735	2.5641	2.5000	0.2832	0.6662	0.3927	0.1516	0.4808	3.3333	3.6630	2.8571	0.2050	3.6101

cost (C_3)" and "production cost (C_4)" by the conventional AHP method.

According to the weights determined by using the conventional AHP method, the final ranking of the alternatives hydrogen production pathways was presented in Table 28, and the result is quite different from that determined by using the developed method in this study. The result is considered to be unreasonable as PVEL was ranked as the most sustainable scenario for hydrogen production, while it still faces many severe problems, for example, low energy efficiency, low exergy efficiency, and high capital cost. Therefore, this case verified the advantage to determine weights of the criteria using the fuzzy ANP method over the conventional AHP method due to the incorporation of the interactions and interdependencies among the criteria in the fuzzy ANP method.

Case 2: PROMETHEE was used to rank the alternatives based on the obtained decision-making matrix, in which, the weights of the criteria for sustainability assessment were determined using the fuzzy ANP method, while only the performance of the alternative pathways with respect to the hard criteria were assessed. This case aims to investigate the advantages of incorporating the soft criteria into the sustainability prioritization. In this case study, the weights of the hard criteria were recalculated according to their relative ratio in Table 20 by ignoring the soft criteria. The obtained sustainability sequence in Table 29 are slightly different from that determined using the proposed method with the consideration of soft criteria, in which, the pathway of stream reforming of methane (SMR) was ranked before PVEL. Moreover, the data

Table 25. Sensitivity Analysis of ω_{53} in the Weighted Supermatrix on the Net Flow of Different Pathways

ω_{53}	CG	SMR	BG	PVEL	WEL
0	−1.7508	−1.1773	1.1540	0.6972	1.0769
0.1	−1.7532	−1.1797	1.1548	0.6994	1.0787
0.2	−1.7555	−1.1821	1.1556	0.7016	1.0805
0.3	−1.7578	−1.1845	1.1564	0.7038	1.0822
0.4	−1.7602	−1.1870	1.1572	0.7060	1.0840
0.5	−1.7625	−1.1894	1.1580	0.7082	1.0857
0.6	−1.7648	−1.1918	1.1587	0.7104	1.0875
0.7	−1.7672	−1.1942	1.1595	0.7126	1.0892
0.8	−1.7695	−1.1967	1.1603	0.7148	1.0910
0.9	−1.7718	−1.1991	1.1611	0.7171	1.0927
1.0	−1.7742	−1.2015	1.1619	0.7193	1.0945

