INTRODUCTION TO HYDROGEN STORAGE

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Great potential for diversity of supply is an important reason why hydrogen is such a potential solution to our energy security needs. Hydrogen can be produced using abundant and diverse domestic resources, including fossil sources, biological methods, nuclear energy and renewable energy sources (lternatives, C. O. et. al 2004, Andreas Zuttel et. al 2008, Hans Larsen et al. 2004, John Andrews & Bahman Shabani 2012). Hydrogen can be converted to water, generating energy without releasing harmful emissions, thus reducing greenhouse gas emissions, pollutants and our dependence on fossil fuels.

Large-scale hydrogen utilisation encounters a constraint in terms of safe, dependable and cost-effective hydrogen storage. Hydrogen storage is a critical enabler for the transition to a hydrogen and fuel cell economy. Although hydrogen has approximately three times greater chemical energy density per unit mass (120 MJ kg^{-1}) of any chemical fuel (e.g., on average the equivalent value for liquid hydrocarbons is 43 MJ kg^{-1}), it also has a low energy density per unit volume (Von Colbe et al., 2019). For example, 1 L of gasoline (31.7 MJ/L, 8.8 kWh/L) contains approximately six times as much energy as a litre of hydrogen compressed to 70 MPa (4.7 MJ/L, 1.3 kWh/L). Hence, in order for the hydrogen to be successfully utilized, it must be compressed, liquefied, or other various ways before it can be used in the industry, such as automobiles or wearable technologies, like a mobile phone (Kayfeci & Keçebaş, 2019).

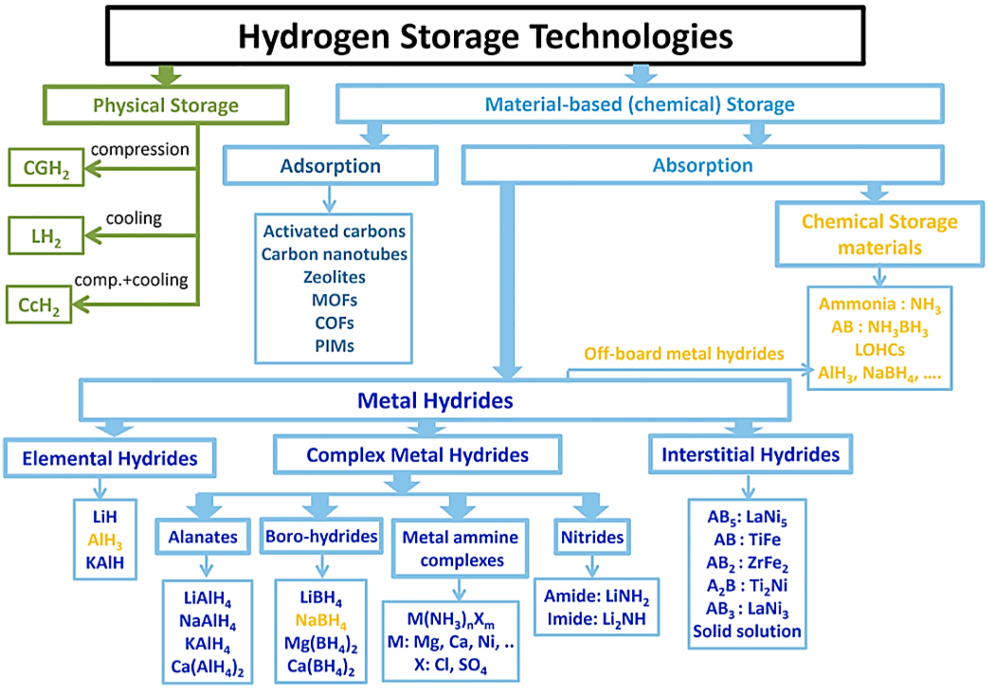

Figure 1. Hydrogen storage techniques (Hassan et al., 2021).

There are a few ways of storing hydrogen, and it can be classified into two categories, which are physical-based and material-based (Moradi & Groth, 2019) as shown in Figure 1. For each physical-based and material-based of storing hydrogen, they have a different of volumetric and energy density, as illustrated in Figure 2.

