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Identification of Critical Success Factors for Sustainable Development of Biofuel Industry in China based on Grey DEMATEL

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Abstract: Biofuel as a promising pathway for substituting the traditional fossil fuels, mitigating environmental contaminations, and enhancing the energy security has attracted more and more attention in China. This study aims at identifying the critical success factors for promoting the sustainable development of biofuel industry and helping the stakeholders/decision-makers to draft the appropriate strategic measures for enhancing the sustainability of biofuel industry in China. A generic methodology in which the decision-makers are allowed to use linguistic terms to express their views and options, multiple decision-makers are allowed to participate in the decision-making, has been developed to prioritize the factors influencing the sustainability of biofuel industry and to identify the cause-effect relationships among these factors. The three factors, including government support degree, competitiveness, and local acceptability are identified as the most critical factors for promoting the sustainable development of biofuel industry in China, but they are all effects rather than the origins of the problems existed in the biofuel industry of China. In contrast, maturity, safety and reliability, complexity, conversion efficiency, and investment cost are the most important causes, and they are also the origins of the problems existed in the biofuel industry of China. Six effective strategic measures including popularizing the use of biofuels in large scales, subsidies and tax exemption policies, investing more on R&D on biofuel technologies, encouraging more private enterprises and joint ventures to participate in the biofuel industry, developing the integrated utilization manner of biofuels by further developing the byproducts of biofuels, and popularizing the use of biodiesel and bioethanol among the vehicle users

through publicity and education have been proposed for promoting the sustainable development of China's biofuel industry according to the obtained results.

Keywords: Sustainable development; biofuel; grey number; DEMATEL

1. Introduction

Due to the depletion of nonrenewable energy resources and the rapid increase of vehicular emissions, human communities has started to become seriously concerned about global warming and the use of non-renewable fossil fuel as their principle energy source (Kiwjaroun et al., 2009). Therefore, the alternative renewable and promising energy sources such as bioethanol and biodiesel have been widely studied and discussed for a more sustainable future.

China faces severe energy security and environment pollution problems with the rapid growth of oil demand and fast increase of carbon dioxide (CO₂) emissions, the motor vehicle population has been significantly increased in China as a country with the most populations due to the booming of its economy (Hu et al., 2008). After the issue of the Kyoto Protocol, China has received more and more stress and criticisms from the international community due to the high consumption of fossil fuels and large amount of CO₂ emission. Biofuel as one of the most promising renewable energy carriers can be produced from various feedstocks such as biomass, algal and some other non-staple food crops that have great potential in China. Thus, the development of biodiesel is one of the most efficient outlets to achieve the objective of fossil energy saving and emissions mitigation in China, and there is also a great

potential for the development of biofuels in China, because as a big agricultural country, it has abundant biomass resources such as soybean, rapeseed, *jatropha* seeds, palm fruit, sunflower seeds. Such products can be used in the production of biofuels.

Biofuel industry in China is still under its infant stage, and it is far from sustainable development. Due to different economic, environmental, social and technical performances of these biofuel pathways, and the complex and interacted relationships among the factors of economic, environmental, social and technical aspects, so the stakeholders in China always face two puzzles when they draft the countermeasures and policies for promoting the sustainable development of biofuel industry: (1) what are the critical success factors for sustainable development of biofuel? (2) How to enhance the sustainability of China's biofuel industry? The answers of the two questions are of vital importance for the stakeholders to take effective actions for enhancing China's biodiesel industry as biofuels have both the advantages to be taken of and the disadvantages to be overcome. The identification of key critical success factors and the investigation of the cause-effect relationships among them are of vital importance for China's decision-makers/policy-makers to draft the roadmap of China's biofuel industry. Therefore, the objective of this study is to develop a methodology to prioritize the factors that influence the sustainability of biofuel industry, to identify the cause-effect relationships among these factors, and to propose some implications for China's decision-makers/stakeholders to promote sustainable development of biofuel industry in China.

Many studies have been published on the analysis of the advantages and weak

points of crop based biofuels, it could be summarized that, compared with conventional diesel, it has the advantages of lower energy consumption, lower waste emissions (carbon monoxide, particulate matter and soot, unburned hydrocarbons, NO_x, SO_x), especially the advantage of low carbon dioxide emissions due to the process of photosynthesis, promoting participation by small and medium-size farms and generate new focal points of development and employment in regions (Harding et al., 2007; Patil et al., 2009; Huang et al., 2010). Beyond these advantages, there are also some debates about the use of crop for biofuels production such as the security of food supply, and food land competition (Diaz-Chavez, 2011; Patil et al., 2009). Hence, biofuel is recognized as an energy carrier in debate.

Many studies focused on investigating the development of China's biofuel industry. Zhong *et al.* (2010), Fang *et al.* (2010), and Qiu *et al.* (2012) reviewed the current status of biofuels development and the challenges ahead in China, including feedstock utilization and technical process of biofuels production (i.e., bioethanol, biodiesel). Latner *et al.* (2006) summarized the characteristics of biofuel development under the strict government dominates production policy in China. Zhu and Zhang (2003) and Sun *et al.* (2006) discussed the significance of biodiesel industry to the national petroleum supply, national economy, environmental protection, and re-adjustment of the agriculture industry. Dai et al. (2006) found cassava fuel ethanol is more energy efficient than gasoline and diesel fuel. Tian *et al.* (2009), Qiu *et al.* (2011), and Qiu *et al.* (2012) identified the potential of using marginal lands for feedstock production, and measured the likely impacts of China's bioethanol

development on the nation's future food self-sufficiency. Huang *et al.* (2012) found the increase biofuel production and use will not compromise food security, but it can improve the income level of the poor people in the northern regions of China. Ou *et al.* (2009) evaluated the energy consumption and greenhouse gas emissions of six biofuel feedstocks in China. Yao *et al.* (2011) stated that expanding the use of biofuel vehicles is the most promising solution for China to cope with energy and greenhouse gas crisis in the long term. Huang *et al.* (2010) developed a software sensor based on the fuzzy neural network model can effectively tackle on both environmental and economic objectives of a real-time anoxic/oxic system. Zhong *et al.* (2010) and Liang *et al.* (2012) concluded the sustainable development of biofuels production highly depends on integrating reliable, low-cost, non-food feedstock biorefineries supplies and efficient, environmentally friendly process technologies, as well as reduction of fresh water use and environmental pollution. Although these studies are beneficial for the stakeholders to understand the pros and cons of biofuel, it lacks the studies on indentifying the critical success factors for sustainable development of biofuel. In other words, a systematic study of the influential factors of biofuel's sustainable development is prerequisite.

