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Research article

Multi-criteria decision making for the prioritization of energy systems under uncertainties after life cycle sustainability assessment

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ABSTRACT

This study aims at developing a life cycle sustainability prioritization framework for ranking the energy systems under uncertainties. The fuzzy two-stage logarithmic goal programming method was firstly employed to determine the weights of the criteria for sustainability assessment, and the interval grey relational analysis method was subsequently used to determine the sustainability order of the alternative energy systems. Then, an illustrative case including four alternatives for electricity generation in UK, namely, coal-pulverized, combined cycle gas turbines, nuclear-pressurized water reactor, and offshore wind powder based electricity, was investigated, and pressurized water reactor was recognized as the most sustainable, followed by combined cycle gas turbines, offshore wind powder, and coal-pulverized in the descending order. Finally, the results were validated by the interval TOPSIS, and sensitivity analysis was also carried used to investigate the effects of the weights of the criteria for sustainability assessment on the final sustainability order of the alternative energy systems.

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1. Introduction

Energy as the food of industry plays a significant important role for promoting the development of the economy of the world (Ren and Sovacool, 2015). The consumptions of energy sources (i.e. coal, petroleum, and natural gas) for power, heat or cooling has leaded to various environmental and social problems (Bose, 2010). The development of renewable energy has high potential for emissions reduction and energy security improvement. However, the use of renewable energy sources (i.e. wind, solar, biomass, geothermal, and hydropower, etc.) also requires various kinds of inputs. For instance, the production of biofuel from biomass requires various inputs, i.e. chemicals, steam, coal and electrifies, etc. (Ren et al., 2014a). There are also various emissions during the whole life cycle of biofuel. Accordingly, it is usually difficult for the decision-makers to know whether or not the energy systems including both non-renewable energy and renewable energy based scenarios are sustainable.

Singh et al. (2009) pointed out that the concept of sustainability or sustainable development attracted more and more attentions of the policy makers in the industry. Accordingly, sustainability assessment of energy systems for helping the decision-makers to select the most sustainable scenario is of vital importance (Ren et al., 2016). As for the evaluation of energy systems, There are usually various ways for the evaluation of energy systems, i.e. thermodynamic method, energy cost evaluation and life cycle method (Afgan and Carvalho, 2004). All these method aimed at using a single index to measure the performances of different energy systems. However, sustainability assessment of energy systems is complex due to the involvement of a number of economic, environmental, social and technological parameters (Begić and Afgan, 2007). Therefore, sustainability assessment of energy systems is a multi-criteria decision analysis problem. There are various studies about using the multi-criteria decision analysis for sustainability assessment of energy systems. For instance, Afgan and Carvalho (2002) employed energy resources, environment capacity, economic indicators, and social indicators to have a multi-criteria assessment of power plants. Maxim (2014) employed the weighted sum multi-attribute utility approach and ten indicators to assess the sustainability of electricity generation technologies. Škobalj et al. (2017) the Analysis and Synthesis of Parameters under Information Deficiency (ASPID) method was used to assess the sustainability of the options for electricity generation with the considerations of the indicators in economic, environmental, social and technological aspects. All the above mentioned studies can help the decision-makers to select the most sustainable energy system, but they only considered the hard criteria for sustainability, while the soft criteria for sustainability assessment are usually neglected. There are also some other studies which incorporate the soft criteria for sustainability assessment by quantifying the energy systems with respect to the soft criteria. For instance, Evans et al. (2009) used multiple sustainability indicators to assess the comprehensive performances of four renewable energy technologies including photovoltaics, wind,

