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Life cycle sustainability decision-support framework for ranking of hydrogen production pathways under uncertainties: An interval multi-criteria decision making approach

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A B S T R A C T

Hydrogen as a clean energy carrier has been recognized as a promising alternative for emissions mitigation and environmental protection. Life cycle sustainability assessment (LCSA) of hydrogen can help the decision-makers/stakeholders to select the most sustainable pathway for hydrogen production in life cycle perspective among several alternatives. This study aims at developing a life cycle sustainability decision-support framework for ranking hydrogen production pathways by combining LCSA and interval multi-criteria decision making (MCDM) method. A novel interval MCDM method which can handle interval numbers in the decision-making matrix was developed by combining the improved decision-making trial and evaluation laboratory (DEMATEL) and interval evaluation based on distance from average solution (EDAS). Four pathways for hydrogen production, including coal gasification (CG), stream reforming of methane (SMR), biomass gasification (BG), and wind turbine electrolysis (WEL), have been studied by the proposed method. BG was recognized as the most sustainable one among these four scenarios, following by SMR, WEL, and CG in the descending order. Sensitivity analysis was carried out to investigate the effects of the weights of the indicators for sustainability assessment on the final ranking. The interval sum weighted method (ISWM) and interval TOPSIS method were also employed to validate the results determined by the proposed interval EDAS in this study and the results reveal that BG was recognized as the most sustainable scenario by all these three methods.

1. Introduction

Hydrogen as an alternative energy carrier for transportation has attracted more and more attentions, because there is no emission during its oxidation (Ren et al., 2015a, 2015b). There are various ways for hydrogen production, i.e. coal gasification, stream reforming of methane, biomass gasification, and water electrolysis. Although there is zero emission during the utilisation stage of hydrogen, there are also some negative impacts on the environmental during its production stage (Bhandari et al., 2014). In order to investigate the environmental impacts of hydrogen comprehensively and completely, life cycle assessment, also called "life cycle environmental assessment", which can measure the life cycle environmental impacts of a product/process, was widely used for studying the environmental performances of hydrogen "from cradle to grave". Koroneos et al. (2004) employed life cycle assessment to investigate the environmental impacts of hydrogen based on natural gas steam reforming and production from renewable energy sources. Cetinkaya et al. (2012) used life cycle assessment to compare the greenhouse gas emissions and consumed energy of five pathways for hydrogen production, including steam reforming of natural gas, coal gasification, water electrolysis via wind and solar electrolysis, and thermochemical water splitting with a Cu–Cl cycle. Dufour et al. (2012) used life cycle assessment to compare different alternatives for hydrogen production from renewable and fossil sources, i.e. water photo-splitting, methane steam reforming with CCS, electrolysis with different electricity sources, solar two-step thermochemical cycles, and auto-maintained methane decomposition with different layouts. All these methods can effectively quantify the environmental impacts (i.e. global warming potential and acidification

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potential) of various hydrogen production pathways, but it is still difficult for the decision-makers/stakeholders to determine the most environmental-friendly scenario among multiple alternatives for hydrogen production. For instance, an alternative for hydrogen production perform better with respect to an indication over another alternative, but it may perform worse on another indicator. Weighting in life cycle assessment to aggregate the multiple aspects of environmental impacts into a general index is the most widely used way to address this (Ren et al., 2015c). However, life cycle assessment can merely investigate the environmental impacts of different alternative hydrogen production pathways, and the economic performances and social influences cannot be studied.

In order to consider the three pillars of sustainability (economic, environmental and social aspects) simultaneously, LCSA by integrating LCA, LCC, and SLCA should be used to investigate the environmental, economic, and social performances of different hydrogen production pathways, and the decision-making matrix can be determined after this. The key issue for sustainability ranking of different hydrogen production pathways is a multi-criteria decision making problem, including weights determination and alternatives prioritization. There are three severe challenges in this life cycle sustainability ranking framework, including (1) data collection: some hydrogen production technologies are new emerging processes, it is usually difficult to obtain the exact data of the alternatives with to the criteria in LCSA; (2) poor assumption: it is usually assumed that all the criteria in LCSA are independent and there is on relationship among them when determining the weights of these criteria in LCSA; (3) inaccurate decision making: the traditional multi-criteria decision making method cannot effectively prioritize the alternative hydrogen production pathways under the conditions of lacking exact data.

