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Selecting sustainable energy conversion technologies for agricultural residues: A fuzzy AHP-VIKOR based prioritization from life cycle perspective

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ABSTRACT

The improper disposal of agriculture residues (ARs) (such as open burning of straw) in China leads to waste of energy potential and atmospheric environmental problems. Converting ARs to energy is of importance for regional energy and environmental sustainability. In order to help decision-makers select optimal technologies among multiple alternatives and promote the development of ARs-to-energy industries, this study conducts integrated assessment and prioritization of seven bioenergy technologies (BETs). A criteria system consisting of four aspects (environmental, technological, economic and social aspects, in total 15 criteria) is constructed. Life cycle environmental and techno-economic assessments are conducted within the boundary ranging from ARs collection and transportation, energy conversion to final use of bioenergy products. Combined with the results of the life cycle assessments and the advices from two groups of experts, the fuzzy Analytic Hierarchy Process (AHP) is adopted to determine the weights of the criteria and quantify the performances of the BETs. Based on the results of the fuzzy AHP, the VIKOR method is finally employed to determine the sustainability sequence of the BETs. From single-dimensional performance, direct-combustion power generation has the best environmental benefit; briquette fuel has the best economic benefit. From performances of integrated-dimensions, direct-combustion power generation, gasification power generation and briquette fuel are recognized as the most sustainable technologies under both the environmental priority situation and economic priority situation. The methods and results presented are expected to provide reference to development planning of ARs as well as other types of bioenergy.

1. Introduction

China is a large agricultural country with abundant agricultural bioresources. It could produce more than 0.7 billion tons of agricultural residues (ARs) every year (Qiu et al., 2014). Most of the ARs are directly burned in fields causing serious environmental issues, such as smog and haze (Sun et al., 2017). In addition, China is the largest energy-consuming country, surpassing even the USA (Yang et al., 2018). It prompts to exploit bioenergy as alternative renewable energy to enhance energy security, reduce Greenhouse Gas (GHG) emissions, increase business opportunities, and accelerate rural economic development, especially in the developing countries (Liu et al., 2018; Wang et al., 2017a). In 2016, the Chinese national energy administration formulated the development goal in the "medium and long-term development plan for bioenergy", where the target of replacing 58 million tons of standard coal (tce) by using bioenergy annually by 2020 was proposed (National Energy Administration, 2016). In this context, converting ARs to energy has become a promising pathway to regional energy and environmental sustainability.

ARs can be converted through numerous bioenergy technologies (BETs) to divergent forms of energy products including heat, power, biofuels or a combination of them (such as converting straw to power, bioethanol, briquette fuel, biogas etc.) (Lo, 2014; Song et al., 2015a). It is usually difficult to select suitable and sustainable energy conversion technologies for ARs (Ren et al., 2014) as different BETs have different performances in terms of economic benefits, environmental impacts, technological concerns and social-political aspects (Sharma et al., 2013). Furthermore, bioenergy systems often have high level of uncertainties that are difficult to quantify because the data available are often vague, incomplete or inconsistent. The stakeholders with potentially conflicting objectives often hold divergence on how to assess and make decisions about the superiority of bioenergy conversion pathways

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Table 1
Summarization of typical literatures.

No.	Author(s) and year	Technique and approach	Application field	Research purpose
1	Luthra et al. (2015)	AHP	Renewable energy technologies selection	Identified and ranked the major barriers in adopting renewable energy technologies
2	Ren et al. (2017)	TOPSIS	Renewable energy technologies selection	Determined the sustainability sequence of technologies for the treatment of urban sewage sludge
3	Buyukozkan and Karabulut (2017)	fuzzy VIKOR	Energy projects selection	Selected concretely defined energy projects
4	Strantzali et al. (2017)	PROMETHEE II	Power generation technologies selection	Determined the best fuel mix for power generation
5	Wu et al. (2016)	ELECTRE-III	Wind power	Selected the site of offshore wind farm
6	Billig and Thraen (2017)	MCDM	Biomethane technologies	Evaluated the technology of biomethane from technical and economic aspects
7	Cremiato et al. (2018)	Life Cycle Assessment	Solid waste management systems	Compared four different solid waste management systems from environmental perspectives
8	Breitschopf et al. (2016)	Costs and benefits assessment	Renewable energy technologies	Made an evaluation of renewable energy technologies from environmental and economic aspects

(An et al., 2018). Accordingly, it is of importance to provide decision-makers with a reliable way to prioritize those BETs by holistically contemplating their comprehensive performances (Sharma et al., 2015).

Determining preferred BETs can be regarded as one of the multi-criterion decision-making (MCDM) problems, which refer to scoring or ranking a finite number of alternatives with the consideration of multiple evaluation criteria (Qureshi et al., 2018). Numerous MCDM methods have been substantially applied in the renewable energy field, including traditional Analytic Hierarchy Process (AHP), technique for order preference by Similarity to Ideal Solution (TOPSIS), Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR), Preference Ranking Organisation METhod for Enrichment Evaluation (PORMETHEE) and ELimination Et Choice Translating REality (ELECTRE). The literatures NO. 1 to 5 in Table 1 are typical studies in the field of renewable energy fields based on MCDM. It has been observed that different MCDM methods may adapt to different problem-solving contexts. Ranking by PROMETHEE gives similar results as ranking “by S” in VIKOR which fails to consider the minimum of the individual regret. Ranking by ELECTRE gives similar results as ranking “by R” in VIKOR which weakens the maximum group utility. The VIKOR method has proven with superiority in solving the complexities and contradictions of the evaluation system (Singh et al., 2016). Both the VIKOR and TOPSIS are the methods to determine the best compromise solution among multiple alternatives. The former provides a maximum “group utility” for the “majority” and a minimum of an individual regret for the “opponent”. The latter determines a solution with the shortest distance to the ideal one and the greatest distance from the negative one, however without incorporating the relative importance of these distances (Opricovic and Tzeng, 2004). The prioritization of multiple BETs is a complex task, as their sustainability, efficiency and economic benefits, as well as diversiform bioenergy products are concerned with various stakeholders with respective focuses. Hence the evaluation system of BETs should be a complex one that includes contradictory criteria like environmental and economic indicators as well as some qualitative ones, such as technology maturity, social acceptability and so on, which are difficult to quantify. The VIKOR method could be an applicable alternative to serve for the evaluation system of BETs.