Çakir *et al.* (2012) pointed out that sustainability created and maintained the conditions under which humans and nature could exist in productive harmony that permit fulfilling the social, economic and other requirements of present and future generations. Thus, sustainability of biofuel is a multidimensional problem that concerns multiple aspects such as economic aspect, environmental aspect,

social-political aspect and technical aspect. Hence, multi-criteria decision-making (MCDM) methodology is the most suitable way to address this multidimensional problem. Most of the MCDM methods are merely used for sustainability assessment to support the decision-makers/stakeholders in the selection of the best scenario. Such methods are also used for assessing the sustainability of biofuels (Meester et al., 2012; Pfromm et al., 2011; Delrue et al., 2012). These studies are of vital importance for China's decision-makers/stakeholders to select the most sustainable pathway for biofuel production among multiple alternative scenarios; however, they cannot obtain the answers for what are the key problems existing in China's biofuel industry and how to enhancing the sustainability of China's biofuel industry. In order to fill this gap, we developed an improved, MCDM method, namely an extend decision-making trial and evaluation laboratory (DEMATEL) method, to address this.

Decision-making trial and evaluation laboratory (DEMATEL) method as one of the most important MCDM methods was originally developed by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva in 1970s to solve the complicated and intertwined problem group (Fontela and Gabus, 1976; Gabus and Fontela, 1973). The traditional DEMATEL method has been widely used in many fields such as supply chain (Ren et al., 2013), carbon management (Hsu et al., 2013), and service quality (Shieh et al, 2010). Before conducting DEMATEL, the stakeholders/decision-makers need to build the relationships among the influential factors in the studied problem based on their judgment, preferences and own knowledge, and the crisp values are usually to depict these in the traditional

DEMATEL, but the crisp numbers are not inadequate in the real world due to the vagueness and imprecise judgments existed in human's decision-making. Therefore, fuzzy logic and grey theory have usually been incorporated in DEMATEL, and the extended DEMATEL methods, so-called "fuzzy DEMATEL" (Chang et al., 2011; Lin, 2013; Kannan et al., 2014) and "grey DEMATEL" (Bai and Sarkis, 2013; Dou and Sarkis, 2013), are usually used to address the complicated and intertwined problem group. As for investigating the complex problem of biofuel industry development, the relationships among the factors that affect the sustainability of biofuel industry are difficult or even impossible to use rigorous quantitative functions to depict, thus, the relationships cannot be presented in the form of crisp values in MCDM due to subjectivity, vagueness, and the impossibility of quantification. However, it is possible to use linguistic terms to describe the views of the stakeholders (Doukas *et al.*, 2007). Grey set theory is usually used in this kind of problem by combining linguistic variables, because it has the ability to address the uncertainty problems and the problems with imprecise information. The transition from vagueness provided by linguistic values to quantification can be performed by applying grey set theory. Therefore, grey set theory is usually incorporated in MCDM. Therefore, a novel grey DEMATEL combining both DEMATEL and grey theory which can also address the vagueness and imprecise judgments existed in human's decision-making has been developed in this study, and the grey numbers in the proposed grey DEMATEL do not need to be transformed into crisp numbers when applying it on real case studies.

In this study, a multi-criteria grey decision-making methodology, namely grey

decision-making trial and evaluation laboratory (grey-DEMATEL) has been used for identifying the critical success factors and the cause-effect relationships among them for promoting sustainable development of biofuel industry. The proposed methodology allows the stakeholders using linguistic terms to express their options and views on the sustainability of biofuels, and the critical success factors for sustainable development of biodiesel industry can be identified based on the collective preferences and wisdoms.

2. Methods

The methods used in this study were been proposed in this section, including criteria system for sustainability assessment of biofuels, grey DEMATEL method, and data collection method.

2. 1 Criteria system for sustainability assessment of biofuels

An in-depth understanding of each stakeholder group's criteria is critical in order for appropriate sustainability assessment (Turcksin et al., 2011). Therefore, a complete criteria system is critical for the accurate sustainability assessment of biofuels. The traditional concept of sustainable development has focused on three pillars including economic aspect, environmental aspect, and social aspect (Diaz-Chavez, 2011; Posada et al., 2013). In addition, other components such as technical aspect and political aspect are also incorporated in sustainability metrics (Perimenis et al., 2011; Nzila et al., 2012) as they can affect the three pillars of sustainability. Based on the review of many published works and the queries of the experts in sustainability assessment of biofuels and renewable energy systems, 19 criteria in four aspects including technical,

economic, environmental and social-political aspects have been considered herein , and these criteria were specified in Table 1.

2.2 Mathematical method

In this section, the theory of grey number was firstly introduced, then the extension of Decision Making Trial and Evaluation Laboratory (DEMATEL), namely “grey DEMATEL” was proposed by combining the traditional DEMATEL method and grey theory.

2.2.1 Grey number

Grey number represents that the information of the number is insufficient and incomplete, and it belongs to a range instead of crisp value (Lin et al., 2008). A grey number x denotes by $\otimes a$

$$\otimes a = [a^-, a^+] = \{x \in \otimes a \mid a^- \leq x \leq a^+\} \quad (1)$$

where a^- and a^+ represent the lower and upper bound of the interval.

Let $\otimes a_1$ and $\otimes a_2$ be two grey numbers, and a be a crisp number, then the grey number arithmetic operations can be shown as follows:

$$\otimes a_1 = [a_1^-, a_1^+] \quad (2)$$

$$\otimes a_2 = [a_2^-, a_2^+] \quad (3)$$

Grey number addition

$$\otimes a_1 + \otimes a_2 = [a_1^-, a_1^+] + [a_2^-, a_2^+] = [a_1^- + a_2^-, a_1^+ + a_2^+] \quad (4)$$

Grey number subtraction

$$\otimes a_1 - \otimes a_2 = [a_1^-, a_1^+] - [a_2^-, a_2^+] = [a_1^- - a_2^+, a_1^+ - a_2^-] \quad (5)$$

Grey number multiplication

$$\otimes a_1 \otimes a_2 = \left[\min \{a_1^- a_2^-, a_1^- a_2^+, a_1^+ a_2^-, a_1^+ a_2^+\}, \max \{a_1^- a_2^-, a_1^- a_2^+, a_1^+ a_2^-, a_1^+ a_2^+\} \right] \quad (6)$$

Grey number division

$$\frac{\otimes a_1}{b} = \left[\frac{a_1^-}{b}, \frac{a_1^+}{b} \right] \quad (7)$$

$$\frac{b}{\otimes a_1} = \left[\frac{b}{a_1^+}, \frac{b}{a_1^-} \right] \quad (8)$$

where $a_1^- > 0, a_2^- > 0, a_1^+ > 0, a_2^+ > 0, b > 0$ are real numbers.

