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Multi-criteria evaluation of hydrogen storage systems for automobiles in Korea using the fuzzy analytic hierarchy process

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ABSTRACT

In this paper, five hydrogen storage systems for automobiles are evaluated using the fuzzy analytic hierarchy process (AHP) in respect to eight criteria. The hydrogen storage systems for automobiles to be evaluated are 350 bar compressed gas hydrogen, 700 bar compressed gas hydrogen, liquefied hydrogen, metal hydride and chemical hydride. The selected criteria used in the evaluation of five hydrogen storage systems are weight efficiency, volume efficiency, system cost, energy efficiency, cycle life, refueling time, safety and infrastructure. According to the evaluation, compressed gas hydrogen ranks the highest in classification in Korea. Liquefied hydrogen ranks higher than metal hydride and chemical hydride. If the infrastructure for liquefied hydrogen were good in Korea, liquefied hydrogen may rank the highest in classification. Also, it should be noted that the rank of hydrogen storage systems can be changed according to the future technological developments.

Introduction

Hydrogen has the highest energy content per unit of weight and it is also the lightest element. Because of hydrogen's low volume energy density, it is inconvenient to store and transport compared with other liquid fuels such as gasoline and diesel. This presents significant challenges to developing hydrogen storage systems which can store large quantities of hydrogen for the realization of the hydrogen economy. Hydrogen storage systems can be classified into stationary, on-board, infrastructure and other uses. This paper focuses on hydrogen storage systems that are necessary for operating hydrogen fuel cell vehicles.

The US Department of Energy (DOE) [1] reported on the current status of evaluation criteria such as weight efficiency, volume efficiency and system cost for hydrogen storage systems of 350 bar compressed gas hydrogen (CH_2 350), 700 bar compressed gas hydrogen (CH_2 700), liquefied hydrogen (LH_2), metal hydride (MH) and chemical hydride (CH). The International Partnership for the Hydrogen Energy (IPHE) [2] suggested cost, weight efficiency, volume efficiency, efficiency, durability, refueling time and codes & standards as major challenging tasks for hydrogen storage systems. The present

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Nomenclature

CH_2	compressed gas hydrogen
LH_2	liquefied hydrogen
MH	metal hydrogen
CH	chemical hydrogen
AHP	analytic hierarchy process
DOE	department of energy
IPHE	international partnership for the hydrogen economy
TFN	triangular fuzzy numbers
WE	weight efficiency
VE	volume efficiency
SC	system cost
EE	energy efficiency
RT	refueling time
CL	cycle life
S	safety
I	infrastructure

study performs a comprehensive evaluation of five hydrogen storage systems for automobiles using the fuzzy analytic hierarchy process (AHP) approach. The selected criteria used to evaluate five hydrogen storage systems are weight efficiency (WE), volume efficiency (VE), energy efficiency (EE), system cost (SC), cycle life (CL), refueling time (RT), safety (S) and infrastructure (I).

The AHP, introduced by Saaty [3], has proven to be a powerful decision analysis technique in the area of multi-criteria decision making problems. The AHP utilizes a hierarchical tree structure to simplify complex problems. At each level of the hierarchy, the AHP uses pairwise comparison judgments to identify the relative priorities of criteria and alternatives. The AHP has been used for several studies in the area of the emission from power plants [4], hydrogen production methods [5] and the hydrogen energy technology [6].

This paper evaluates five hydrogen systems using the fuzzy AHP approach, in which the decision maker's pairwise comparison judgments are represented as fuzzy triangular numbers (TFN). Fuzzy theory, introduced by Zadeh [7], includes elements such as the fuzzy set, membership functions and fuzzy numbers. Since the fuzzy set theory utilizes a method similar to human thinking and perception, it effectively represents human thoughts and judgments. The AHP cannot take into account uncertainty when evaluating criteria and alternatives. However, the fuzzy AHP can tackle the problems of vague decision making by using the fuzzy scale with interval values of lower, median and upper values. The fuzzy AHP have been used for studies in the area of evaluating hydrogen production methods [8] and assessing the national competitiveness in the hydrogen technology sector [9].

This paper is organized as follows. Section 2 describes the selected criteria to evaluate five hydrogen storage systems for automobiles and the hierarchical structure of the criteria. Section 3 deals with the current status and the relative comparison results on each selected criterion of five hydrogen storage systems. Section 4 explains the fuzzy AHP approach used for the comprehensive evaluation of hydrogen storage systems. In Section 5, an illustrative example of the comprehensive evaluation of five hydrogen storage systems for automobiles in Korea using the fuzzy AHP is presented. The conclusion is then carried out in Section 6.

Selection and hierarchy of criteria

The indicators selected for the evaluation of hydrogen storage systems for automobiles are storage efficiency, economy, durability and operability, safety and infrastructure. Storage efficiency in turn consists of WE and VE, and economy is classified into SC and EE. Also, RT and CL are selected for representing indicators of durability and operability.

Weight efficiency, volume efficiency and system cost

The US DOE [1] reported the current status of WE, VE and SC. WE is defined as the usable specific energy from hydrogen (kW h/kg) or the net useful energy per maximum system mass (kg H_2/kg). VE is defined as the usable energy density from hydrogen (kW h/L) or the net useful energy per maximum system volume (kg H_2/L). SC means the initial cost of the storage system including the any component replacement if needed over 15 years or 150,000 miles.

Other criteria

At this time, the evaluation values of EE, CL, RT, S and I are not clearly determined. EE is defined as the net energy output divided by the energy input for the hydrogen storage system. The energy required to get hydrogen in and out of storage is an issue for solid-state materials storage systems. In addition, the energy associated with compression, liquefaction, leakage and ventilation must be factored in when considering compressed and liquefied hydrogen storage systems.

There are many evaluation criteria for representing durability and operability, but we only selected CL and RT as representing durability and operability of hydrogen storage systems. Storage media, materials of construction and balance-of-plant components are needed that allow hydrogen systems with CL of at least 1500 cycles. RT is defined as the fill time to refuel 5 kg of hydrogen to hydrogen fuel cell vehicles.

Safety is defined as the extent to which the unit is safe from risk factors such as explosion of hydrogen storage systems or harmful substances that could be generated from hydrogen storage systems. Infrastructure refers to the current status or the future construction plan of the infrastructure for hydrogen storage systems.

Hierarchy of criteria

The evaluation of hydrogen storage systems for automobiles consists of one-tier criteria. The hierarchy structure of the criteria is shown in Fig. 1.

At the top of the control hierarchy, there exists the goal of the problem. The goal is to evaluate hydrogen storage systems. At level 1, there exist five evaluation criteria: storage efficiency, economy, durability & operability, safety and infrastructure. At level 2, storage efficiency in turn consists of 2 sub-criteria, namely WE and VE. Economy in turn consists of