There are many studies by integrating life cycle tools and multi-criteria decision making methods for selecting the best industrial process among multiple alternatives (Hermann et al., 2007; Myllyviita et al., 2012; Rabl and Holland, 2008). However, the previous studies focusing on the combinations life cycle tools and multi-criteria decision making methods can only help the decision-makers/stakeholders to learn the life cycle environmental or sustainability performances and assistant them to select the most environmental-friendly or the most sustainable hydrogen production pathway under the condition that all the data can obtained exactly and accurately. In other words, these methods cannot achieve life cycle sustainability ranking under uncertainty conditions-if the data are not crisp numbers, because there are still two weak points in these multi-criteria decision making methods:

(1) The lack of considering various uncertainties: all the data used in LCA or LCSA were assumed to be crisp numbers. Accordingly, the data used in multi-criteria decision making were also crisp numbers, and various uncertainty factors were neglected. Actually, there are usually various uncertainties in life cycle sustainability ranking due to the lack of information and knowledge as well as the variations of data caused by external influences, but it lacks the multi-criteria decision making methods for ranking the alternative hydrogen production pathways under uncertainties;
(2) The lack of considering the independences and interactions among the criteria in multi-criteria decision making: as for the weights of the criteria determined in LCA or LCSA, the users usually neglect to interdependences and interactions among the criteria when calculating their weights using AHP and various modified AHP (i.e. fuzzy AHP and grey AHP) methods in the previous studies.

In order to resolve the above-mentioned two academic gaps, a life cycle sustainability ranking formwork has been developed for ranking hydrogen production pathways in life cycle perspective under uncertainty conditions, the multi-criteria decision making method has been extended to uncertainty conditions, and an interval multi-criteria decision making method for addressing uncertainties has been developed in this study for ranking the alternative processes/products after LCSA, and a novel weighting method which can incorporate the interdependences and interactions among the criteria for sustainability assessment was developed to determine the relative weights (relative importance) of these criteria. More specifically, this study has two main innovations:

(1) Developing an interval evaluation based on distance from average solution method for ranking the alternative processes/products in life cycle perspective under uncertainty conditions, and all the data used in the decision-making matrix are interval numbers rather than crisp numbers-the uncertainty factors have been incorporated in decision-making;
(2) Developing an improved decision-making trial and evaluation laboratory method which can incorporate the interdependences and interactions among the criteria in LCSA for calculating the weights of these criteria.

Besides the introduction section, the remainder parts of this study have been organized as follows: a comprehensive literature review of the weighting method in LCA and the combinations of multi-criteria decision making methods and life cycle tools was presented in section 2; the methods used in this study including the weighting method and the improved multi-criteria decision making method were presented in section 3; an illustrative case has been studied in section 4; the results have been discussed through sensitivity analysis and validation in section 5; and finally, this study has been concluded in section 6.

2. Literature review

Life cycle assessment generates the data with respect to different environmental impact categories, and it is difficult for the users to judge which the best alternative is among multiple options. As mentioned above, weighting method used in life cycle assessment which can aggregate the multiple categories of environmental impacts into a general index is the most widely used way to help the users to identify the best alternative is. Within LCA, weighting is an optional step and is performed after characterisation or normalisation in order to weight against each other the results of the different environmental categories analysed (Ahlroth, 2014; Ahlroth et al., 2011; Myllyviita et al., 2014). The application of weighting arises in situations where it is difficult to decide that one option is environmentally preferable than another and leads to a single score, which can seem a reduction of complexity but actually is the adding of new information (Bengtsson and Steen, 2000). The decision-makers usually have to face this situation in life cycle assessment of hydrogen production methods.

Several issues have been debated over the past years about the necessity and the modality of weighting within life cycle assessment procedures. Finnveden (1997) raised three important questions about the necessity of weighing and the possibility to give priority to some aspects, the methodological approach to use and finally the weighting factors to be chosen. He also discussed that