For the two grey number, the possible degree of $\otimes a_2 \geq \otimes a_1$ (Tseng, 2009) can be calculated by Eq.9.

$$P\{\otimes a_2 \geq \otimes a_1\} = \frac{\max\{0, L - \max(0, a_1^+ - a_2^-)\}}{L} \quad (9)$$

where $L = |a_1^- - a_1^+| + |a_2^- - a_2^+|$

The possible degree of $\otimes a_2 \geq \otimes a_1, P\{\otimes a_2 \geq \otimes a_1\} \in [0, 1]$, and the positive relationships could be specified as follows:

- If $a_1^- = a_2^-$ and $a_1^+ = a_2^+$, that $\otimes a_2 = \otimes a_1$, then $P\{\otimes a_2 \geq \otimes a_1\} = 0.5$.
- If $a_2^- > a_1^+$, that $\otimes a_2 > \otimes a_1$, then $P\{\otimes a_2 \geq \otimes a_1\} = 1$.
- If $a_2^+ < a_1^-$ and $a_2^+ < a_1^+$, that $\otimes a_2 < \otimes a_1$, then $P\{\otimes a_2 \geq \otimes a_1\} = 0$.
- If there is an intercrossing part between $\otimes a_2$ and $\otimes a_1$, when $P\{\otimes a_2 \geq \otimes a_1\} > 0.5$, then $\otimes a_2 > \otimes a_1$. On the contrary, $P\{\otimes a_2 \geq \otimes a_1\} < 0.5$, then $\otimes a_2 < \otimes a_1$.

Based on Eq.9, it is apparent that the possible degree of $\otimes a_2 \geq 0$ could be calculated by Eq.10, and it could be further explained in Eq.11

$$P\{\otimes a_2 \geq 0\} = \frac{\max\{0, |a_2^- - a_2^+| - \max(0, -a_2^-)\}}{|a_2^- - a_2^+|} \quad (10)$$

$$P\{\otimes a_2 \geq 0\} = \begin{cases} < 0.5 & \otimes a_2 < 0 \\ = 0.5 & \otimes a_2 = 0 \\ > 0.5 & \otimes a_2 > 0 \end{cases} \quad (11)$$

2.2.2 Grey DEMATEL

Different from the previous grey DEMATEL method, the developed grey DEMATEL method does not need to transform the grey numbers into crisp number, and the grey DEMATEL consists of five main steps, and the thoughts were based on the work of Bai and Sarkis (2013), and Dou and Sarkis (2013):

- (1) Determining the direct-influenced matrices using linguistic terms.
- (2) Determining the grey direct-influenced matrix.
- (3) Normalizing the initial direct-influenced matrix.
- (4) Calculate the total relation matrix.
- (5) Determining the prior sequence of the factors from most to least important, and identifying the cause-effect relations.

These five steps are specified as follows:

Step 1: Determining the grey direct-influenced matrices using linguistic terms. The objective is to determine the direct relationships among the factors (criteria) using linguistic terms. The stakeholders and decision-makers are asked to present their options and views on how a factor influences other factors.

The stakeholders and decision-makers are asked to judge the degree which represents they believe a criterion affects another criterion. Assuming there are n factors to be considered. The influence of factor i on factor j determined by the stakeholders/decision-makers is determined by using linguistic terms including “No influence $([0, 0])$ ”, “Extremely low influence $([0, 1])$ ”, “Moderately low influence $([1, 2])$ ”, “Medium influence $([2, 3])$ ”, “Moderately high influence $([3, 4])$ ”, and “Extremely high influence $([4, 5])$ ”, respectively.

Step 2: Determining the grey direct-influenced matrix. All these linguistic terms used in step 1 can be transformed into grey numbers (as presented in Table 2). The influence of factor i on factor j determined by the stakeholders/decision-makers denotes by $\otimes a_{ij} = [a_{ij}^-, a_{ij}^+]$. The results provided by the stakeholders/decision-makers can form an n by n matrix, as shown in Eq.12.

$$\otimes A^k = \begin{bmatrix} [0,0] & \otimes a_{12} & \cdots & \otimes a_{1n} \\ \otimes a_{21} & [0,0] & \cdots & \otimes a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \otimes a_{n1} & \otimes a_{n2} & & [0,0] \end{bmatrix} \quad (12)$$

where $\otimes A$ is the grey direct-influenced matrix, and $\otimes a_{ij} = [a_{ij}^-, a_{ij}^+]$ represents the element in $\otimes A$.

Step 3: Normalizing the initial direct-relation matrix. The normalized initial direct-relation matrix D can be determined by Eq.13 and Eq.14.

$$s = \max \left(\max_{1 \leq i \leq n} \sum_{j=1}^n a_{ij}^+, \max_{1 \leq j \leq n} \sum_{i=1}^n a_{ij}^+ \right) \quad (13)$$

$$\otimes D = [\otimes d_{ij}]_{n \times n} = \left[(d_{ij}^-, d_{ij}^+) \right]_{n \times n} = \frac{\otimes A}{s} \quad (14)$$

where $\otimes D$ is the normalized initial direct-relation matrix, and s is the auxiliary parameter for normalizing the initial direct-relation matrix.

Step 4: Calculating the total relation matrix. The powers of $\otimes D$ represent the indirect effects between any factors. Then, the total relation matrix $\otimes T$ can be calculated by Eq.15-19.

$$\otimes T = [\otimes t_{ij}]_{n \times n} = \left[(t_{ij}^-, t_{ij}^+) \right]_{n \times n} = \otimes D + (\otimes D)^2 + \cdots + (\otimes D)^\infty \quad (15)$$

$$T^- = [t_{ij}^-]_{n \times n} = D^- (I - D^-)^{-1} \quad (16)$$

$$T^+ = [t_{ij}^+]_{n \times n} = D^+ (I - D^+)^{-1} \quad (17)$$

$$D^+ = [d_{ij}^+]_{n \times n} \quad (18)$$

$$D^- = [d_{ij}^-]_{n \times n} \quad (19)$$

where $\otimes T$ represents the total relation matrix, and I is the identity matrix.

