Chapter 20
Hydrogen Storage: Conclusions and Future Perspectives

Hai-Wen Li and Etsuo Akiba

Abstract This chapter summarizes the preceding chapters on hydrogen storage, and provides an outlook for the future of these technologies in the larger hydrogen society landscape.

Keywords Hydrogen storage · Interstitial hydride · Non-interstitial hydride · Adsorption · Absorption · Liquid hydrogen · Compressed hydrogen

Hydrogen has been extensively regarded as a clean energy carrier. The energy density of hydrogen per unit volume at ambient temperature and pressure is no more than 1/3000 of gasoline, which means that storage of hydrogen in a limited space is a big challenge. Therefore, storage and transport of hydrogen in a safe, compact, and economic way is indispensable for realizing a sustainable hydrogen society.

Hydrogen can be stored in gaseous, liquid, and solid states. The volumetric and gravimetric density in various systems are shown in Fig. 20.1.

Compressed hydrogen using high pressure tanks has been widely used as the most convenient way to supply hydrogen as chemical raw material or process gas in many fields, with the pressure lower than 20 MPa. Since hydrogen has been considered as an energy carrier, much higher pressure is required to increase the volumetric energy density, e.g., 70 MPa is adopted for onboard storage in the commercialized FCV MIRAI. Further improvement of the compression efficiency

H.-W. Li (✉)
International Research Center for Hydrogen Energy, Kyushu University,
Fukuoka 819-0395, Japan
e-mail: li.haiwen.305@m.kyushu-u.ac.jp

E. Akiba
Department of Mechanical Engineering, Faculty of Engineering, Kyushu University,
Fukuoka 819-0395, Japan
e-mail: e.akiba@mech.kyushu-u.ac.jp

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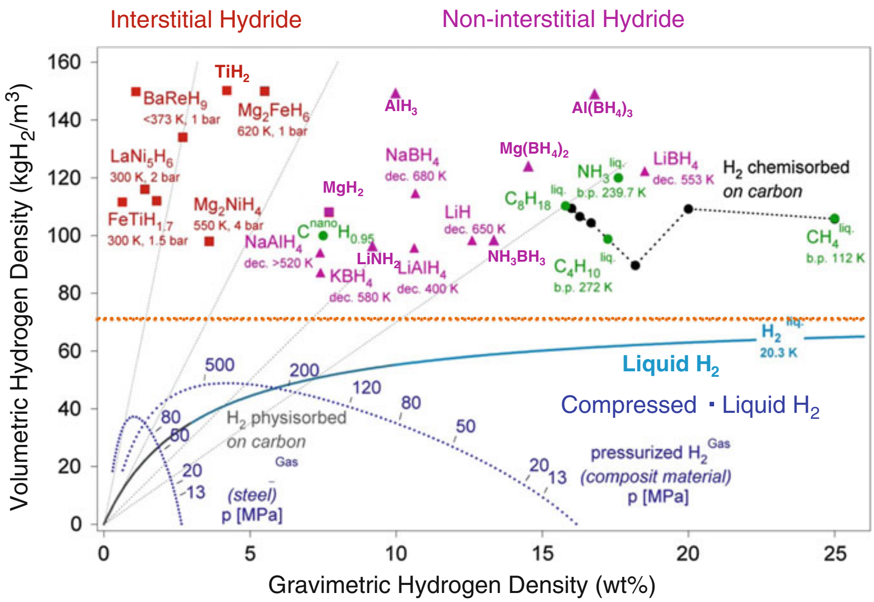

Fig. 20.1 Volumetric and gravimetric hydrogen density of some hydrogen storage systems [1] (used with permission from Elsevier, Copyright 2004)

and the development of low cost materials that can withstand the high pressure hydrogen under practical temperatures are crucial for widespread adoption of hydrogen energy applications.

Hydrogen can be stored in liquid carriers, such as liquid hydrogen, organic hydrides, and ammonia, which are assumed for large-scale hydrogen storage and transport in Japan. Liquid hydrogen is commonly used as liquid rocket fuel for space applications. The liquefaction of hydrogen needs an extremely low temperature of 20 K, which consumes approximately 30 % of the energy that hydrogen possesses. Development of high efficiency liquefaction processes and highly insulating systems to reduce the amount of boil off gas are therefore expected for use of liquid hydrogen for large-scale hydrogen storage and transport. Organic hydrides like methylcyclohexane (C_7H_{14}) keep their liquid state during hydrogen release and reabsorption processes, and are therefore potential hydrogen transport media. Such kinds of organic hydrides have similar chemical properties to gasoline, and therefore, can be transported using the current infrastructure. Development of advanced catalysts that reduce the hydrogen absorption and desorption temperature and separation technology of hydrogen from the organic hydrides are expected for the practical applications of organic hydrides for large-scale hydrogen storage. Ammonia, which can be readily liquefied by pressurizing to approximately 1.2 MPa at room temperature, is therefore also considered as a potential liquid energy carrier. It is well known that the performance of a proton exchange membrane fuel cell (PEFC) is seriously decreased by exposure to NH_3 as an impurity with ppm concentration. For this reason, development of solid oxide fuel cell that is robust to NH_3 and combustion technology of NH_3 for power generation are expected for the realization of ammonia as a clean energy carrier.