The evaluation results of VIKOR method depend on the accuracy of the weight given by the experts. Due to the vagueness of human’s feeling and recognition, it is difficult to evaluate the performance of some uncertainty criteria by using exact numerical values (Mahpour, 2018). To solve this problem, fuzzy theory has been proposed, allowing the users to use fuzzy numbers to evaluate the performance of each case under every criteria (Li and Yuan, 2017). There have been some literatures applying integrated fuzzy AHP-VIKOR method to solve complex decision-making problems. Kaya and Kahraman (2010) used fuzzy VIKOR-AHP approach to determine the best renewable energy alternative for Istanbul. Singh et al. (2016) optimized sustainable manufacturing strategies by integrated AHP-VIKOR method under interval-valued fuzzy environment. These studies verified the applicability and advantage of the combination of fuzzy AHP and VIKOR.

As emerging energy technologies, BETs have aroused widespread concern, but the evaluation system is still incomplete. Having reviewed previous studies, on the one hand, we found that few studies evaluated the BETs from the full dimension of technical, economic, environmental and social perspectives. They tend to make evaluation from some of the four perspectives, without demonstrating the advantages and disadvantages of the technologies completely (as the literatures No.6 to 8 in Table 1). On the other hand, we noticed that researchers focused on comparing the BETs with multiple bioresource feedstock and akin bioenergy products. Ren et al. (2014) made an assessment of the energy efficiency of six approaches for bioethanol production by using Data Envelopment Analysis (DEA). Liang et al. (2013) developed a mixed-unit input–output life cycle assessment method to evaluate seven categories of biodiesel feedstock from the economic and environmental performances. They scarcely placed emphasis on the BETs with the same kind of bioresource feedstock (such as ARs) and multiple bioenergy products (such as power, bioethanol, briquette fuel and biogas). With abundant reserve and potential for production of multiple kinds of energy products, ARs have a promising prospect for substituting traditional fossil energy and mitigating GHG emissions. However, no study on the comparison and prioritization of BETs for ARs has ever been conducted.

Considering the deficiency in full dimension of the assessment of utilizing ARs to produce electricity and solid, gaseous and liquid biofuels, this study attempts to use a combined fuzzy AHP -VIKOR method to prioritize seven BETs for ARs from life cycle perspective. The results of the life cycle environmental and techno-economic assessments of the BETs, combined with the advices from two groups of experts with focus on either the environmental or economic benefits of the BETs will be deliberated to determine the weights of the criteria in the fuzzy AHP system. The final sustainability sequence of the BETs in terms of their performance from environmental, technological, economic and social dimensions will be provided using VIKOR.

2. Methods

The framework of the whole assessment process is shown in Fig. 1. The life cycle environmental and techno-economic assessments of the BETs are aimed to quantify the quantitative criteria in the assessment criteria system. The advices from the experts are aimed to help to give the weights of all criteria (including both the quantitative and qualitative ones) by fuzzy AHP, with which VIKOR could provide the final ranking of the BETs.

2.1. Fuzzy AHP

Assuming there are in total n criteria, and the i-th (i = 1, 2, …, n) criterion is denoted by C_i. In this step, a comparative matrix ($n \times n$) is created in which each pair of criteria are compared using linguistic terms. The linguistic ratings given by experts are expressed as Triangular fuzzy numbers (TFNs). The comparison matrix can be established with the linguistic terms and scales presented in the Supplementary data (Table S-1).

The elements the in matrix can be transformed into fuzzy numbers using the scales presented in Table S-1 in the Supplementary data, resulting in the matrix M'. $\tilde{m}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ is a triangular fuzzy number that represents the relative importance of the i-th criterion compared with the j-th criterion, and $\tilde{m}_{ij} = \frac{1}{\tilde{m}_{ji}}$ $i,j = 1, 2, \ldots, n$. The fuzzy synthetic extent of the i-th criterion is denoted by S_i in Eq. (2). The fuzzy numbers are summed in order to obtain $\sum_{j=1}^{n} M_{ij}$ in Eqs. (3) and (4).

$$M' = \begin{array}{cccccc} & C_1 & C_2 & \cdots & C_n \\ C_1 & \tilde{1} & \tilde{m}_{12} & \cdots & \tilde{m}_{1n} \\ C^2 & \tilde{m}_{21} & \tilde{1} & \vdots & \tilde{m}_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_n & \tilde{m}_{n1} & \tilde{m}_{n2} & \cdots & \tilde{1} \end{array} \tag{1}$$

$$S_i = \sum_{j=1}^{n} M_{ij} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{n} M_{ij} \right]^{-1} \tag{2}$$

$$\sum_{j=1}^{n} M_{ij} = (\sum_{j=1}^{n} l_{j,} \sum_{j=1}^{n} m_{j,} \sum_{j=1}^{n} u_j) \quad i = 1, 2, \ldots., n \tag{3}$$

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{n} M_{ij}^{j} \right]^{-1} = (\frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{n} u_{ij}}, \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{n} m_{ij}}, \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{n} l_{ij}}) \tag{4}$$

The possibility matrix V in Eq. (5) is used to depict the relative magnitude between each pair of criteria in terms of the corresponding values of their fuzzy synthetic extent. $\tilde{V}_{ij}$ denotes the degree of $S_i = (l_i, m_i, u_i) \geq S_j = (l_j, m_j, u_j)$, which is equal to the expression in Eq. (6). Note that both $V(S_i \geq S_j)$ and $V(S_j \geq S_i)$ are prerequisites for comparing S_i and S_j.

$$V = \begin{array}{cccccc} & C_1 & C_2 & \cdots & C_n \\ C_1 & / & \tilde{V}_{12} & \cdots & \tilde{V}_{1n} \\ C^2 & \tilde{V}_{21} & / & \vdots & \tilde{V}_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_n & \tilde{V}_{n1} & \tilde{V}_{n2} & \cdots & / \end{array} \tag{5}$$

$$\tilde{V}_{ij} = V(S_i \geq S_j) = \sup_{y>x}(\min\{\mu_{\tilde{A}}(x), \mu_{\tilde{A}}(y)\}) = height(S_i \cap S_j)$$
$$= \begin{cases} 1 if \quad m_i \geq m_j \\ 0 if \quad l_j \geq u_i \\ \frac{l_j - u_i}{(m_i - u_i) - (m_j - l_j)} otherwise \end{cases} \tag{6}$$

The degree of the possibility for the fuzzy synthetic extent, with respect to the i-th criterion greater than all the other criteria is defined as Eq. (7). The weight vector W' given by Eq. (9) is normalized by Eq. (10) and expressed as Eq. (11). W_i is a non-fuzzy number, denoting the weight of the i-th criterion.