Step 5: Determining the prior sequence of the factors from most to least important, and identifying the cause-effect relations. The total effect that directly and indirectly exerted by the i -th factor, is denoted by $\otimes R_i$, could be calculated by Eq.20.

$$\otimes R_i = \sum_{j=1}^n \otimes t_{ij} \quad (20)$$

The total effect including direct and indirect effects received by the j -th factor, is denoted by $\otimes C_j$ could be calculated by Eq.21.

$$\otimes C_j = \sum_{i=1}^n \otimes t_{ij} \quad (21)$$

The sum $\otimes R_i + \otimes C_i$ represents the total effects given and received by the i -th factor. In other words, $\otimes R_i + \otimes C_i$ is a measure of the degree of the importance of the i -th factor in the system. The prior sequence of the n criteria could be determined based on the rule that the bigger the value of $\otimes R_i + \otimes C_i$, the more important the criterion will be. This rule could be conducted by comparing the values of $\otimes R_i + \otimes C_i$ using Eq.9.

The difference $\otimes R_i - \otimes C_i$ called “relation” shown the net effect that contributed by the i -th factor to the system. When $\otimes R_i - \otimes C_i > 0$, the i -th factor is a net cause, it belongs to the ‘cause group’. In the contrary, $\otimes R_i - \otimes C_i < 0$, the i -th factor is a net receiver or result, it belongs to the ‘effect group’. It is worth pointing out that $\otimes R_i - \otimes C_i (i=1, 2, \dots, n)$ are grey numbers, thus, the possibility of

$\otimes R_i - \otimes C_i > 0$ belongs to the interval $[0, 1]$. Then, Eqs.10-11 can be used to judge which group of the i -th criterion belongs to.

2.3 Data collection

Data collection, especially the determination of the direct-influenced matrix, is the foundation to implement grey DEMATEL, and the accuracy of the data is critical for obtaining accurate results. In order to study the influential factors of biofuels comprehensively, the preferences and willingness of all the representative stakeholders such as agricultural experts for crops cultivation, engineers in the plants for biodiesel production, administrative executors for biodiesel planning and citizens for the use of biodiesel should be incorporated in the decision-making. Accordingly, the representative experts including agricultural experts who have abundant experience on crop science and energy crops, the researchers who worked on biofuel technologies, and professors and PhD students who study on sustainability engineering and bioenergy were invited to participate in a focus group meeting.

The focus group meeting consists of two professors, three engineers, two PhD researchers, and an agricultural expert, the objective of this meeting is to determine the direct-influenced matrix, a coordinator was also nominated in this meeting, and he introduced some knowledge concerning this topic to the participants. In this study, some published works have been provided to the participants. Then, the participants were asked to use the linguistic terms presented in Table 2 to express the relationship between each pair of criteria, and each of the participants determined a

direct-influenced matrix by using linguistic terms. It is worth pointing out that the direct-influenced matrices are different as different participants have different preferences/willingness. In order to achieve a consensus among the participants, the coordinator determined a final direct-influenced matrix by using linguistic terms by the rule of “the minority is subordinate to the majority” (Ren et al, 2015).

3 Results and Discussion

The direct-influenced matrix using linguistic terms is determined after the focus group meeting, as presented in Table 3. For instance, the experts held the view that conversion efficiency (T_3) has ‘Extremely low influence (EL)’ on land use change and biodiversity (EN_2), then ‘EL’ was put in the corresponding cell of Table 3. The linguistic terms, as presented in Table 3, can be transformed into grey numbers according to Table 2, then, the direct-influenced matrix using grey numbers has been obtained, as presented in Table 4. Finally, the developed Grey DELATEL has been used to analyze the data presented in Table 4. The results of grey DEMATEL analysis are presented in Table 5. According to the values of $\otimes R_i + \otimes C_i$, the importance of the criteria could be ranked from most to least important using Eq.9, and the final prior sequence is government support degree, competitiveness, local acceptability, maturity, safety and reliability, complexity, conversion efficiency, investment cost, cost of production, operation and maintenance cost, working conditions, non-renewable energy use, employment, reduction of GHG emissions, regional development contribution, water use, security for food supply, land use change and biodiversity, and soil quality. As for the types of the criteria, they could be determined by

comparing the values of $\otimes R_i - \otimes C_i$ with 0 using Eqs.10-11, the corresponding criteria belong to cause group when $\otimes R_i - \otimes C_i$ is greater than 0, in the contrast, the corresponding criteria belong to effect group when $\otimes R_i - \otimes C_i$ is less than 0. The results were presented in Table 6. Maturity, complexity, conversion efficiency, safety and reliability, investment cost, operational and maintenance cost, reduction of GHG emissions, regional development contribution, non-renewable energy use, water use, and soil quality, and security for food supply are recognized as cases, but other criteria including cost of production, competitiveness, local acceptability, regional development contribution, government support degree, working conditions, and employment are regarded as effects. Thus, government support degree, competitiveness, and local acceptability are the most factors for sustainable development of biofuels, but they are all effects not the origins of the problems existed in biofuel industry of China. In contrast, maturity, safety and reliability, complexity, and conversion efficiency, investment cost are the most important causes, and they are also the origins of the problems existed in biofuel industry of China.

4 Conclusion

In order to help the decision-makers/stakeholders investigate the critical success factors for sustainable development of biofuel industry in China, identify the cause-effect relationships among, and propose strategic measures for promoting the sustainable development of the biofuel industry, a grey DEMATEL methodology has been developed and applied in China's biofuel industry. According to the obtained results, some effective suggestions can be recommended to China's

decision-makers/stakeholders for them to implement the most effective strategic measures for enhancing the sustainability of China's biofuel industry.

In order to promote the sustainable development of biofuel industry in China, the stakeholders, policy-makers and decision-makers should pay more attention on in following factors: government support degree, competitiveness, local acceptability, maturity, safety and reliability, complexity, conversion efficiency, investment cost, cost of production, and operation and maintenance cost. These ten factors are the most influential factors that have significant effects on the sustainability of biofuel industry in China. More specifically, the following implications are suggested for China's stakeholders/decision-makers:

- (i) Popularizing the use of biofuels in large scales, i.e. the mandatory policies of using ethanol gasoline and biodiesel diesel by mixing bioethanol and gasoline, and blending the biodiesel into the market diesels, respectively, should also be expanded to more cities of China.
- (ii) more and more subsidies and tax exemption policies and measures should be drafted in China to attract more foreign and native investors for investing on biofuel industry and to give substantially fiscal support for biofuel corporations for developing biofuel in large scales.
- (iii) investing more on R&D on biofuel technologies to develop the 2nd generation or 2.5nd generation biofuels that are based on non-staple food crop, to lower the life cycle cost of biofuels, and to improve the market competitiveness of biofuels;

- (iv) encouraging more private enterprises and joint ventures to participate in the biofuel industry to bring revenue, knowledge, and intellectual property for promoting the development of biofuel in large scales;
- (v) developing the integrated utilization manner of biofuels by further developing the byproducts of biofuels, i.e. developing biogas projects in bioethanol projects and using the Distillers Dried Grains with Solubles for improving the economic competitiveness;
- (vi) popularizing the use of biodiesel and bioethanol among the vehicle users through publicity and education.