Solid-state hydrogen storage can be divided into two groups of physical adsorption and chemical storage using hydrides. Physical adsorption uses high-surface materials like activated carbon, zeolite, metal organic framework (MOF), etc. Molecular hydrogen is physically adsorbed on the material surface via van der Waals forces with a binding energy of 5–10 kJ/mol, therefore, higher hydrogen storage density can only be realized at lower temperature such as 77 K. According to the empirical Chahine's rule, approximately 1 wt% of hydrogen at maximum can be adsorbed at 77 K per 500 m^2/g, suggesting higher surface area enables the storage of more hydrogen. Hydrogen can be also chemically stored through making chemical bonds with neighboring atoms by formation of interstitial hydrides and non-interstitial hydrides. Hydrogen occupies tetrahedral and octahedral sites to form a metallic bond in the interstitial hydrides (i.e., hydrogen storage alloys) that are usually comprised of transition metals. Most of the interstitial hydrides can reversibly store hydrogen near room temperature with reasonable reaction rates. Hydrogen tends to form covalent bonds (sometime mixed with ionic bonding nature) in the non-interstitial hydrides of which most are comprised of light elements so that exhibit high gravimetric hydrogen density than that of interstitial hydrides.

Each hydrogen storage method as mentioned above, has its own unique characteristics, therefore, systematic and thorough investigations are expected to explore and develop the right applications for each method. With regard to the most

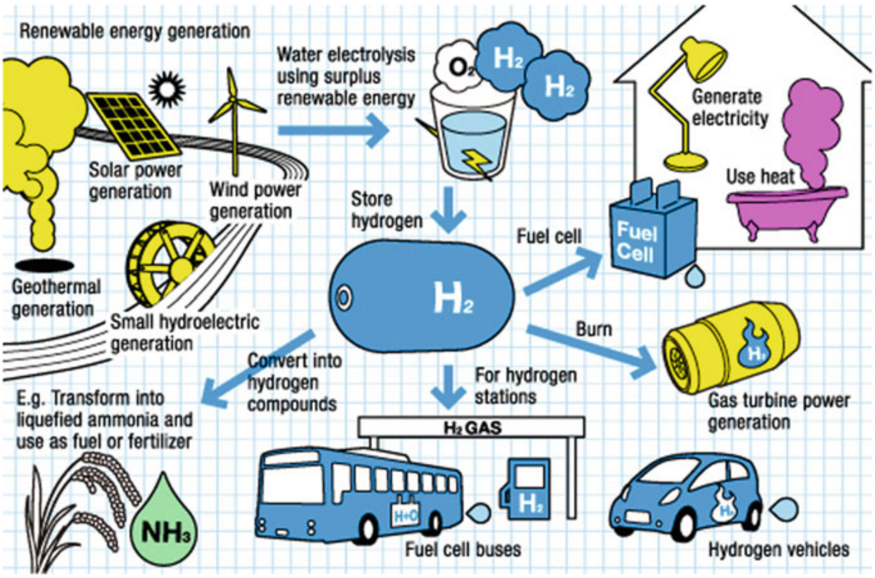

Fig. 20.2 An image of a sustainable hydrogen society [2]

challenging onboard hydrogen storage for FCV, due to the limited volumetric hydrogen density in the well-established compressed hydrogen and liquid hydrogen, solid-state hydrides comprised of light elements possessing high volumetric and gravimetric densities are highly expected for the realization of paradigm shift of hydrogen storage. Establishment of a *hydrogen materials science* based on further intensive fundamental researches will bring breakthrough in the development of hydrogen storage materials as well as structural materials for hydrogen infrastructure. Integration of several hydrogen storage methods is also expected from the engineering point of view to figure out a safe, compact, and economic way for storage and transport of hydrogen, aiming at the acceleration of the wide spread of a sustainable hydrogen society (see Fig. 20.2), as shown in the Strategic Road Map for Hydrogen and Fuel Cells compiled by the Ministry of Economy, Trade and Industry (METI) in Japan [3].

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