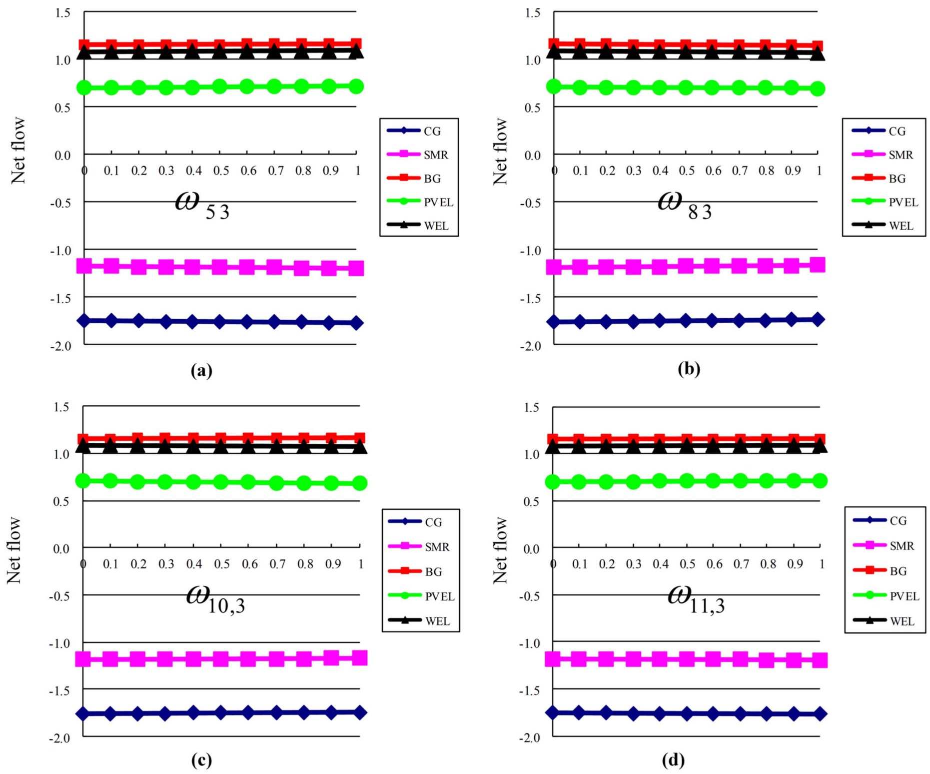


Figure 7. Sensitivity analysis of the weights of C_5, C_8, C_{10}, and C_{11} with respect to C_3 on the final ranking of alternative hydrogen production pathways. (a) Net flow of the alternative pathways under different ω_{53}; (b) net flow of the alternative pathways under different ω_{83}; (c) net flow of the alternative pathways under different $\omega_{10,3}$; (d) net flow of the alternative pathways under different $\omega_{11,3}$.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

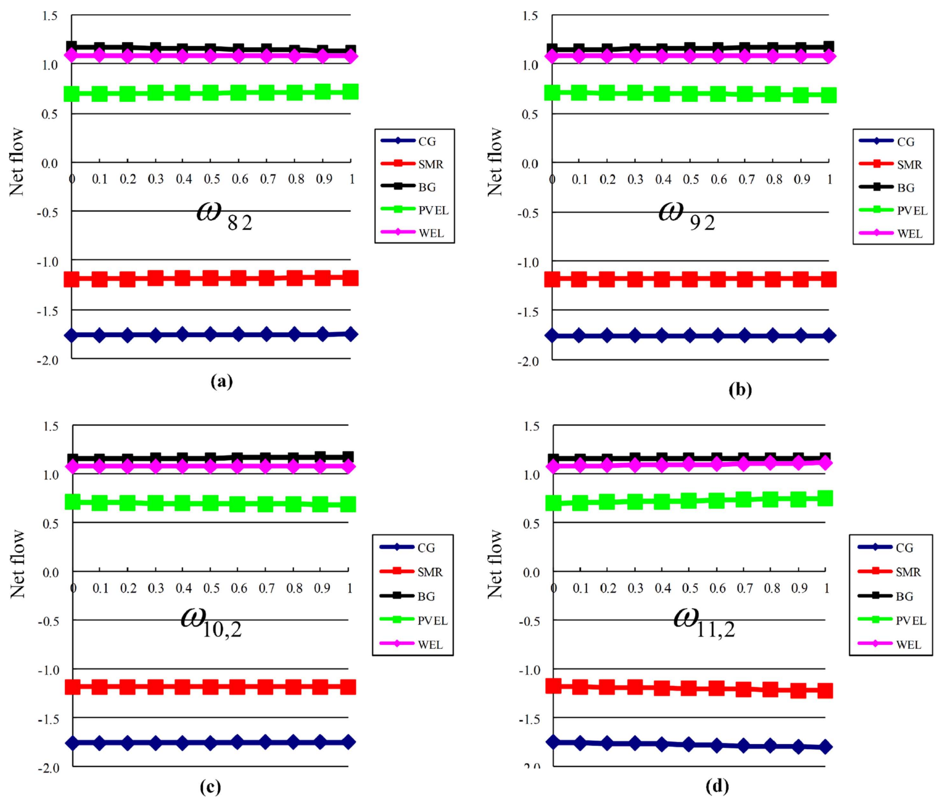


Figure 8. Sensitivity analysis of the weights of C_8, C_9, C_{10}, and C_{11} with respect to C_2 on the final ranking. (a) Net flow of the alternative pathways under different ω_{82}; (b) net flow of the alternative pathways under different ω_{92}; (c) net flow of the alternative pathways under different $\omega_{10,2}$; (d) net flow of the alternative pathways under different $\omega_{11,2}$.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