$$V(S_i \geq S_1, S_2, \cdots, S_K, \cdots, S_n) = V(S_i \geq S_2) and \cdots$$
$$and V(S_i \geq S_n) = \min V(S_i \geq S_k)$$

$$k = 1, 2, \ldots, \text{n and } k \neq i \tag{7}$$

$$d'(A_1) = \min V(S_i \geq S_k) \; k = 1, 2, \ldots, \text{n and } k \neq i, \tag{8}$$

$$W' = (d'(A_1), d'(A_2), \cdots d'(A_n))^T \tag{9}$$

$$d(C_i) = \frac{d'(C_i)}{\sum_{i=1}^{n} d'(C_i)} \tag{10}$$

$$W = (d(C_1), d(C_2), \cdots, d(C_n))^T = (W_1, W_2, \cdots W_n) \tag{11}$$

2.2. VIKOR method

VIKOR is a multi-criteria optimization method based on the closeness between the evaluation value of each alternative and the ideal solution (Silgado et al., 2017). It includes a set of feasible alternatives $\{A^{(1)}, A^{(2)}, \ldots A^{(m)}\}$ and a set of the predefined assessment criteria $\{C_1, C_2, \ldots C_n\}$. x_{ij} represents the value of alternative $A^{(i)}$ under criterion C_j. w_j denotes the weight of criterion C_j. The number of alternatives and the number of criteria are respectively denoted by m and n.

There are two groups of criteria. For one group, a larger value of the criterion indicates better performance of the alternative. Its best and worst values are calculated by Eq. (12). For the other group, a smaller value indicates better performance of the alternative. Its best and worst values are calculated by Eq. (13).

$$f_j^* = \max_j f_{ij}; \; f_j^- = \min_j f_{ij} \tag{12}$$

$$f_j^* = \min_j f_{ij}; \; f_j^- = \max_j f_{ij} \tag{13}$$

S_i and R_i in Eqs. (14) and (15) represent the maximum group utility ("majority" rule) and the minimum of the individual regret of the "opponent". Q is another parameter used for ranking the alternatives, which is defined as Eq. (16). $S^* = min\ S_i$; $S^- = max\ S_i$; $R^* = min\ R_i$; $R^- = max\ R_i$. v is introduced as the weight of the strategy of the maximum group utility. (1-v) is the weight of the individual regret. The compromise solution can be selected with "voting by majority" ($v > 0.5$), "by consensus" ($v = 0.5$), and "with veto" ($v < 0.5$). In this study v is determined as 0.5. The alternatives are ranked according to the values of S, R and Q in an ascending order. Then three ranking lists can be obtained.

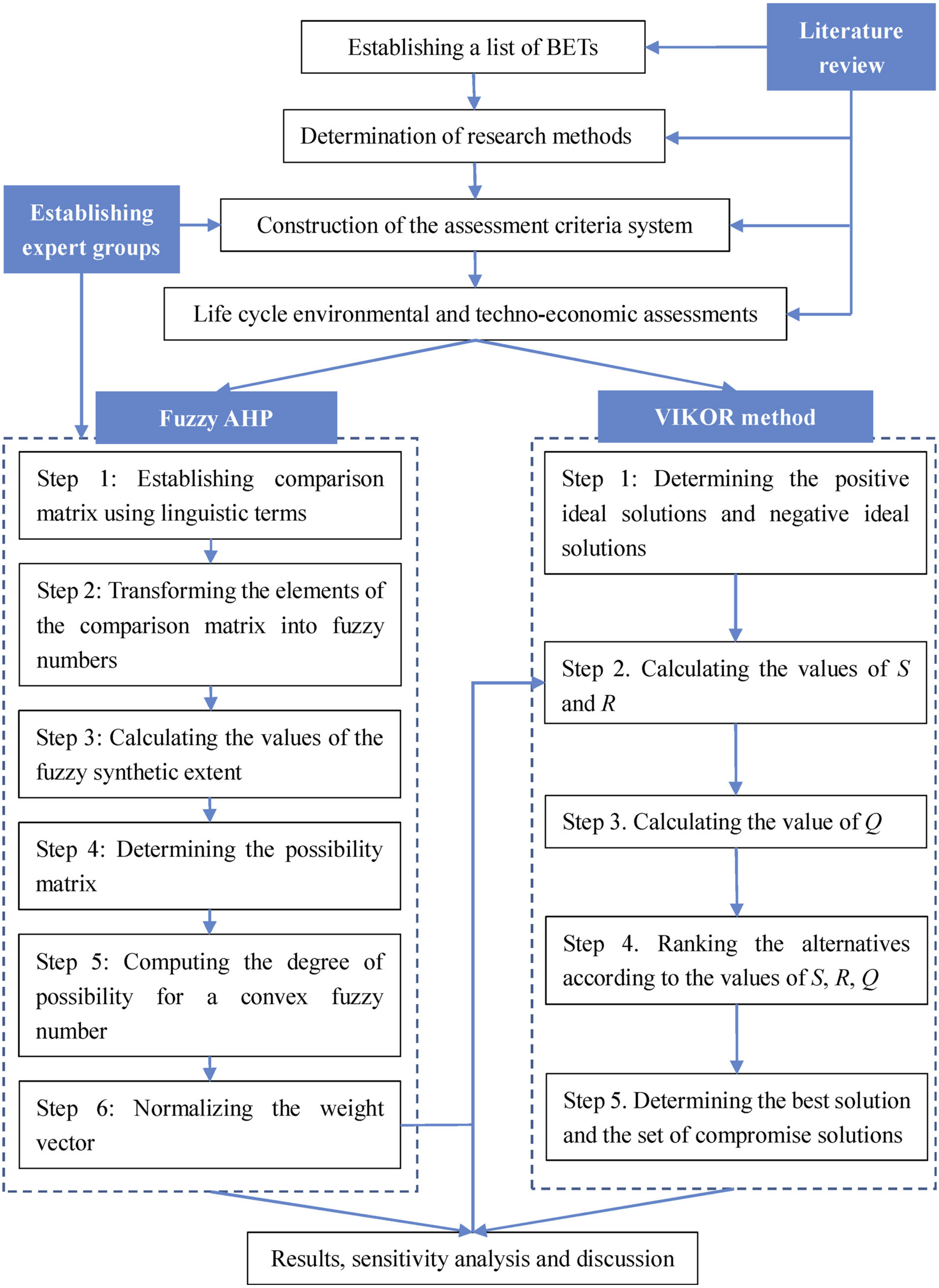

Fig. 1. The framework of the MCDM method based on Fuzzy AHP and VIKOR method.

$$S_i = \sum_{j=1}^{n} w_j (f_j^* - f_{ij})/(f_j^* - f_j^-) \tag{14}$$

$$R_i = \max_j [w_j (f_j^* - f_{ij})/(f_j^* - f_j^-)] \tag{15}$$

$$Q_i = v(S_i - S^*)/(S^- - S^*) + (1 - v)(R_i - R^*)/(R^- - R^*) \tag{16}$$

The alternative with the smallest Q is nominated as the best alternative if the following conditions are satisfied.

