Available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Multi-criteria evaluation of on-board hydrogen storage technologies using the MACBETH approach

F. Montignac*, I. Noirot, S. Chaudourne

CEA, LITEN, Département des Technologies de l'Hydrogène, 17 rue des Martyrs, 38054 Grenoble, France

ARTICLE INFO

Article history:
Received 21 March 2008
Received in revised form
8 August 2008
Accepted 23 September 2008
Available online 20 November 2008

Keywords:
Hydrogen technologies
Hydrogen storage
Multi-criteria evaluation
Attractiveness

ABSTRACT

This paper provides some results obtained from the implementation of the MACBETH multi-criteria evaluation approach for the evaluation and comparison of the technical performance of three hydrogen storage technologies: a type IV 70 MPa hydrogen storage system, a cylindrical steel made liquid hydrogen storage system and a solid storage system. The evaluation is carried out considering a 6 kg hydrogen fuel cell vehicle application. Five technical evaluation criteria are taken into account in the analysis: system volume, system mass, refuelling time, hydrogen loss rate and conformability. The outcomes and added-value of this multi-criteria approach are finally discussed.

1. Introduction

Research for new energy technologies is a major issue for the future. Hydrogen energy is often considered as one possible solution to overcome global warming and climate change phenomena [1–3] and a wide variety of technologies is currently being investigated all over the world in the fields of hydrogen production (water electrolysis, natural gas reforming, thermochemical cycles, biomass gasification...), hydrogen storage (compressed gaseous hydrogen, liquid hydrogen, metal hydrides...), hydrogen distribution (gaseous hydrogen by pipelines or trucks, liquid hydrogen by trucks...) and final use (polymer electrolyte membrane fuel cells, solid oxide fuel cells, internal combustion engines...). The evaluation of the performances of these technologies is often necessary for orientating Research and Development towards the most promising solutions for the envisaged stationary and mobile applications [4–6]. The assessment of the maturity and relevancy of hydrogen technologies should be done taking into account the multiplicity of the attributes of these technologies: technical performances, safety, economics, environmental impacts, social impacts. To do so, some authors propose the use of multi-criteria evaluation methods and decision support systems [7,8]. This paper illustrates the implementation of an innovative multi-criteria evaluation method for the assessment of the performances of on-board hydrogen storage systems. Such evaluation method has been implemented close to car manufacturers in the framework of the STORHY FP6 European project (hydrogen storage systems for automotive applications). This paper provides some results obtained from the implementation of this evaluation method close to STORHY car manufacturers. The evaluation of this methodology by these end-users is reported and discussed. Three hydrogen storage technologies are evaluated and compared: a type IV 70 MPa hydrogen storage system ($C\text{-}H_2$), a cylindrical steel made liquid hydrogen storage system ($L\text{-}H_2$) and a solid storage system. The problematic of hydrogen storage for automotive applications is reminded at first. Then the implementation of the MACBETH multi-criteria

* Corresponding author.
E-mail address: florent.montignac@cea.fr (F. Montignac).
0360-3199/$ – see front matter
doi:10.1016/j.ijhydene.2008.09.098

Nomenclature

C-H_2	Compressed hydrogen
L-H_2	Liquid hydrogen
a	Alternative to be evaluated
g_i	Criterion i
$g_i(a)$	Performance of alternative a regarding criterion g_i
f_i	Fictitious alternative (satisfying on criterion g_i and acceptable on all other criteria)
w_i	Scale constant (weight) for criterion g_i
$v(a)$	Global performance of alternative a

evaluation-aiding method for the assessment of the technical performances of hydrogen storage systems for automotive applications is presented. The advantages and limits of the implementation of such method are finally discussed based on the experience gathered within the STORHY European project.

2. The challenge of hydrogen storage for automotive applications

2.1. *Hydrogen storage technologies*

Compared to other fuels, hydrogen is characterized by a high gravimetric energy density (120.1 MJ/kg, versus 42.0 MJ/kg for oil) and, in standard conditions, by a very low volumetric energy density (0.011 GJ/m^3, versus 34.5 GJ/m^3 for oil, i.e. 3136 times lower than oil). Fig. 1 illustrates the gravimetric and volumetric energy density of conventional fuels and hydrogen, including compressed and liquid hydrogen.