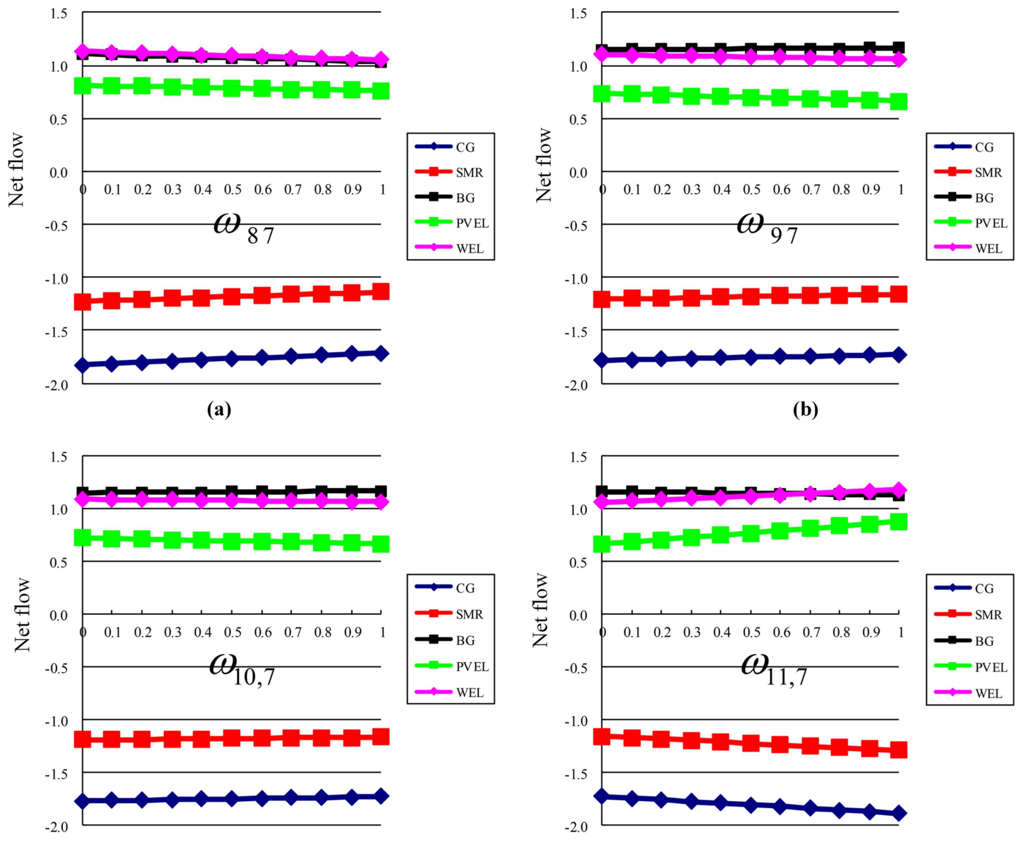


Figure 9. Sensitivity analysis of the weights of C_8, C_9, C_{10}, and C_{11} with respect to C_7 on the final ranking. (a) Net flow of the alternative pathways under different ω_{87}; (b) net flow of the alternative pathways under different ω_{97}; (c) net flow of the alternative pathways under different $\omega_{10,7}$; (d) net flow of the alternative pathways under different $\omega_{11,7}$.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

of the net flow indicate that the sustainability of BG seems much better than that of WEL, which does not conform with the fact that the two technologies are two comparable pathways for the hydrogen production if neglecting the soft criteria.

Case 3: Three different MCDM methods, that is, Sum Weighted Model (SWM), TOPSIS method, and VIKOR method, were used to rank the sustainability sequence of the five alternative hydrogen production pathways based on the decision-making matrix presented in Table 20. This case aims to test the effectiveness of PROMETHEE in the sustainability prioritization of alternative industrial systems.

Table 26. Comparison Matrix for Determining the Weights of the Four Aspects

	EC	EN	TE	SP	Weights
EC	1	3	2	4	0.4717
EN	1/3	1	1/2	2	0.1644
TE	1/2	2	1	2	0.2562
SP	1/4	1/2	1/2	1	0.1078
$\lambda_{max}=4.0458$, CI = 0.0153, CR = 0.0170 < 0.1					

λ_{max} is the maximum eigenvalue of the comparison, CI represents the consistency index, and CR represents the consistency ratio. The CR value is less than 10%, meaning that the comparison matrix is acceptable for consistency check.

Table 27. Weights of the 14 Criteria Determined Using the Conventional AHP Method

Aspect	Weights	Criteria	Local Weights	Global Weights
Economic	0.4717	Capital cost (C_1)	0.1443	0.0681
		O&M cost (C_2)	0.0456	0.0215
		Feedstock cost (C_3)	0.2733	0.1289
		Production cost (C_4)	0.4601	0.2170
		Resource availability (C_5)	0.0767	0.0362
Environmental	0.1644	Global warming potential (C_6)	0.5000	0.0822
		Acidification potential (C_7)	0.5000	0.0822
Technological	0.2562	Maturity (C_8)	0.4236	0.1085
		Energy efficiency (C_9)	0.2270	0.0582
		Exergy efficiency (C_{10})	0.2270	0.0582
		Technology innovation (C_{11})	0.1223	0.0313
Social-political	0.1078	Social acceptability (C_{12})	0.4434	0.0478
		Effect for energy security (C_{13})	0.1692	0.0182
		Policy applicability (C_{14})	0.3874	0.0418