Condition 1. "Acceptable advantage":

$$Q\ (A^{(2)}) - Q\ (A^{(1)}) \geq 1/(m - 1) \tag{17}$$

where alternative $A^{(1)}$ and $A^{(2)}$ denote the top two alternatives according to Q.

Condition 2. "Acceptable stability in decision-making": Alternative $A^{(1)}$ must correspond to the best ranked S or R.

If the above two conditions are satisfied, then alternative $A^{(1)}$ is the best alternative. If the two conditions are not satisfied at the same time, a set of compromise solutions are proposed as follows:

(1) Alternatives $A^{(1)}$ and $A^{(2)}$: if only condition 1 is satisfied, both alternatives $A^{(1)}$ and $A^{(2)}$ are proposed as the best solutions;
(2) Alternatives $A^{(1)}, A^{(2)},\ldots, A^{(m)}$: if condition 1 is not satisfied, a set of alternatives $A^{(1)}, A^{(2)},\ldots, A^{(m)}$ is proposed as the best choices; $A^{(m)}$ is determined by the relation $A^{(m)}- A^{(1)} \leq 1/(m\text{-}1)$ for the maximum m (the positions of these alternatives are 'in closeness').

2.3. Life cycle environmental and techno-economic assessments of the BETs

2.3.1. Functional unit and system boundary

In this study, seven most commonly adopted BETs for converting ARs into energy products are considered, including direct-combustion power generation (A1), gasification power generation (A2), briquette fuel (A3), hydrogen (A4), bioethanol (A5), biogas (A6) and syngas (A7) (Wang et al., 2009). Fig. 2 depicts the system boundary of seven BETs for the life cycle environmental and techno-economic assessments. The functional unit is a reference to normalize the input and output data, providing a quantified comparison standard for the BETs. The functional unit in this study is determined as 10^6 tons of standard coal (tce). All comparisons of pollutant emissions, costs, job creation etc. are based on this functional unit. The system boundary of each BET is comprised of the processes of collection of ARs, road transportation, bioenergy conversion and bioenergy utilization. Due to inaccessibility of relevant data on the construction process of bioenergy projects and transportation process of bioenergy products to consumers, these two processes are excluded out of the system boundary (Xu et al., 2016).

Table 2
Assessment criteria of the BETs (Ren and Lutzen, 2015).

Criteria	Sub-criteria	Nomenclature	Index attribute
Environmental criteria	GHG mitigation	C1	Quantitative
	SO_2 mitigation	C2	Quantitative
	NO_x mitigation	C3	Quantitative
	COD discharge	C4	Quantitative
Technological criteria	Energy efficiency [a]	C5	Quantitative
	Energy grade [b]	C6	Qualitative
	Technology maturity [c]	C7	Qualitative
	Development potential [d]	C8	Qualitative
Economic criteria	Return on investment [e]	C9	Quantitative
	Net present value [f]	C10	Quantitative
	Payback period [g]	C11	Quantitative
	Unit cost [h]	C12	Quantitative
Social criteria	Policy adaptability [i]	C13	Qualitative
	Social acceptability [j]	C14	Qualitative
	Job creation [k]	C15	Quantitative

[a] The ratio of energy outputs (total bioenergy products produced) and energy inputs (calorific value of ARs and fossil energy use) of a BET.

[b] The percentage of useful ingredients contained in energy sources. The higher the percentage of the useful ingredients, the higher the grade is.

[c] An indicator of how a technology is widespread at national and international levels, reflecting whether there is still space for the improvement of the technology.

[d] The development potential for a BET with regard to the preference of the use of its energy product.

[e] The percentage of annual net profit in total capital investment.

[f] The whole current value of cash flow within a time period.

[g] The time it takes for a project to make its accumulative profit equivalent to the initial investment.

[h] The cost for producing unit energy product, calculated by total cost (consisting of fixed cost and variable cost) and total amount of energy product of a BET.

[i] The adaptedness of a BET to the national policies (whether a country encourages the development of a certain kind of BET).

[j] The acceptance of pertinent people to a BET/bioenergy project.

[k] The employment chances created by a bioenergy project (which calls for labor to maintain its operation).

