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Cost-benefit analysis of different hydrogen production technologies using AHP and Fuzzy AHP

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ABSTRACT

In this paper, cost-benefit analysis is performed to compare eight different hydrogen production technologies using the classical analytic hierarchy process (AHP) and the Fuzzy AHP. The technologies considered are steam methane reforming, coal gasification, partial oxidation of hydrocarbons, biomass gasification, photovoltaic-based electrolysis, wind-based electrolysis, hydro-based electrolysis, and water splitting by chemical looping. For each of the hydrogen production technologies, five criteria are used for evaluation: greenhouse gas emissions, raw material and utilities consumption, energy efficiency, scalability, as well as waste disposal and atmospheric emissions. The results obtained for benefits category using AHP and Fuzzy AHP are plotted against the normalized equivalent annual costs of each technology. It is concluded that the fossil fuel based processes appear to have less beneficial qualities including greater environmental impacts, but are more cost-effective. On the other hand, the renewable based processes appear to have more benefits as well as being more expensive for hydrogen production. However, the cost-benefit analysis results imply that the process of water splitting by chemical looping among the renewable approaches is the most promising new technology.

Introduction

The current global distribution of energy usage is estimated to be 80% fossil fuels, 14% renewable energy and 6% nuclear power [1]. It is predicted that the global energy consumption will rise by more than one-third in the next twenty years [2]. This will result in adverse environmental impacts if fossil fuels continue to be used at a similar rate. Hence, there is a need of a sustainable, secure, and accessible supply of energy to meet the global energy demand. Hydrogen can act as a possible solution as an important energy carrier that can be produced by both fossil fuels and renewable sources [3]. The route by which hydrogen is

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produced would be the determining factor for its environmental performance. The demand for hydrogen is expected to significantly increase in the near future owing to the growing needs of refinery, chemical industries, as well as new applications such as synthetic fuel, bio-fuel production [4,5], and use in fuel cells.

Life cycle analysis (LCA) is the systematic methodology that includes all the life cycle stages from extraction of raw materials to final wastes management [4]. Several LCA have been performed on hydrogen storage, production and use, and integrated systems [6–11]. Primary drawback of LCA includes requirement of detailed inventory data and extensive literature survey for comparison of different alternatives.

Some researchers have evaluated the hydrogen production methods on the basis of thermodynamic analysis (i.e., energy and exergy efficiencies) [1,12,13]. These approaches may prove beneficial to compare the processes in thermodynamic regard, but they cannot be used for overall comparison of technologies as a whole (i.e., to include factors such as emission, cost, scalability, etc.). Furthermore, both LCA and thermodynamic methods do not provide any economic assessment, and it is difficult for these approaches to include both qualitative and quantitative attributes together for critical comparison of different options.

The multi-criteria decision making (MCDM) has emerged as a potential tool for analyzing complex problems with the potential to critically analyze the alternatives for different criteria to select the best/suitable alternative(s) [14,15]. These alternatives may need to be further explored in-depth for their final implementation. The Analytic Hierarchy Process (AHP) proposed by Saaty [16] is a very popular approach to MCDM that can take care of both quantitative and qualitative criteria. AHP has been used in several engineering applications such as the emissions from power plants [17], hydrogen fueling systems for transportation [18], evaluation of liquid bio-fuels [19] and for hydrogen energy technology [20,21].

There are only a few studies which used AHP to study different hydrogen production processes. Pilavachi et al. [22] evaluated seven hydrogen production methods using AHP for the criteria of CO_2 emissions, operation and maintenance cost, capital cost, feedstock cost and hydrogen production cost. The potential of AHP is not fully utilized in this case as it did not include any qualitative factors but only the quantitative attributes which could have been easily compared without AHP. Chui et al. [20] performed LCA on 11 different hydrogen production pathways [20]. Recently, Heo et al. [23] evaluated six different hydrogen production methods using Fuzzy AHP.

The present study reports a comprehensive assessment of eight of the most common hydrogen production technologies using AHP and Fuzzy AHP in terms of cost-benefit analysis including both economic and environmental aspects. The five different criteria used in the evaluation under the benefits category are greenhouse gas emissions, raw material and utilities consumption, energy efficiency, scalability, as well as waste disposal and atmospheric emissions. The criteria under benefits category are evaluated using both AHP and Fuzzy AHP for two different cases, first for assumed logical weights of criteria based on the objective, and second for equal weights of each criterion. Cost is a separate attribute against which the results obtained for benefits using AHP and Fuzzy AHP are plotted to give the final trade-offs so as to find a cost-effective environmentally benign hydrogen production technology.

Hydrogen production technologies

Natural gas, heavy oil, and coal are currently the main feedstock used for commercial hydrogen production. The technology for hydrogen production from each of these feedstocks is well advanced, and significant experience exists in the operation of these plants [7]. The non-hydrocarbon processes normally use the energy source to produce hydrogen through electricity or heat or a thermo-chemical process to split water into hydrogen and oxygen. Biomass gasification is still a developing technology and research is currently being done on the use of biomass to produce hydrogen from more advanced thermo-chemical and biological approaches [5,7]. Water splitting by chemical looping or thermo-chemical water splitting using metal–metal oxide cycles can be categorized as renewable based approaches of hydrogen production. The process considered in this category is the thermo-chemical water splitting using Zn/ZnO [24,25].

Fig. 1 shows the simplified process block diagrams for the eight hydrogen production processes: steam methane reforming (SMR), coal gasification (CG), partial oxidation of hydrocarbons (POX), biomass gasification (BG), photovoltaic-based electrolysis (PV-EL), wind-based electrolysis (W-EL), hydro-based electrolysis (H-EL), and water splitting by chemical looping (WS-CL). The details of each of these technologies are available in the literature [4,7,26–31]. All the technologies are considered without CO_2 sequestration, and are compared for the capacity of 254.6 tonnes H_2/day (i.e., 100×10^6 scfd H_2/day) [27]. To ensure that all plants operate 24 h per day, the PV-based electrolysis technology is assumed to be supplemented by an equal amount of conventional electricity and the wind-based electrolysis technology is assumed to be supplemented with 20% conventional electricity. In both cases, the additional electricity is assumed to have been generated by a pulverized coal power station.

Selection of attributes

As the main objective of this work is to consider the trade-offs from a cost-benefit analysis for different alternatives of hydrogen production, the two major attributes are the costs associated with each technology and the benefits. The cost is a quantitative attribute representing the normalized equivalent annual cost (EAC) which includes the factors such as capital cost, fixed operating cost, and variable operating cost. The criteria selected under the benefits category are the greenhouse gas (GHG) emissions, raw material and utilities consumption, energy efficiency, scalability, waste disposal and non GHG atmospheric emissions. These five criteria are chosen to evaluate the fossil and renewable based hydrogen production processes