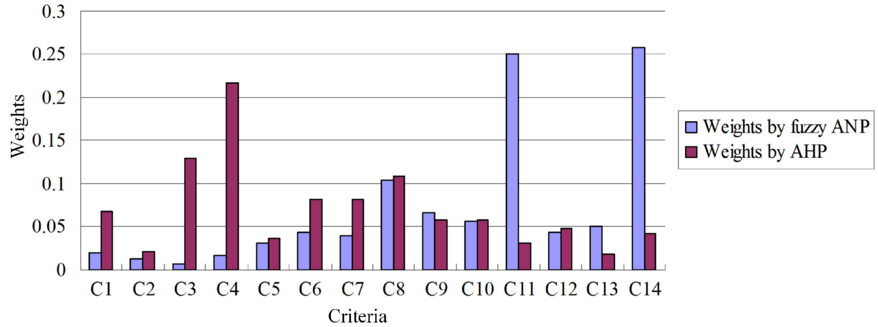


Figure 10. Comparison of the weights determined by the fuzzy ANP method with those by the conventional AHP method.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table 28. Sustainability Sequence of the Five Hydrogen Production Pathways in Case 1

	CG	SMR	BG	PVEL	WEL
Net flow	−0.4874	−0.7407	0.3648	0.6651	0.1982
Ranking	4	5	2	1	3

Table 29. Sustainability Sequence of the Five Hydrogen Production Pathways in Case 2

	CG	SMR	BG	PVEL	WEL
Net flow	−0.2343	−0.0404	0.3584	−0.2309	0.1472
Ranking	5	3	1	4	2

Table 30. Sustainability Sequence of the Five Hydrogen Production Pathways Determined by SWM, TOPSIS, and VIKOR in Case 3

	CG	SMR	BG	PVEL	WEL
Score by SWM	0.2286	0.3763	0.7616	0.7117	0.7799
Ranking	5	4	2	3	1
Score by TOPSIS	0.2776	0.4151	0.7142	0.6629	0.7433
Ranking	5	4	2	3	1
Score by GRA	0.4566	0.5097	0.7494	0.7976	0.8277
Ranking	5	4	3	2	1

The sustainability sequences ranked by the SWM, TOPSIS, and VIKOR methods are same (Table 30), and the only difference with that obtained by the PROMETHEE method is that the priority order between BG and wind turbine electrolysis is reversed. As discussed above, the result determined using the PROMETHEE method conforms better with the actual conditions as it is rational to consider that BG is superior to wind turbine according to the current conditions. Therefore, ROMETHEE is more suitable for the sustainability prioritization of alternative industrial systems than SWM, TOPSISI, and VIKOR.

Conclusion and Discussion

Sustainability assessment and prioritization of various industrial systems is of vital importance for the stakeholders/decision-makers to select the most sustainable scenario. Accordingly, this article proposed a MCDM methodology for sustainability assessment of industrial systems that can consider both hard and soft criteria, as well as the interdependencies and interactions among these criteria. The methodology incorporates a fuzzy AHP method to quantify the soft criteria, which allows the decision-makers to assess the performances of various scenarios with respect to the soft criteria using linguistic terms. A fuzzy ANP method is employed to calculate the weight of each criterion, which can not only reflect the preference and willingness of the stakeholders, but also incorporate the interdependencies and interactions among the criteria. The final priority sequence of various technologies is ranked using the PROMETHEE method according to their net outranking flow. Moreover, a sensitivity analysis method was developed to indentify the most critical and sensitive criteria that have significant effects on the sustainability sequence of alternative industrial systems, and to analyze the effects of the interactions and interdependencies among the criteria on the final priority ranking.

The developed methodology was illustrated by a case study to rank the sustainability of five alternative hydrogen production technologies (CG, stream reforming of methane, BG, PVEL and wind turbine electrolysis). The results demonstrated that the proposed methodology is feasible to find the most sustainable scenario for hydrogen production among various alternatives. The proposed method is object-oriented and has the ability to determine the priority sequence of alternative industrial systems according to the preferences of the decision-makers/stakeholders and the actual conditions. Finally, the advantages of the developed methodology were verified by the other three case studies. The necessity for considering the interactions and interdependencies among the criteria when calculating the criteria weights, the advantages of incorporating the soft criteria into the sustainability assessment, and the effectiveness of PROMETHEE to prioritize the sustainability of alternative industrial systems were proved, respectively.