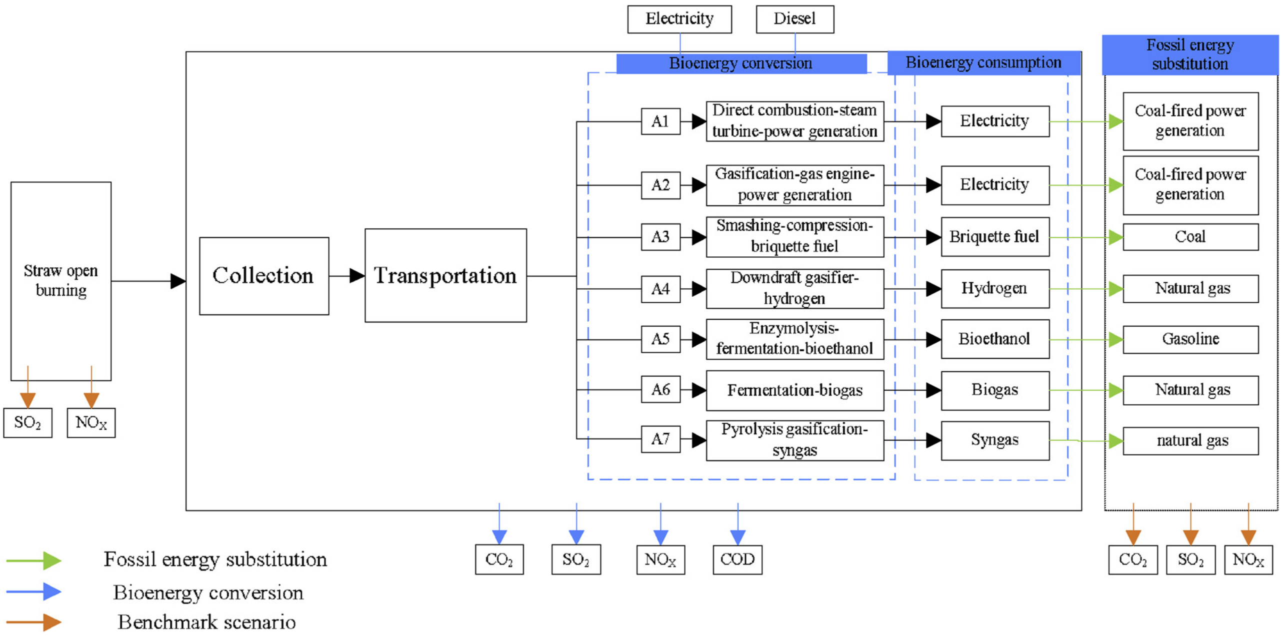

Fig. 2. System boundary of seven BETs.

2.3.2. Assessment criteria system

Four groups of criteria are set to make assessments of the performances of the BETs from environmental, technological, economic and social perspectives. The details of the sub-criteria of each group of criteria are presented in Table 2.

2.3.3. Life cycle environmental assessment

(1) Benchmark scenario

In the benchmark scenario, it is set that if the ARs are not utilized for bioenergy production through the BETs, they would be originally open-burned, resulting in GHG and air pollutant emissions.

$$Q_{pi}^{B} = M_i \times \varphi_P \tag{18}$$

where Q_{pi}^{B} is the emission amount of the p-th pollutant in the benchmark scenario corresponding to the i-th BET; M_i is the ARs utilization amount of the i-th BET (t/a); φ_p is the emission factor of the p-th pollutant.

(2) Pollutant emissions from ARs transportation

Considering scattered distribution of ARs, a resource-island distribution pattern for ARs is assumed. Several resource-islands are evenly distributed around one bioenergy project, forming a circular collection range. Different types of ARs are evenly distributed within one resource island with no differences in collection and transportation processes. The collected ARs are first transported to the center of the resource islands for processing and storage, and then transported to the bioenergy project (Song et al., 2017; Wang et al., 2018).

$$S_i = \frac{M_i}{d} = \frac{M_i}{Y \times \beta \times \eta \times \lambda} \tag{19}$$

$$R_i = \sqrt{\frac{S_i}{\pi}} \tag{20}$$

$$n_i = \frac{M_i}{\pi R_k^2 d} \tag{21}$$

$$D_{i1} = n_i \times \int_0^{R_k} 2\pi d c \gamma r_k^2 dr_k = \frac{2}{3}\pi n_i d c \gamma R_k^3 \tag{22}$$

$$D_{i2} = M_i \times \varsigma \tag{23}$$

$$D_{i3} = c n_i \pi R_k^2 d l_i \gamma \tag{24}$$

$$Q_{pi}^{T} = (D_{i1} + D_{i2} + D_{i3})\kappa \tag{25}$$

where S_i is the area of the collection range (km^2); d is the ARs density of a certain region (t/km^2); Y is the grain yield per unit area (kg/km^2); β is the AR-grain ratio; η is the collection coefficient (%); λ is the energy utilization proportion of all ARs collected (%); R_i is the collection radius of the i-th bioenergy project (km); n_i is the number of resource islands for the i-th bioenergy project; R_k is the radius of the k-th island (km); D_{i1} is the consumption amount of diesel for transporting the ARs demanded by the i-th bioenergy project within the k-th resource island (L); c is the diesel consumption coefficient for transporting unit AR for unit distance (L/t·km); γ is the tortuosity factor of the roads; D_{i2} is the consumption amount of diesel for preprocessing the ARs demanded by the i-th bioenergy project; ζ is the diesel consumption coefficient for processing unit AR (L/t); D_{i3} is the consumption amount of diesel for transporting the ARs demanded by the i-th bioenergy project from the storage station (the center of each resource island) to the bioenergy project (L); l_i is the distance between the storage station and the i-th bioenergy project (km); Q_{pi}^{T} is the emission amount of the p-th pollutant for transporting the ARs demanded by the i-th bioenergy project (t); κ is the emission factor of the p-th pollutant of diesel (kg/L).

(3) Pollutant emissions from bioenergy project operation

During energy conversion process, a bioenergy project has to consume fossil fuels or thermal power to maintain its operation. This leads to GHG and pollutant emissions.

$$Q_{pi}^{O} = N_i^{C} \times f_p \tag{26}$$

where $Q_{pi}^{O}$is the emission amount of the p-th pollutant during operational process of the i-th bioenergy project; N_i^{C} is the consumption amount of fossil fuels or thermal power during operational process; f_p is the emission factor of the p-th pollutant (corresponding to the fossil fuels and thermal power).

(4) Pollutant mitigation of fossil energy substitution

The bioenergy products of the BETs could substitute fossil fuels (the details of the substitutional relationships are presented in Fig. 2) and thus contribute to emission reduction.

$$Q_{pi}^{S} = N_i^{S} \times f_p \tag{27}$$

where Q_{pi}^{S} is the amount of emission reduction of the p-th pollutant due to substitution of fossil fuels with bioenergy product of the i-th BET; N_i^{S} is the amount of fossil fuels substituted by bioenergy product.

(5) Pollutant emission from bioenergy utilization

There are pollutant emissions when consuming bioenergy products.

$$Q_{pi}^{U} = B_i \times \delta_p \tag{28}$$

where Q_{pi}^{U} is the emission amount of the p-th pollutant due to consumption of the bioenergy product of the i-th BET; B_i is the amount of bioenergy product; δ_p is the emission factor of the p-th pollutant (corresponding to the bioenergy products).

(6) Pollutant mitigation within the whole life cycle

The total mitigation amount of the p-th pollutant of the i-th BET Q_{pi} is calculated by the above five variables: (1) pollutant emissions due to open-burning of ARs (Q_{pi}^{B}); (2) pollutant emissions due to transportation of ARs (Q_{pi}^{T}); (3) reduced emissions due to substitution of fossil fuels (Q_{pi}^{S}); (4) pollutant emissions during bioenergy production process (Q_{pi}^{O}); (5) pollutant emissions due to consumption of bioenergy products (Q_{pi}^{U}):

$$Q_{pi} = Q_{pi}^{B} - Q_{pi}^{T} + Q_{pi}^{S} - Q_{pi}^{O} - Q_{pi}^{U} \tag{29}$$

Table 3 concludes the variables and corresponding pollutants. Particularly, considering the "carbon neutral" feature of biomass, GHG emissions in the benchmark scenario and caused by bioenergy consumption are not included. The discharge of COD is only considered in project operation process.