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hydro, and geothermal. Ren and Liang (2017a) developed an intuitionistic fuzzy set theory based group multi-attribute decision analysis for ranking the wastewater treatment technologies. Ren and Liang (2017b) combined the fuzzy logarithmic least squares method and the fuzzy TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) to prioritize the marine fuels according to their sustainability performances. Ren and Lützen (2017) combined the Dempster–Shafer theory and the trapezoidal fuzzy AHP (analytic hierarchy process) to rank the alternative energy source under incomplete information condition. However, all these methods reply on using the judgments of the decision-makers to rate the alternative energy systems, and the performances of the energy systems with respect to the criteria for sustainability assessment were determined based on the subjective judgments of the decision-makers. Meanwhile, the data of the energy systems with respect to the criteria for sustainability assessment determined by life cycle sustainability assessment cannot be fully used. Life cycle sustainability assessment can help the decision-makers to collect the data of the energy systems with respect to economic, environmental and social dimensions; this has been illustrated in many studies (Atilgan and Azapagic, 2016). Accordingly, life cycle sustainability assessment has been combined with multi-criteria decision making methods for sustainability ranking of energy systems in more and more studies recently. For instance, Santoyo-Castelazo and Azapagic (2014) combined life cycle tools (life cycle assessment and life cycle costing), social sustainability assessment, and multi-criteria decision analysis for sustainability assessment of energy systems, and the alternative power plant technologies were studied. Ren et al. (2015) employed life cycle sustainability assessment and multi-criteria decision making method (VIKOR method) to prioritize the alternative pathways for bioethanol production according to their life cycle sustainability performance. The studies can help the decision-makers to determine the life cycle sustainability order of the energy systems; however, there are usually various uncertainties which cannot be addressed by these methods. Uncertainties refer to the variations of data caused by the influences of external environment, estimations and various assumptions in life cycle sustainability assessment. In addition, the determination of the weights of the criteria sustainability which cannot only reflect the relative importance of the evaluation criteria, but also the preferences of the decision-makers, is of vital importance for determining the sustainability order of energy systems accurately. Most of the studies employed Analytic Hierarchy Process (AHP) and various method derived from AHP to determine the weights of the criteria for sustainability assessment (He et al., 2017). However, all these methods have two weak points: one is the difficulty of addressing the vagueness and ambiguity existing in human's judgments when comparing each pair of factors and another is the difficulty of guarantee the consistency when establishing the comparison matrix. In order to solve these two weak points, various fuzzy AHP methods (Chang, 1996; Zhu et al., 1999) were developed to capture the vagueness and ambiguity existing in human's judgments in weights determinations; meanwhile, the Best–Worst method developed by Rezaei (2015) which can reduce the times of comparisons and has better consistency performances for weights determination were widely used for its significant advantages (Ren et al., 2017). However, the vagueness and ambiguity existing in human's judgments cannot be addressed. Based on the above-mentioned literature reviews, a method which can simultaneously capture the following issues is prerequisite for sustainability prioritization of energy systems:

(1) The collection of the data with respect to the criteria for sustainability assessment in life cycle perspective instead of only the production stage, the economic, environmental, and social performances should be accounted in a "cradle to grave" approach;
(2) The vagueness and ambiguity existing in human's judgments should be addressed in the determination of the weights of the criteria for sustainability assessment; and
(3) The data uncertainties in multi-criteria decision making for ranking the alternative energy systems.

In order to capture the above-mentioned three issues in sustainability prioritization of energy systems, this study aims at developing a life cycle sustainability prioritization framework for ranking the alternative energy systems under data uncertainties conditions. The fuzzy two-stage logarithmic goal programming method was employed to determine the weights of the criteria for sustainability assessment, and the interval grey relational analysis method was used to determine the sustainability order of the alternative energy systems.

Besides the introduction, the remainder parts of this study were organized as follows: the methods for life cycle sustainability prioritization of energy systems were presented in Section 2; an illustrative case has been studied by the proposed method in Section 3; the results were discussed in Section 4; and finally, this study has been concluded in Section 5.

2. Methods

In order to get the data of different alternative energy systems with respect to the criteria in the three categories (environmental impacts, economic performances and social influences) of sustainability in "cradle to grave" thinking, the data with respect to the environmental–economic–social criteria for sustainability assessment of energy systems should be collected in life cycle perspective (Ren and Toniolo, 2018). Therefore, life cycle sustainability assessment was employed to determine the data in the decision-making matrix with respect to the criteria in the three pillars of sustainability. The uncertainties of data were incorporated in the life cycle data collection process, and interval numbers were used to replace the crisp numbers to represent the variations of the data.

In order to overcome the vagueness, ambiguity and hesitations existing in human's judgments, the weights of the criteria for life cycle sustainability assessment were determined by the fuzzy two-stage logarithmic goal programming method after determining the decision-making matrix, and the decision-makers can use fuzzy numbers rather than the crisp numbers to address the vagueness, ambiguity and hesitations existing in human's judgments (Wang et al., 2017). The weights of the criteria determined by this method were also interval numbers.

After determining the weights of the criteria, interval grey relational analysis which can address interval numbers in the decision-making matrix was employed to rank the alternative energy systems according to their integrated life cycle sustainability performances by aggregating the criteria in economic, environmental and social pillars into a sustainability index.

The framework of life cycle sustainability prioritization method developed in this study was illustrated in Fig. 1, and it can be divided into three stages: (1) stage 1: data collection for multi-criteria sustainability ranking based on life cycle sustainability assessment; (2) stage 2: determining the weights of the criteria for sustainability assessment based on the fuzzy two-stage logarithmic goal programming method; and (3) stage 3: ranking the alternative energy systems based on the data collection in stage 1 and the weights of the criteria in stage 2.

Stage 1: life cycle sustainability assessment (LCSA) which consists of life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (SLCA) was employed to determine the data of the energy systems with respect to economic, environmental, and social criteria. Note that the decision-makers should select

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