Acknowledgment

This work is financially supported by the National Science Foundation of China (21176270, 51272296).

Literature Cited

1. Ebenstein A. The consequences of industrialization: evidence from water pollution and digestive cancers in China. *Rev Econ Stat*. 2012;94(1):186–201.
2. Sun Y, Zhuang G, Tang A, Wang Y, An Z. Chemical characteristics of $PM_{2.5}$ and PM_{10} in haze-fog episodes in Beijing. *Environ Sci Technol*. 2006;40(10):3148–3155.
3. Zheng N, Wang Q, Zhang X, Zheng D, Zhang Z, Zhang, S. Population health risk due to dietary intake of heavy metals in the industrial area of Huludao city, China. *Sci Total Environ*. 2007;387(1):96–104.

4. Fang Y, Cote RP, Qin R. Industrial sustainability in China: practice and prospects for eco-industrial development. *J Environ Manage.* 2007;83(3):315–328.
5. Ren J, Gao S, Tan S, Dong L. Prediction of the yield of biohydrogen under scanty data conditions based on GM (1,*N*). *Int J Hydrogen Energy.* 2013;38(30):13198–13203.
6. Simbeck D, Chang E. *Hydrogen Supply: Cost Estimate for Hydrogen Pathways–Scoping Analysis.* Bolden, CO: NREL, 2002.
7. Lee JY, Yoo M, Cha K, Lim TW, Hur T. Life cycle cost analysis to examine the economical feasibility of hydrogen as an alternative fuel. *Int J Hydrogen Energy.* 2009;34(10):4243–4255.
8. Ricci M, Bellaby P, Flynn R. What do we know about public perceptions and acceptance of hydrogen? A critical review and new case study evidence. *Int J Hydrogen Energy.* 2008;33(21):5868–5880.
9. Yetano Roche M, Mourato S, Fischedick M, Pietzner K, Viebahn P. Public attitudes towards and demand for hydrogen and fuel cell vehicles: a review of the evidence and methodological implications. *Energy Policy.* 2010;38(10):5301–5310.
10. Manzardo A, Ren J, Mazzi A, Scipioni A. A grey-based group decision-making methodology for the selection of hydrogen technologies in life cycle sustainability perspective. *Int J Hydrogen Energy.* 2012;37(23):17663–17670.
11. Othman MR, Repke JU, Wozny G, Huang Y. A modular approach to sustainability assessment and decision support in chemical process design. *Ind Eng Chem Res.* 2010;49(17):7870–7881.
12. Afgan NH, Veziroglu A, Carvalho MG. Multi-criteria evaluation of hydrogen system options. *Int J Hydrogen Energy.* 2007;32(15): 3183–3193.
13. Pilavachi PA, Chatzipanagi AI, Spyropoulou AI. Evaluation of hydrogen production methods using the analytic hierarchy process. *Int J Hydrogen Energy.* 2009;34(13):5294–5303.
14. Bozoglan E, Midilli A, Hepbasli A. Sustainable assessment of solar hydrogen production techniques. *Energy.* 2012;46(1):85–93.
15. Tugnoli A, Landucci G, Cozzani V. Sustainability assessment of hydrogen production by steam reforming. *Int J Hydrogen Energy.* 2008;33(16):4345–4357.
16. Khoo HH, Wong LL, Tan J, Isoni V, Sharratt P. Synthesis of 2-methyl tetrahydrofuran from various lignocellulosic feedstocks: sustainability assessment via LCA. *Resour Conserv Recy.* 2015;95:174–182.
17. Hacatoglu K, Dincer I, Rosen MA. Sustainability assessment of a hybrid energy system with hydrogen-based storage. *Int J Hydrogen Energy.* 2015;40(3):1559–1568.
18. Nzila C, Dewulf J, Spanjers H, Tuigong D, Kiriamiti H, Van Langenhove H. Multi criteria sustainability assessment of biogas production in Kenya. *Appl Energy.* 2012;93:496–506.
19. Gangadharan P, Zanwar A, Zheng K, Gossage J, Lou HH. Sustainability assessment of polygeneration processes based on syngas derived from coal and natural gas. *Comput Chem Eng.* 2012;39:105–117.
20. Ren J, Fedele A, Mason M, Manzardo A, Scipioni A. Fuzzy multi-actor multi-criteria decision making for sustainability assessment of biomass-based technologies for hydrogen production. *Int J Hydrogen Energy.* 2013;38(22):9111–9120.
21. Chang PL, Hsu CW, Chang PC. Fuzzy Delphi method for evaluating hydrogen production technologies. *Int J Hydrogen Energy.* 2011; 36(21):14172–14179.
22. Ren J, Gao S, Tan S, Dong L, Scipioni A, Mazzi A. Role prioritization of hydrogen production technologies for promoting hydrogen economy in the current state of China. *Renew Sustain Energy Rev.* 2015;41:1217–1229.
23. Wang JJ, Jing YY, Zhang CF, Zhao JH. Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renew Sustain Energy Rev.* 2009;13:2263–2278.
24. McDowall W, Eames M. Towards a sustainable hydrogen economy: a multi-criteria sustainability appraisal of competing hydrogen futures. *Int J Hydrogen Energy.* 2007;32:4611–4626.
25. Fernandez-Sanchez G, Rodriguez-Lopez F. A methodology to identify sustainability indicators in construction project management-application to infrastructure projects in Spain. *Ecol Indic.* 2010; 10(6):1193–1201.