2.3.4. Life cycle techno-economic assessment

The details of the techno-economic parameters are provided in Table 4. Within the system boundary, the life cycle cost of a bioenergy project consists of the fixed costs (initial investment for properties and equipment) and variable costs (including feedstock procurement, materials, auxiliary energy, labor, maintenance, depreciation and tax). The feedstock procurement cost is comprised of the purchase cost, process cost, transportation cost and storage cost of the ARs. The gross revenue is calculated by total production amount and unit price of the energy product of the project (Wang et al., 2018). The quantification of the quantitative technological, economic and social criteria (C5, C9, C10, C11, C12, C15) is according to the descriptions (a, e, f, g, h, k) in Table 2 combined with the parameters in Table 4.

Table 3
Variables of pollutant emission/mitigation.

	GHG	SO_2	NO_x	COD
Q_{pi}^{B}	×	√	√	×
Q_{pi}^{T}	√	√	√	×
Q_{pi}^{S}	√	√	√	×
Q_{pi}^{O}	√	√	√	√
Q_{pi}^{U}	×	√	√	×
Q_{pi}	C1	C2	C3	C4

Table 4
Techno-economic parameters of the BETs (Hong et al., 2016; Wang et al., 2018; Song et al., 2015b; Wang et al., 2017b; Garcia et al., 2017; Jiang et al., 2012; Song and Qiu, 2016).

	A1	A2	A3	A4	A5	A6	A7
Scale	25MW	2MW	20,000 t	133 t	50000 t	210,000 m^3	480,000 m^3
Energy product	Electricity	Electricity	Briquet	Hydrogen	Bioethanol	Biogas	Syngas
AR demand (dry t/a)	210,000	16,200	20,619	1,934	300,000	856	243
Depreciation life (year)	20	20	10	15	15	20	15
Job creation (man)	120	43	33	9	685	3	2
Initial investment (10^3 CNY)	230000	10000	11200	37800	481140	2800	1200
Variable costs (10^3 CNY/a)							
Procurement	57,430	3,848	5,124	887	97,105	171	49
Materials	7,120	192	500	2,164	40,500	30	30
Auxiliary energy	1,780	48	816	689	66,600	12	12
Labor	2,880	1,032	792	216	7,200	72	24
Maintenance	3,720	200	224	996	59,700	26	24
Depreciation	11,500	500	560	2,056	42,076	140	30
Tax	11,355	765	1,200	1,197	36,367	0	0
Gross revenue (10^3 CNY/a)	113,552	7,650	12,000	11,970	363,674	315	170
Net profit (10^3 CNY/a)	17,766	1,065	2,784	3,765	14,126	64	2
Unit price of energy product	0.75 CNY/KWh	0.75 CNY/KWh	600 CNY/t	90000 CNY/t	7273 CNY/t	0.6 CNY/m^3	0.35 CNY/m^3

3. Results

3.1. Results of the life cycle environmental and techno-economic assessments

Considering that the amount of corn straw accounts for more than 75% of the total amount of straw in China, we use corn straw to represent all types of straw when determining relevant parameters of straw (Song et al., 2018). The data regarding the environmental and techno-economic parameters are obtained from published articles and industrial reports of typical demonstration bioenergy projects and processed by the authors.

The four environmental criteria for seven BETs are quantified and the results are illustrated in Fig. 3. Syngas (A7) has the best GHG mitigation benefit, followed by briquette fuel (A3), direct-combustion power generation (A1), and gasification power generation (A2). In terms of SO_2 mitigation, direct-combustion power generation (A1) and gasification power generation (A2) have obvious advantages. Hydrogen (A4) cannot reflect SO_2 mitigation benefit. Similar to the performance under the criterion of SO_2 mitigation, direct-combustion power generation (A1) and gasification power generation (A2) have obvious NO_x mitigation benefit. In addition, COD discharge should be considered for gasification power generation (A2), hydrogen (A4), bioethanol (A5), and syngas (A7) as consequential environmental impacts.

The results of the quantitative technological, economic and social criteria are presented in Table 5. Briquette fuel (A3) has the best economic benefit with regard to all economic criteria. As for hydrogen (A4), biogas (A6), syngas (A7), the net present value are negative and the payback period is more than the depreciation life. Therefore, these technologies are disadvantageous in terms of economic performance.

3.2. Weight calculation by fuzzy AHP

In order to identify the weights accurately, two groups of experts have been invited to participate in the decision-making, with one group consisting of scholars paying more attention to environmental benefits (DM#1), the other consisting of engineers who focus on the economic benefits (DM#2). Their role is to examine the reasonability of criteria and determine the relative importance of each criteria. When the reasonability of the criteria is approved, the experts are asked to adopt linguistic terms provided in Table S-1 in the Supplementary data to compare each pair of criteria based on their own experience and the provided information. Table S-2 and S-3 give the integrated results of the pairwise comparisons of the four main criteria made by two groups of experts. Then in the following fuzzy AHP steps, the weights of the main criteria are obtained using the data presented in Table S-4 and S-5. The same procedures are repeated for determining the weights of the sub-criteria and relative performances of the five qualitative criteria (C6, C7, C8, C13, C14). The pairwise comparison results are provided in Table S-6 to S-10. The global weights are obtained by the value of the main weights multiplied by the value of corresponding sub-weights as in Table 6.

3.3. Prioritization of the BETs with VIKOR

After determining the global weights and the performance under qualitative criteria, the data of the seven BETs with respect to each criterion can be obtained. Table S-11 in the Supplementary data presents the normalized data of the BETs. The two values of S_i and R_i which are the maximum group utility and the minimum of the individual regret respectively are computed using Eqs. (14) and (15). As well, the value of Q_i with $v = 0.5$, is computed using Eq. (16). Table S-12 and S-13 show the values of S_i, R_i and Q_i. According to S, R and Q, the BETs are ranked in an increasing order. Then the compromise solution can be determined by checking if either/both of the two conditions in the VIKOR method could be met. The associated rankings are provided in Table 7. Under environmental priority situation, the ranking result is A1, A2, A3, A5 ≻ A4, A6, A7. Under economic priority situation, the ranking result is A1, A2, A3 ≻ A5, A7 ≻ A6 ≻ A4.