In order to increase its volumetric energy density, hydrogen is stored in gaseous form (compressed gas), or as a liquid (20 K) and also in solid media. Compressed and liquid storage technologies are rather established methods but still have some limitations concerning safety, hydrogen losses (boil-off phenomenon for liquid technology) and their energy intensive character (compression, liquefaction). Solid state storage appears as a possible attractive alternative due to its higher safety and volumetric energy density but improvements have to be made in order to increase gravimetric energy density, thermal management and up-scaling.

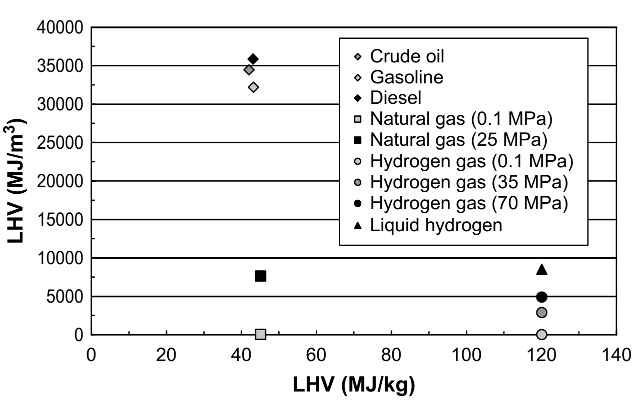

Fig. 1 – Lower heating value (LHV) of some conventional fuels comparing to hydrogen.

2.2. *Automotive applications*

Two technologies are feasible to run a road vehicle on hydrogen: i) to burn hydrogen in an internal combustion engine (ICE) with oxygen from air, or ii) to convert hydrogen electrochemically in a fuel cell with oxygen from air and so producing electricity and driving an electric engine. The efficiency of the direct process of electron transfer from oxygen to hydrogen is quoted as being able to reach 50–60%, twice as much as the thermal conversion in internal combustion engines (which is limited by the Carnot efficiency – around 25% for hydrogen–air mixtures) [9]. In practice, a modern, commercially available car with a range of 400 km burns about 24 kg of petrol in a combustion engine. For a similar performance, 8 kg of hydrogen is needed for the ICE version or 4 kg of hydrogen for an electric car with a fuel cell. To conclude, the amount of hydrogen to be stored on-board depends on the type of application (private car, bus...), the range and the motorization technology (fuel cell, internal combustion engine, hybrid technologies).

2.3. *Targets for hydrogen storage systems*

Hydrogen storage technologies have to comply with a number of requirements specified by manufacturers and end-users. Car manufacturers are asking for a safe and economical hydrogen storage solution that fulfils technical requirements related to system volume, system mass, refuelling time, conformability... On the other hand, end-users are looking for vehicles that are at least comparable to today's conventional gasoline vehicles in terms of performance, cost, vehicle range, comfort, reliability, and cost-competitive fuel. A set of quantified engineering-oriented targets for hydrogen storage systems has been provided by the US Department of Energy (DoE) and the US Council for Automotive Research [10]. These ideal targets are often compared by industrial and scientific communities to the performances of the currently developed hydrogen storage systems. These targets are based on the US weighted average corporate vehicle that includes minivans, light trucks, economy cars, and SUV/crossover vehicles in proportion of their sales. These targets are not related to one specific final automotive application. In the next part, a new innovative "application-oriented" evaluation approach is proposed, complementary to the engineering-orientated US DoE targets.

3. Proposal of a multi-criteria evaluation-aiding method for the evaluation of technical performances of hydrogen storage systems for automotive applications

3.1. *Aim of the approach*

The aim of this innovative approach is to help car manufacturers expressing their technical requirements related to a specific final application, and to obtain a global positioning of the performances of the currently developed hydrogen storage technologies regarding these requirements, using the notion of "scales of attractiveness". The methodological aspects and the results provided in the next paragraphs have