26. Jayswal A, Li X, Zanwar A, Lou HH, Huang Y. A sustainability root cause analysis methodology and its application. *Comput Chem Eng.* 2011;35(12):2786–2798.
27. Zhou Z, Jiang H, Qian L. Life cycle sustainability assessment of fuels. *Fuel.* 2007;86:256–263.
28. Ding ZJ. *Study on Comprehensive Evaluation of Hydrogen Production Technology from Biomass* (in Chinese). PhD Thesis. China University of Mining and Technology, China, 2009.
29. Mohsen MS, Akash BA. Evaluation of domestic solar water heating system in Jordan using analytic hierarchy process. *Energy Convers Manage.* 1997;38:1815–1822.
30. Spangenberg JH, Fuad-Luke A, Blincoe K. Design for sustainability (DfS): the interface of sustainable production and consumption. *J Clean Prod.* 2010;18:1485–1493.
31. Dagdeviren M, Yuksel I. A fuzzy analytic network process (ANP) model for measurement of the sectoral competition level (SCL). *Expert Syst Appl.* 2010;37:1005–1014.
32. Chang DY. Applications of the extent analysis method on fuzzy AHP. *Eur J Oper Res.* 1996;95:649–655.
33. Saaty TL. *Decision Making with Dependence and Feedback: the Analytic Network Process.* Pittsburgh, PA: RWS Publications, 1996.
34. Brans JP. L'ingénierie de la décision. Elaboration d'instruments d'aide à la décision. Méthode PROMETHEE. In: Nadeau R, Landry M, editors. *L'aide à la décision: Nature, instruments et perspectives d'avenir.* Québec, Canada: Presses de l'Université Laval, 1982:183–214.
35. Brans JP, Vincke PH. A preference ranking organization method: (the PROMETHEE method for multiple criteria decision-making). *Manage Sci.* 1985;31:647–656.
36. Ren J, Manzardo A, Toniolo S, Scipioni A. Sustainability of hydrogen supply chain. Part I: identification of critical criteria and cause–effect analysis for enhancing the sustainability using DEMATEL. *Int J Hydrogen Energy.* 2013;38(33):14159–14171.
37. Acar C, Dincer I. Comparative assessment of hydrogen production methods from renewable and non-renewable sources. *Int J Hydrogen Energy.* 2014;39(1):1–12.
38. Piluso C, Huang J, Liu Z, Huang Y. Sustainability assessment of industrial systems under uncertainty: a fuzzy logic based approach to short-term to midterm predictions. *Ind Eng Chem Res.* 2010;49(18): 8633–8643.
39. Sikdar SK. Sustainable development and sustainability metrics. *AIChE J.* 2003;49(8):1928–1932.
40. Liu Z, Huang Y. Technology evaluation and decision making for sustainability enhancement of industrial systems under uncertainty. *AIChE J.* 2012;58(6):1841–1852.
41. Lou HH, Kulkarni MA, Singh A, Hopper JR. Sustainability assessment of industrial systems. *Ind Eng Chem Eng.* 2004;43(15):4233–4242.
42. Schwarz J, Beloff B, Beaver E. Use sustainability metrics to guide decision-making. *Chem Eng Prog.* 2002;98(7):58–63.
43. Sikdar SK. Sustainability perspective and chemistry-based technologies. *Ind Eng Chem Eng.* 2007;46(14):4727–4733.
44. Ruiz-Mercado GJ, Smith RL, Gonzalez MA. Sustainability indicators for chemical processes: I. Taxonomy. *Ind Eng Chem Res.* 2012; 51(5):2309–2328.
45. Martins AA, Mata TM, Costa CA, Sikdar SK. Framework for sustainability metrics. *Ind Eng Chem Res.* 2007;46(10):2962–2973.
46. Li X, Zanwar A, Jayswal A, Lou HH, Huang Y. Incorporating exergy analysis and inherent safety analysis for sustainability assessment of biofuels. *Ind Eng Chem Res.* 2011;50(5):2981–2993.
47. Sadhukhan J, Ng KS. Economic and European union environmental sustainability criteria assessment of bio-oil-based biofuel systems: refinery integration cases. *Ind Eng Chem Res.* 2011;50(11):6794–6808.
48. Kostevšek A, Klemeš JJ, Varbanov PS, Čuček L, Petek J. Sustainability assessment of the locally integrated energy sectors for a Slovenian municipality. *J Clean Prod.* 2015;88:83–89.
49. Halog A, Manik Y. Advancing integrated systems modelling framework for life cycle sustainability assessment. *Sustainability.* 2011; 3(2):469–499.
50. Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R. ReCiPe 2008: *A Life Cycle Impact Assessment Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level, 1st ed., Version 1.08.* Report I: Characterisation, Netherlands, ReCiPe, 2009. Available at http://www.lcia-recipe.net.
51. Stamford L, Azapagic A. Life cycle sustainability assessment of electricity options for the UK. *Int J Energy Res.* 2012;36(14):1263–1290.
52. You F, Tao L, Graziano DJ, Snyder SW. Optimal design of sustainable cellulosic biofuel supply chains: multiobjective optimization coupled with life cycle assessment and input–output analysis. *AIChE J.* 2012;58(4):1157–1180.
53. Foolmaun RK, Ramjeeawon T. Comparative life cycle assessment and social life cycle assessment of used polyethylene terephthalate (PET) bottles in Mauritius. *Int J Life Cycle Assess.* 2013;18(1),155–171.