According to the cause-effect relationships among the factors that affect on China's biofuel industry, we could conclude that the keys for solving the problems existed in biofuel industry that limit the sustainable development are to improve maturity, enhance safety and reliability, mitigate complexity, increase conversion efficiency, lower investment cost that are the most important causes. All these are related to the technological level of biofuels, thus, R&D on biofuel technologies is the most efficient way for promoting sustainable development of biofuel industry in China.

The developed grey DEMATEL allows the stakeholders/decision-makers to use linguistic terms to make decision, and the vagueness and imprecise judgments in human's decision-making can be overcome. It also allows multiple groups of representative stakeholders/decision-makers to participate in the decision-making. The users of this methodology can invite more groups of representative

stakeholders/decision-makers to participate in building the relationships among the influential factors that influence sustainable development biofuel industry to have a more complete and accurate survey. Besides this, the developed grey DEMATEL is a generic method and can be popularized for identifying the critical success factors for sustainable biofuel development in some other countries.

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References

- Bai, C., Sarkis, J., 2013. A grey-based DEMATEL model for evaluating business process management critical success factors. *International Journal of Production Economics* 146(1), 281-292.
- Çakir, U., Çomakli, K., Yüksel, F., 2012. The role of cogeneration systems in sustainability of energy. *Energy Conver. Manage.*, 63, 196-202.
- Chang, B., Chang, C. W., Wu, C. H., 2011. Fuzzy DEMATEL method for developing supplier selection criteria. *Expert Systems with Applications* 38(3), 1850-1858.
- Dai, D., Hu, Z., Pu, G., Li, H., Wang, C., 2006. Energy efficiency and potentials of

cassava fuel ethanol in Guangxi region of China. *Energy Conver. Manag.* 47(13), 1686-1699.

Delrue, F., Setier, P.A., Sahut, C., Cournac, L., Roubaud, A., Peltier, G., Froment, A.K., 2012. An economic, sustainability, and energetic model of biodiesel production from microalgae. *Biosour. Technol.* 111, 191-200.

Diaz-Chavez, R.A., 2011. Assessing biofuels: Aiming for sustainable development or complying with the market? . *Energy Policy* 39, 5763-5769.

Doukas, H.C., Andreas, B.M., Psarras, J.E., 2007. Multi-criteria decision aid for the formulation of sustainability technological energy priorities using linguistic variables. *Eur J Oper Res* 182, 844-855.

Dou, Y., Sarkis, J., 2013. A multiple stakeholder perspective on barriers to implementing China RoHS regulations. *Resources, Conservation and Recycling* 81, 92-104.

Fang, X., Shen, Y., Zhao, J., Bao, X., Qu, Y., 2010. Status and prospect of lignocellulosic bioethanol production in China. *Bioresour. Tech.* 101(13), 4814-4819.

Fritsche, U.R., 2012. Sustainable Bioenergy: Key Criteria and Indicators.

Gnansounou, E., 2011. Assessing the sustainability of biofuels: A logic-based model. *Energy* 36, 2089-2096.

Fontela, E., Gabus, A., 1976. The DEMATEL Observer, DEMATEL 1976 Report. Switzerland, Geneva, Battelle Geneva Research Center.

Gabus, A., Fontela, E., 1973. Perceptions of the world problematique: Communication procedure, communicating with those bearing collective responsibility, DEMATEL

Report No. 1, Battelle Geneva Research Center, Geneva, Switzerland.

Global Bioenergy Partnership (GBEP), 2011. GBEP Sustainability Indicators for Bioenergy.http://www.globalbioenergy.org/fileadmin/templates/gbep/images/Ylenia/Summary_table_website_12-11.pdf (Access on October 25, 2015)

Harding, K.G., Dennis, J.S., Blottnitz, H.V., Harrison, S.T.L., 2007. A life-cycle comparison between inorganic and biological catalysis. *J. Clean. Prod.* 16, 1368-1378.

Hayashi, T., van Ierland, E.C., Zhu, X., 2014. A holistic sustainability assessment tool for bioenergy using the Global Bioenergy Partnership (GBEP) sustainability indicators. *Biomass Bioenergy*. (in press).

Hsu, C. W., Kuo, T. C., Chen, S. H., Hu, A. H., 2013. Using DEMATEL to develop a carbon management model of supplier selection in green supply chain management. *Journal of Cleaner Production* 56, 164-172.

Hu, Z., Tan, P., Yan, X., Lou D., 2008. Life cycle energy, environment and economic assessment of soybean-based biodiesel as an alternative automotive fuel in China. *Energy* 33, 1654-1658.

Huang, M., Wan, J., Ma, Y., Li, W., Sun, X., Wan, Y., 2010. A fast predicting neural fuzzy model for on-line estimation of nutrient dynamics in an anoxic/oxic process. *Bioresour. Technol.* 101, 1642-1651.

Huang, J., Yang, J., Msangi, S., Rozelle, S., Weersink, A., 2012. Global biofuel production and poverty in China. *Appl. Energy* 98, 246-255.

Kannan, G., Kannan, D., Shankar, K. M., 2014. Evaluating the drivers of corporate social responsibility in the mining industry with multi-criteria approach: A

- multi-stakeholder perspective. *Journal of Cleaner Production* 84, 214-232.
- Kahraman, C., Kaya, I., 2009. A fuzzy multicriteria methodology for selection among energy alternatives. *Expert Syst with Appl* 37, 6270-6281.
- Kiwjaroun, C., Tubtimdee, C., Piumsomboon, P., 2009. LCA studies comparing biodiesel synthesized by conventional and supercritical methanol methods. *J. Clean. Prod.* 17, 143-153.
- Koizumi, T., 2013. Biofuel and food security in China and Japan. *Renew. Sustain. Energy Rev.* 21, 102-109.
- Latner, K., O'Kray, C., Jiang, J., 2006. Strict government control characterizes Chinese biofuel development. An online review of Foreign Agricultural Service initiatives and services. United States Department of Agriculture (USDA). http://www.frankhaugwitz.info/doks/bio/2006_09_China_RE_Biofuels_Strict_Govt_Market_Development_USDA.pdf (Access on 30 September, 2015)
- Li, S. Z., Chan-Halbrendt, C., 2009. Ethanol production in (the) People's Republic of China: potential and technologies. *Appl. Energy* 86, S162-S169.
- Liang, S., Xu, M., Zhang, T., 2012. Unintended consequences of bioethanol feedstock choice in China. *Bioresour. Tech.* 125, 312-317.
- Lin, R. J., 2013. Using fuzzy DEMATEL to evaluate the green supply chain management practices. *Journal of Cleaner Production* 40, 32-39.
- Lin, Y.H., Lee, P., Ting, H.I., 2008. Dynamic multi-attribute decision making model with grey number evaluations. *Expert Syst. Appl.* 35, 1638-1644.
- Meester, S.D., Demeyer, J., Velghe, F., Peene, A., Langenhove, H.V., Dewulf, J., 2012.