3.4. Sensitivity analysis

In this section, a sensitivity analysis by varying the values of the main weights is performed. Five different weighting scenarios are considered and the sensitivity of the BETs' ranking to each criteria is analyzed. The settings of the values of the weights are presented in Table S-14 in the Supplementary data. The first scenario is set with equal preference weights to all criteria. The rest scenarios are set emphasizing the impact of a certain group of criteria with an assumption that the sub-criteria have the same importance degree. The prioritizations of the BETs obtained from the sensitivity analysis with respect to these scenarios are presented in Table S-15.

According to the results of the sensitivity analysis, direct-combustion power generation (A1), gasification power generation (A2) and briquette fuel (A3) are recognized as the most sustainable technologies. Hydrogen (A4) and biogas (A6) are identified as the most negative ones. The results are in accordance with those determined with reference of the two groups of experts. Both the rationality of the weights provided

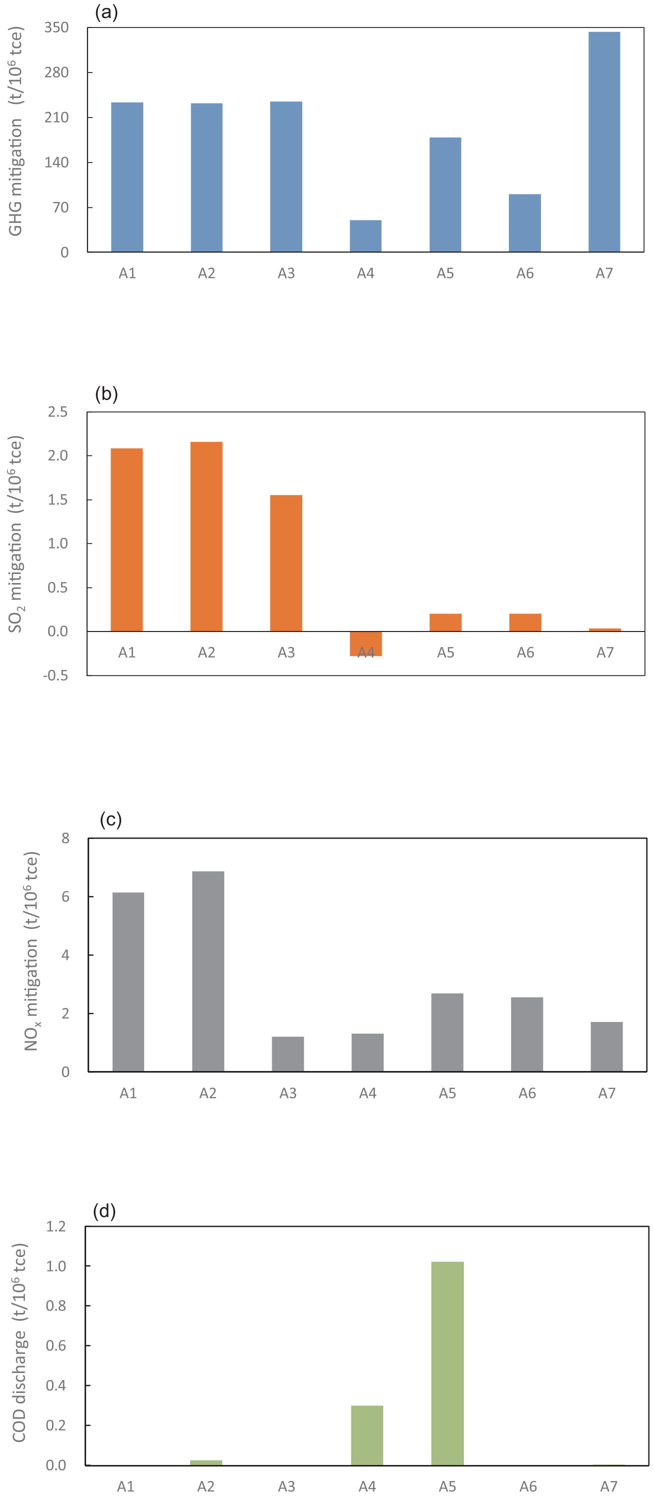

Fig. 3. The results of seven BETs under environmental criteria.

Table 6
Weights of the criteria determined by using fuzzy AHP.

Criteria	DM#1	DM#2	Sub-criteria	DM#1	DM#2
Environment criteria	0.444	0.327	C1	0.185	0.137
			C2	0.086	0.063
			C3	0.086	0.063
			C4	0.087	0.064
Technological criteria	0.117	0.125	C5	0.045	0.047
			C6	0.043	0.046
			C7	0.017	0.019
			C8	0.012	0.013
Economic criteria	0.329	0.444	C9	0.073	0.098
			C10	0.083	0.112
			C11	0.081	0.110
			C12	0.092	0.124
Social criteria	0.109	0.102	C13	0.071	0.069
			C14	0.022	0.020
			C15	0.016	0.013

Table 7
Associated ranking under environmental priority situation (a) and economic priority situation (b).

(a)	A1	A2	A3	A4	A5	A6	A7
S_i	3	2	1	7	4	6	5
R_i	3	4	2	7	1	6	5
Q_i	2	3	1	7	4	6	5
Ranking	1	1	1	2	1	2	2
(b)	A1	A2	A3	A4	A5	A6	A7
S_i	2	1	3	7	5	6	4
R_i	2	3	1	7	5	6	4
Q_i	3	2	1	7	5	6	4
Ranking	1	1	1	4	2	3	2

in Section 3.2 and the reliability of the conclusion in Section 3.3 are verified and approved. To be detailed, briquette fuel (A3) is generally ranked as top two, but determined as the third alternative under Scenario II. It could be inferred that briquette fuel (A3) does not have good environmental benefit compared with direct-combustion power generation (A1) and gasification power generation (A2). While bioethanol (A5) performs well under the last three scenarios, it has poor performance under Scenario II, which indicates its sensitivity to environmental criteria.

4. Discussion

It could be noted from the ultimate prioritization of the BETs that the results under environmental priority situation (referred to scholars' suggestions) and under economic priority situation (referred to the engineers' suggestions) are consistent mutually overall. Direct-combustion power generation (A1), gasification power generation (A2), briquette fuel (A3) are recognized as the most sustainable technologies. These three technologies, as relatively mature technologies, have been developing for years, with better performances on the mitigation of GHG, SO_2, NO_x emissions and economic benefits. The implementation

Table 5
The results of seven BETs under quantitative technological, economic and social criteria.