54. Lehmann A, Zschieschang E, Traverso M, Finkbeiner M, Schebek L. Social aspects for sustainability assessment of technologies—challenges for social life cycle assessment (SLCA). *Int J Life Cycle Assess.* 2013;18(8):1581–1592.
55. Saaty TL. *The Analytic Hierarchy Process.* New York: McGraw-Hill, 1980.
56. Ren J, Andreasen KP, Sovacool BK. Viability of hydrogen pathways that enhance energy security: a comparison of China and Denmark. *Int J Hydrogen Energy.* 2014;39(28):15320–15329.
57. Ren J, Sovacool BK. Enhancing China's energy security: determining influential factors and effective strategic measures. *Energy Convers Manage.* 2014;88:589–597.
58. Afgan NH, Carvalho MG, Pilavachi PA, Martins N. Evaluation of natural gas supply options for Southeast and Central Europe: part 2. Multi-criteria assessment. *Energy Convers Manage.* 2008;49(8): 2345–2253.
59. Zadeh LA. Fuzzy sets. *Inf Control.* 1965;8:338–353.
60. Amindoust A, Ahmed S, Saghafinia A, Bahreininejad A. Sustainable supplier selection: a ranking model based on fuzzy inference system. *Appl Soft Comput.* 2012;12(6):1668–1677.
61. Mazloumzadeh SM, Shamsi M, Nezamabadi-pour H. Evaluation of general-purpose lifters for the date harvest industry based on a fuzzy inference system. *Comput Electron Agric.* 2008;60(1):60–66.
62. Tseng ML, Lin YH, Chiu AS. Fuzzy AHP-based study of cleaner production implementation in Taiwan PWB manufacturer. *J Clean Prod.* 2009;17(14):1249–1256.
63. Choudhary D, Shankar R. An STEEP-fuzzy AHP-TOPSIS framework for evaluation and selection of thermal power plant location: a case study from India. *Energy.* 2012;42(1):510–521.
64. Heo E, Kim J, Boo KJ. Analysis of the assessment factors for renewable energy dissemination program evaluation using fuzzy AHP. *Renew Sustain Energy Rev.* 2010;14(8):2214–2220.
65. Escobar MT, Moreno-Jimenez JM. A linkage between the analytic hierarchy process and the compromise programming models. *Omega.* 2002;30:359–365.
66. Xu P, Chan EH. ANP model for sustainable building energy efficiency retrofit (BEER) using energy performance contracting (EPC) for hotel buildings in China. *Habitat Int.* 2013;37:104–112.
67. Luo ZM, Zhou JZ, Zheng LP, Mo L, He YY. A TFN-ANP based approach to evaluate Virtual Research Center comprehensive performance. *Expert Syst Appl.* 2010;37:8379–8386.
68. Atmaca E, Basar HB. Evaluation of power plants in Turkey using analytic network process (ANP). *Energy.* 2012;44:555–563.
69. Lee H, Kim C, Cho H, Park Y. An ANP-based technology network for identification of core technologies: a case of telecommunication technologies. *Expert Syst Appl.* 2009;36:894–908.
70. Gharakhlou M, Faraji Sabokbar HA, Givehchi S. Access enhancement by making changes in the route network to facilitate rescue operations in urban disasters. *Int J Environ Res.* 2010;4(2):183–192.