The environmental sustainability of anaerobic digestion as a biomass valorization technology. *Biosour. Technol.* 121, 396-403.

Nzila, C., Dewulf, J., Spanjers, H., Tuigong, D., Kiriamiti, H., Langenhove, H.V., 2012. Multi criteria sustainability assessment of biogas production in Kenya. *Appl. Energy* 93, 496-506.

Ou, X., Zhang, X., Chang, S., Guo, Q., 2009. Energy consumption and GHG emissions of six biofuel pathways by LCA in (the) People's Republic of China. *Appl. Energy* 86, S197-S208.

Patil, P.D., Gude, V.G., Deng, S., 2009. Biodiesel production from jatropha curcas, waste cooking and camelina sativa oils. *Ind. Eng. Chem. Res.* 48, 10850-10856.

Perimenis, A., Walimwipi, H., Zinoviev, S., Müller-Langer, F., Miertus, S., 2011. Development of a decision support tool for the assessment of biofuels. *Energy Policy* 39(3), 1782-1793.

Pfromm, P.H., Amanor-Bordu, V., Nelson, R., 2011. Sustainability of algae derived biodiesel: A mass balance approach. *Biosour. Technol.* 102, 1185-1193.

Posada, J.A., Patel, A.D., Roes, A., Blok, K., Faaij, A.P.C., Patel, M.K., 2013. Potential of bioethanol as a chemical building block for biorefineries: Preliminary sustainability assessment of 12 bioethanol-based products. *Bioreour. Technol.* 135, 490-499.

Qiu, H., Huang, J., Yang, J., Rozelle, S., Zhang, Y., Zhang, Y., Zhang, Y., 2010. Bioethanol development in China and the potential impacts on its agricultural economy. *Appl. Energy* 87(1), 76-83.

- Qiu, H., Huang, J., Keyzer, M., van Veen, W., Rozelle, S., Fisher, G., Ermolieva, T., 2011. Biofuel development, food security and the use of marginal land in China. *J Environ. Quality* 40(4), 1058-1067.
- Qiu, H., Sun, L., Huang, J., Rozelle, S., 2012. Liquid biofuels in China: current status, government policies, and future opportunities and challenges. *Renew. Sustain. Energy Rev.* 16(5), 3095-3104.
- Ren, J., Manzardo, A., Toniolo, S., Scipioni, A., 2013. Sustainability of hydrogen supply chain. Part I: Identification of critical criteria and cause–effect analysis for enhancing the sustainability using DEMATEL. *International Journal of Hydrogen Energy*, 38(33), 14159-14171.
- Ren, J., Gao, S., Tan, S., Dong, L. (2015). Hydrogen economy in China: Strengths–weaknesses–opportunities–threats analysis and strategies prioritization. *Renewable and Sustainable Energy Reviews*, 41, 1230-1243.
- Shieh, J. I., Wu, H. H., Huang, K. K., 2010. A DEMATEL method in identifying key success factors of hospital service quality. *Knowledge-Based Systems* 23(3), 277-282.
- Sun, Y. M., Yuan, Z. H., Sun, Z. J., 2006. The status and future of bioenergy and biomass utilization in China. *Renewable Energy* 2, 78-82. (in Chinese).
- Sultana, A., Kumar, A., 2012. Ranking of biomass pellets by integration of economic, environmental and technical factors. *Biomass Bioenergy* 39, 344-355.
- Tian, Y., Zhao, L., Meng, H., Sun, L., Yan, J., 2009. Estimation of un-used land potential for biofuels development in (the) People’s Republic of China. *Appl. Energy* 86, S77-S85.

- Tseng, M. L., 2009. A causal and effect decision making model of service quality expectation using grey-fuzzy DEMATEL approach. *Expert Syst. Appl.* 36(4), 7738-7748.
- Turcksin, L., Maharis, C., Lebeau, K., Boureima, F., Mierlo, J.V., Bram, S., Ruyck, J.D., Mertens, L., Jossart, J.M., Gorissen, L., Pelkmans, L., 2011. A multi-actor multi-criteria framework to assess the stakeholder support for different biofuel options: The case of Belgium. *Energy Policy* 39, 200-214.
- Wang, J.J., Jing, Y.Y., Zhang, C.F., Zhao, J.H., 2009. Review on multi-criteria decision analysis aid in sustainable energy decision making. *Renew Sustain Energy Rev* 13, 2263-2278.
- Yao, M., Liu, H., Feng, X., 2011. The development of low-carbon vehicles in China. *Energy Policy* 39(9), 5457-5464.
- Yang, Q., Chen, G. Q., 2012. Nonrenewable energy cost of corn-ethanol in China. *Energy Policy* 41, 340-347.
- Yang, B., Lu, Y. , 2007. The promise of cellulosic ethanol production in China. *J Chem. Tech. Biotech.* 82(1), 6-10.
- Yang H., Zhou, Y., Liu, J., 2009. Land and water requirements of biofuel and implications for food supply and the environment in China. *Energy Policy* 37(5), 1876-1885.
- Yuan, J. S., Qu, Y., Li, S., Stewart, C. N., 2011. US–China collaborative biofuel research: towards a global solution for petroleum replacement. *Biofuels* 2(5), 487-489.

- Zhang, P.D., Yang, Y.L., Shi, J., Zheng, Y.H., Wang, L.S., Li, X.R., 2009. Opportunities and challenges for renewable energy policy in China. *Renew Sustain Energy Rev* 13, 439-49.
- Zhong, C., Cao, Y. X., Li, B. Z., Yuan, Y. J., 2010. Biofuels in China: past, present and future. *Biofuels, Bioproducts Biorefining* 4(3), 326-342.
- Zhu, J., Zhang, G., 2003. Current situation and development trend of the research and production of biodiesel. *Chem. Indus. Times* 18(1), 23-27.
- Ziolkowska, J. R., 2013. Evaluating sustainability of biofuels feedstocks: A multi-objective framework for supporting decision making. *Biomass Bioenergy* 59, 425-440.