	A1	A2	A3	A4	A5	A6	A7
C5 (%)	19.20	15.12	83.00	61.45	30.95	16.27	67.95
C9 (%)	7.72	16.17	24.86	9.96	14.26	2.29	0.15
C10 (10^3 CNY)	2746.11	618.42	8033.62	−5160.1	46530	−2085.18	−1094.42
C11 (year)	10.00	9.39	4.02	10.04	6.00	43.73	65.36
C12 (10^6 CNY/10^6 tce)	5111.84	5252.96	848.6	11120.64	7287.02	3006.86	1876.72
C15 (10^3/10^6 tce)	0.64	3.43	0.30	1.39	1.48	2.00	2.23

of BETs could all bring environmental benefits to some extent, with no significant differences under environmental priority situation and the final ranking of each BET is close to one another (see Table 7(a)). However, the differences are obvious under economic priority situation (see Table 7(b)). At present, the development level of the BETs is not the same, thus leading to huge differences in the performance of economic benefits.

The setting of the life cycle range of the bioenergy system may magnify the environmental benefits in this study. On the one hand, in the benchmark situation it assumes that if the ARs are not utilized for bioenergy production through the BETs, they would be open-burned. While actually, a part of ARs are used as feed, returning to fields, etc. On the other hand, the pollutants from burning the fossil fuels substituted by bioenergy are regarded as directly emitted into the atmosphere without any treatment. Both of these assumptions may lead to over-estimated environmental consequences. The air pollutant emissions occurred in the stage of ARs procurement (including collection, preprocessing and transportation) account for remarkably large proportion of the total emissions, which is closely affected by the collection radius determined by the scale of the bioenergy projects. The syngas technology has the best environmental performance in terms of GHG mitigation (see Fig. 3(a)), attributed to its lower GHG emission (smaller production scale and thus smaller collection range of the ARs) and more fossil fuel substitution per unit energy output.

The techno-economic assessment of the BETs are according to the information of currently operated bioenergy projects with regard to the scale, cost structure, government subsidies etc. Hydrogen has been considered as a promising alternative, whereas the technology has been recognized as the worst under the economic priority situation. Because there are still existing technical barriers in biomass-based hydrogen technology currently. Both of syngas and biogas are gaseous energy products, however the syngas technology is ranked prior to the biogas technology under the economic priority situation. This is partially owing to its higher energy efficiency technically, which is more favorable from the perspective of the engineers. The briquette fuel technology is one of the most preferable BETs, contributed by its simplest conversion process and highest energy efficiency. It should be reiterated that the aim of this study is to assess the BETs with the most widely adopted scale (see Table 4). The economic performance of the BETs is directly related to the scale of the bioenergy project. A large-scale project inevitably calls for more investment, which is less affordable for the investors. They generally need to loan from the banks, thus may involve the issue of repayment of loans as well as the accompanying interest, which are not included in the cost accounting for the projects in this study. In this respect, the advantages of the large-scale projects may be exaggerated. The economic performances of the BETs, as well as the performance under the criterion of policy adaptability (C13) are tightly connected to the national strategies. With more subsidies from the government and more incentive policies, the bioenergy enterprises tend to be more profitable and have more promising development prospect. The current government policies have laid more emphasis on the promotion of the power generation and briquette fuel technologies, resulting in more preference from the experts for corresponding BETs and thus better performances of them in this study. In a word, the final ranking under the economic priority situation are more inclined to change over time, due to changes in the price of bioenergy products, governmental policies for subsidies, technological development and other factors.

The assessment scope of this study focuses on a generally nationwide perspective, rather than specific regional/city level. However regional factor is an indispensable one to be considered when formulating local planning for ARs utilization. For instance, although the biogas technology develops well in some regions, it still has limitations in the northern China, where the technology cannot be normally operated (especially in winter) to ensure the benefits. Apart from the climatic factor, the reserve of the ARs is another affecting factor when choosing proper BETs for a specific region, as the supply of ARs determines whether a large-scale project can be operated stably. Therefore, region-specific prioritization of the BETs has to involve more pertinent factors to ensure the completeness of the assessment.

A lot of sustainability criteria for bioenergy systems have been referred to in order to make the index system of this study as complete as possible. However, there are still some limitations. Due to data availability, the index system of this study only includes one criterion related to water pollution, with the rest relevant to air pollution (see Table 2). In addition, there are interactional effects among the assessment criteria that are difficult to avoid. Finally, since the assessment criteria of the BETs are in conflict in most cases, it is always unrealistic to determine the most optimal technology. Methodologically the VIKOR method help to get compromise solutions, which allow decision-makers space to make choice.

5. Conclusions

Converting ARs to energy has great potential for enhancing China's regional energy and environmental sustainability. In order to help decision-makers understand the current status of BETs in China and draft a proper bioenergy development plan, a combined fuzzy AHP and VIKOR method is adopted to assess and prioritize the BETs for ARs from a life cycle perspective. Seven types of BETs are included as alternatives in this study, which convert ARs into four forms of bioenergy products (gaseous fuel, solid fuel, liquid fuel and electricity). An assessment criteria system for the alternatives is established, incorporating fifteen criteria in four aspects (environmental, technological, economic, and social aspects).

Life cycle environmental and techno-economic assessments of the BETs are conducted within the boundary ranging from ARs collection, ARs transportation, energy conversion to ultimate use of bioenergy products. Contributed by the results of LCA and the advices from two groups of experts, prioritization of the BETs are obtained under the environmental priority situation and economic priority situation. It could be noted that direct-combustion power generation (A1), gasification power generation (A2) and briquette fuel (A3) are recognized as the most sustainable ones under both situations. The parameters of BETs are mainly acquired from published literatures and industrial reports of typical bioenergy projects in China. The prioritization of the alternatives represents current status and technological levels of the BETs in China. The final ranking is inclined to change over time, due to changes in the government guidance, technological development and other factors.

The developed method in this study can effectively incorporate the environmental and social benefits in the selection of the most sustainable BETs for ARs among multiple choices rather than considers only economic benefits. Finally a compromise solution by considering economic, environmental and social values simultaneously could be obtained. Future studies may be extended to prioritize the technologies for energy conversion using more types of bioresources including livestock manure, forestry residues, organic municipal solid wastes, sewage and so on.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2018.11.011.

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