71. Ren J, Manzardo A, Mazzi A, Fedele A, Scipioni A. Emergy analysis and sustainability efficiency analysis of different crop-based biodiesel in life cycle perspective. *Sci World J.* 2013;2013:1–12.
72. Cavallaro F. A comparative assessment of thin-film photovoltaic production processes using the ELECTRE III method. *Energy Policy.* 2010;38(1):463–474.
73. Parreiras RO, Vasconcelos JA. A multiplicative version of Promethee II applied to multiobjective optimization problems. *Eur J Oper Res.* 2007;183(2):729–740.
74. Cavallaro F. Multi-criteria decision aid to assess concentrated solar thermal technologies. *Renew Energy.* 2009;34(7):1678–1685.
75. Zhang K, Kluck C, Achari G. A comparative approach for ranking contaminated sites based on the risk assessment paradigm using fuzzy PROMETHEE. *Environ Manage.* 2009;44(5):952–967.
76. Li WX, Li BY. An extension of the Promethee II method based on generalized fuzzy numbers. *Expert Syst Appl.* 2010;37(7):5314–5319.
77. Goumas M, Lygerou V. An extension of the PROMETHEE method for decision making in fuzzy environment: ranking of alternative energy exploitation projects. *Eur J Oper Res.* 2000;123(3):606–613.
78. De Keyser W, Peeters P. A note on the use of PROMETHEE multicriteria methods. *Eur J Oper Res.* 1996;89(3):457–461.
79. Silva VB, Morais DC, Almeida AT. A multicriteria group decision model to support watershed committees in Brazil. *Water Resour Manage.* 2010;24(14):4075–4091.
80. Chou WC, Lin WT, Lin CY. Application of fuzzy theory and PROMETHEE technique to evaluate suitable ecotechnology method: a case study in Shihmen Reservoir Watershed, Taiwan. *Ecol Eng.* 2007;31(4):269–280.
81. Albadvi A, Chaharsooghi SK, Esfahanipour A. Decision making in stock trading: an application of PROMETHEE. *Eur J Oper Res.* 2007;177(2):673–683.
82. Hajkowicz S, Higgins A. A comparison of multiple criteria analysis techniques for water resource management. *Eur J Oper Res.* 2008; 184(1):255–265.
83. Triantaphyllou E, Sánchez A. A sensitivity analysis approach for some deterministic multi-criteria decision-making methods. *Decis Sci.* 1997;28(1):151–194.
84. Triantaphyllou E, Kovalerchuk B, Mann L, Knapp GM. Determining the most important criteria in maintenance decision making. *J Qual Maint Eng.* 1997;3(1):16–28.
85. Ozbilen A, Dincer I, Rosen MA. A comparative life cycle analysis of hydrogen production via thermochemical water splitting using a Cu–Cl cycle. *Int J Hydrogen Energy.* 2011;36(17):11321–11327.
86. British Pertoleum Company. BP. *Statistical Review of World Energy.* British Pertoleum Company, 2008.
87. Gim B, Kim JW. Multi-criteria evaluation of hydrogen storage systems for automobiles in Korea using the fuzzy analytic hierarchy process. *Int J Hydrogen Energy.* 2014;39(15):7852–7858.

Manuscript received Feb. 3, 2015, and revision received June 18, 2015.