Tables

Table 1 The criteria system for sustainability assessment of biofuel industry

Aspects	Criteria	Abbreviation	Description	References
Technical	Maturity	T ₁	T ₁ is the criteria to measure the degree of maturity of the technology	(Wang et al. , 2009)
	Complexity	T ₂	T ₂ refers to the number of required steps for a given process of the associated technology	(Permenis et al., 2011)
	Conversion efficiency	T ₃	T ₃ is defined as the amount of product (biofuels) divided by the amount of feedstock input	(Perimenis et al., 2011)
	Safety and reliability	T ₄	T ₄ is a criteria to measure the risk and the system reliability of the process for biofuels production	(Wang et al. , 2009)
Economic	Investment cost	EC ₁	EC ₁ consists of all the costs related to the purchase of mechanical equipment, technological installations, and incidental construction work	(Wang et al. , 2009)
	Operation and maintenance cost	EC ₂	EC ₂ is the cost for operation and maintenance for the whole process of biodiesel production	(Wang et al. , 2009)
	Cost of production	EC ₃	EC ₃ represents the costs related to the production of biodiesel.	(Sultana & Kumar, 2012; Ziolkowska, 2013)
	Competitiveness	EC ₄	EC ₄ measures the competitiveness of feedstock and biofuels production, and that of biofuels on fuels retail market.	(Gnansounou, 2011)
Environment	Reduction of GHG emissions	EN ₁	EN ₁ measures the effect of biofuels on mitigating global warming during the whole life cycle of biodiesel comparing to fossil fuels	(Hayashi et al., 2014; GBEP, 2011)

Aspects	Criteria	Abbreviation	Description	References
	Land use change and Biodiversity	EN ₂	EN ₂ evaluates the integrated performance of land use change and the impacts on biodiversity caused by all the activities for biodiesel production	(Hayashi et al., 2014; Ziolkowska, 2013).
	Non-renewable energy use	EN ₃	EN ₃ measures the total non-renewable energy use for biofuels production in the whole life cycle	(Gnansounou, 2011)
	Water use	EN ₄	EN ₄ measures the impacts of biofuels on water	(Zhang et al., 2009; Ziolkowska, 2013)
	Soil quality	EN ₅	EN ₅ refers the percentage of land for which soil organic carbon is maintained or improved out of total land	(GBEP, 2011)
	Local acceptability	SP ₁	SP ₁ expresses the overview of the opinions related to the biodiesel production systems by local residents regarding the hypothesized realization of the projects under review from the consumer aspect	(Wang et al. , 2009)
Social-political	Regional development contribution	SP ₂	SP ₂ expresses the economic contribution for a local region by introducing a new technology	(Doukas, 2007)
	Government support degree	SP ₃	SP ₃ represents the acceptance of the projects by the political leaders	(Kahraman, 2009)
	Working conditions	SP ₄	SP ₄ measures the comport of the working place, and the health and safety status of the workers	(Gnansounou, 2011)
	Security for food supply	SP ₅	SP ₅ evaluates the reduction of the supplied food and influence on the security of food supply owing to the production of crop based biodiesel	(Diaz-Chavez, 2011; Ziolkowska, 2013)
	Employment	SP ₆	SP ₆ represents the number of job creation in local region by the development of biofuels industry	(Hayashi et al., 2014; Perimenis et al., 2011)

Table 2 Linguistic terms and the corresponding grey number used in grey DEMATEL

Linguistic terms	Abbreviation	Grey numbers
No influence	N	[0, 0]
Extremely low influence	EL	[0, 1]
Moderately low influence	ML	[1, 2]
Medium influence	M	[2,3]
Moderately high influence	MH	[3, 4]
Extremely high influence	EH	[4, 5]

Table 3 Direct-influenced matrix using linguistic terms

	T ₁	T ₂	T ₃	T ₄	EC ₁	EC ₂	EC ₃	EC ₄	EN ₁	EN ₂	EN ₃	EN ₄	EN ₅	SP ₁	SP ₂	SP ₃	SP ₄	SP ₅	SP ₆
T ₁	N	M	EH	MH	N	ML	M	MH	MH	ML	M	M	N	MH	N	EH	EH	N	ML
T ₂	EL	N	M	M	MH	MH	MH	M	N	N	ML	ML	N	ML	N	M	MH	N	M
T ₃	M	N	N	N	EL	EL	MH	MH	M	EL	MH	MH	N	M	N	MH	N	MH	N
T ₄	MH	M	N	N	N	EH	EL	MH	N	N	N	N	N	EH	N	MH	EH	N	ML
EC ₁	M	ML	ML	M	N	ML	EL	EH	N	N	N	N	N	MH	EH	EH	ML	N	MH
EC ₂	N	N	N	MH	N	N	N	M	N	N	N	N	N	ML	EL	M	EL	N	EL
EC ₃	N	N	N	N	N	N	N	ML	N	N	N	N	N	MH	MH	EH	N	N	N
EC ₄	N	N	N	N	N	N	N	N	N	N	N	N	N	MH	EL	MH	N	N	EL
EN ₁	N	N	N	N	N	N	N	MH	N	N	ML	N	N	MH	N	MH	N	N	N
EN ₂	N	N	N	N	N	N	N	M	N	N	N	N	N	MH	N	MH	N	N	N
EN ₃	N	N	N	N	N	N	M	MH	N	N	N	N	N	MH	N	MH	N	N	N
EN ₄	N	N	N	N	N	N	EL	M	N	N	N	N	N	M	N	M	N	N	N
EN ₅	N	N	N	N	N	N	N	ML	N	N	N	N	N	ML	N	ML	N	N	N
SP ₁	N	N	N	N	N	N	N	M	N	N	N	N	N	N	N	MH	N	N	N
SP ₂	N	N	N	N	N	N	N	MH	N	N	N	N	N	M	N	M	N	N	N
SP ₃	N	N	N	N	N	N	N	MH	N	N	N	N	N	ML	N	N	N	N	ML
SP ₄	N	N	N	ML	EL	N	N	ML	N	N	N	N	N	ML	N	ML	N	N	N
SP ₅	N	N	N	N	N	N	N	MH	N	N	N	N	N	MH	N	MH	N	N	ML
SP ₆	N	N	N	N	N	N	N	ML	N	N	N	N	N	M	N	M	N	N	N

Table 4 Direct-influenced matrix using grey numbers

	T ₁	T ₂	T ₃	T ₄	Ec ₁	Ec ₂	Ec ₃	Ec ₄	En ₁	En ₂	En ₃	En ₄	En ₅	SP ₁	SP ₂	SP ₃	SP ₄	SP ₅	SP ₆
T ₁	[0,0]	[2,3]	[4,5]	[3,4]	[0,0]	[1,2]	[2,3]	[3,4]	[3,4]	[1,2]	[2,3]	[2,3]	[0,0]	[3,4]	[0,0]	[4,5]	[4,5]	[0,0]	[1,2]
T ₂	[0,1]	[0,0]	[2,3]	[2,3]	[3,4]	[3,4]	[3,4]	[2,3]	[0,0]	[0,0]	[1,2]	[1,2]	[0,0]	[1,2]	[0,0]	[2,3]	[3,4]	[0,0]	[2,3]
T ₃	[2,3]	[0,0]	[0,0]	[0,0]	[0,1]	[0,1]	[3,4]	[3,4]	[2,3]	[0,1]	[3,4]	[3,4]	[0,0]	[2,3]	[0,0]	[3,4]	[0,0]	[3,4]	[0,0]
T ₄	[3,4]	[2,3]	[0,0]	[0,0]	[0,0]	[4,5]	[0,1]	[3,4]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[4,5]	[0,0]	[3,4]	[4,5]	[0,0]	[1,2]
EC ₁	[2,3]	[1,2]	[1,2]	[2,3]	[0,0]	[1,2]	[0,1]	[4,5]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[4,5]	[4,5]	[1,2]	[0,0]	[3,4]
EC ₂	[0,0]	[0,0]	[0,0]	[3,4]	[0,0]	[0,0]	[0,0]	[2,3]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[1,2]	[0,1]	[2,3]	[0,1]	[0,0]	[0,1]
EC ₃	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[1,2]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[3,4]	[4,5]	[0,0]	[0,0]	[0,0]
EC ₄	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[0,1]	[3,4]	[0,0]	[0,0]	[0,1]
EN ₁	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[0,0]	[0,0]	[1,2]	[0,0]	[0,0]	[3,4]	[0,0]	[3,4]	[0,0]	[0,0]	[0,0]
EN ₂	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[2,3]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[0,0]	[3,4]	[0,0]	[0,0]	[0,0]
EN ₃	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[2,3]	[3,4]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[0,0]	[3,4]	[0,0]	[0,0]	[0,0]
EN ₄	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,1]	[2,3]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[2,3]	[0,0]	[2,3]	[0,0]	[0,0]	[0,0]
EN ₅	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[1,2]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[1,2]	[0,0]	[1,2]	[0,0]	[0,0]	[0,0]

SP ₁	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[2,3]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]
SP ₂	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[2,3]	[0,0]	[0,0]
SP ₃	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[1,2]	[0,0]	[0,0]
SP ₄	[0,0]	[0,0]	[0,0]	[1,2]	[0,1]	[0,0]	[0,0]	[0,0]	[1,2]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[1,2]	[0,0]	[0,0]
SP ₅	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[3,4]	[0,0]	[0,0]
SP ₆	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[1,2]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[0,0]	[2,3]	[0,0]	[0,0]

Table 5 The results of grey DEMATEL analysis

		$\otimes R_i$	$\otimes C_i$	$\otimes R_i + \otimes C_i$	$\otimes R_i - \otimes C_i$
Maturity	T ₁	[0.6345,0.9794]	[0.1196,0.1994]	[0.7541,1.1788]	[0.4351,0.8598]
Complexity	T ₂	[0.4579,0.7814]	[0.0858,0.1467]	[0.5437,0.9281]	[0.3112,0.6956]
Conversion efficiency	T ₃	[0.4273,0.7018]	[0.1167,0.1765]	[0.5439,0.8783]	[0.2507,0.5851]
Safety and reliability	T ₄	[0.4341,0.6671]	[0.1863,0.2909]	[0.6204,0.9580]	[0.1432,0.4808]
Investment cost	EC ₁	[0.4685,0.7665]	[0.0494,0.1072]	[0.5179,0.8736]	[0.3613,0.717]
Operation and maintenance cost	EC ₂	[0.1477,0.2931]	[0.1541,0.2550]	[0.3018,0.5481]	[-0.1073,0.1389]
Cost of production	EC ₃	[0.1822,0.2610]	[0.1679,0.3035]	[0.3501,0.5646]	[-0.1214,0.0931]
Competitiveness	EC ₄	[0.0984,0.1721]	[0.7556,1.1831]	[0.8540,1.3552]	[-1.0847,-0.5835]
Reduction of GHG emissions	EN ₁	[0.1663,0.2465]	[0.0847,0.1262]	[0.2510,0.3726]	[0.0401,0.1617]
Land use change and Biodiversity	EN ₂	[0.1317,0.1904]	[0.0170,0.0542]	[0.1487,0.2445]	[0.0775,0.1734]
Non-renewable energy use	EN ₃	[0.1842,0.2654]	[0.1176,0.1947]	[0.3017,0.4601]	[-0.0105,0.1479]
Water use	EN ₄	[0.0989,0.1752]	[0.1011,0.1606]	[0.2000,0.3358]	[-0.0617,0.0741]
Soil quality	EN ₅	[0.0494,0.1041]	[0.0000,0.0000]	[0.0494,0.1041]	[0.0494,0.1041]
Social acceptability	SP ₁	[0.0825,0.1223]	[0.7292,1.1538]	[0.8117,1.2761]	[-1.0713,-0.6069]
Regional development contribution	SP ₂	[0.1155,0.1739]	[0.1167,0.2150]	[0.2322,0.3888]	[-0.0994,0.0572]
Government support degree	SP ₃	[0.0827,0.1395]	[0.8630,1.3039]	[0.9458,1.4434]	[-1.2211,-0.7235]
Working conditions	SP ₄	[0.0712,0.1813]	[0.2050,0.3107]	[0.2762,0.4921]	[-0.2396,-0.0237]
Security for food supply	SP ₅	[0.1647,0.2426]	[0.0508,0.0713]	[0.2155,0.3139]	[0.0934,0.1919]
Employment	SP ₆	[0.0823,0.1383]	[0.1597,0.3491]	[0.2419,0.4874]	[-0.2668,-0.0214]

Table 6 Ranks and categories of the criteria

	T ₁	T ₂	T ₃	T ₄	EC ₁	EC ₂	EC ₃	EC ₄	EN ₁	EN ₂	EN ₃	EN ₄	EN ₅	SP ₁	SP ₂	SP ₃	SP ₄	SP ₅	SP ₆
Rank	4	6	7	5	8	10	9	2	14	18	12	16	19	3	15	1	11	17	13
Cause	√	√	√	√	√	√			√	√	√	√	√					√	
Effect							√	√						√	√	√	√		√