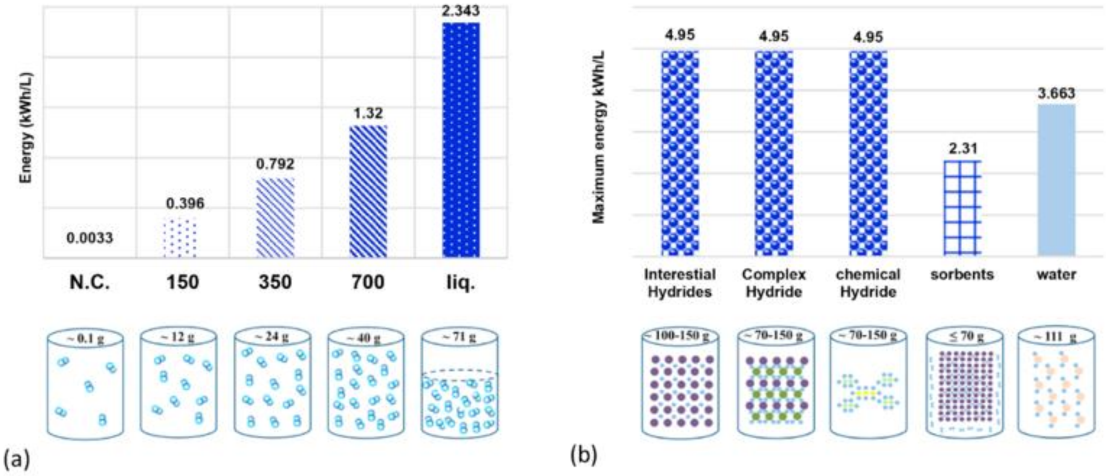

Figure 2. Volumetric capacity and energy density (a) physical-based, and (b) material-based (Hassan et al., 2021).

Physical-based Hydrogen Storage

a) Liquid System

The density of liquid hydrogen (LH_2) is greater than that of CGH_2. At atmospheric pressure or greater, hydrogen liquefies at a temperature of −253°C. LH_2 has sufficient volumetric and gravimetric capabilities. Although LH_2 is an excellent technique, it uses a lot of energy during the liquefaction process. To create 1 kilogram of liquid hydrogen, it takes approximately 4 to 10 kWh supposedly. This accounts for more than a third of the hydrogen's stored combustion energy. During actual usage, this proportion will be much higher. Another negative feature is the boil-off characteristic, which will decrease LH_2 efficiency even further. Approximately 2 to 3% of evaporated hydrogen will be lost each day due to the inevitable heat input into the storage containers. As a result, LH_2 is more popular in high-tech sectors, where performance is more important than cost, such as aeronautics sectors that engage with the production of aircraft vehicles (Yanxing et al., 2019).

The hydrogen is kept at −253°C at atmospheric pressure in relatively well insulated containers in this method. Because hydrogen is a liquid, it holds three times more energy than equal weight gasoline and requires 2.7 times more space to contain the same amount of energy (Kayfeci & Keçebaş, 2019).

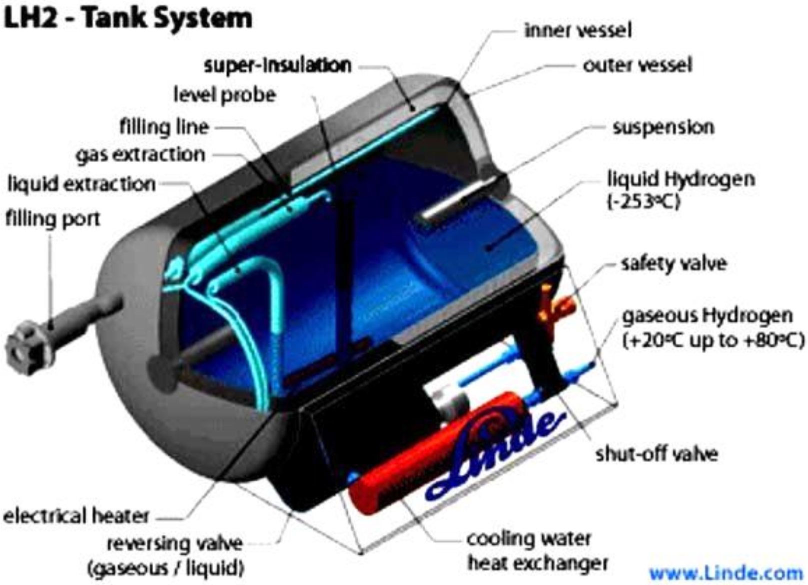

Figure 3. Example of liquid hydrogen storage tank (Suyamburajan et al., 2021).

b) Gaseous System

Compressed gaseous hydrogen storage (CGH_2) is the most established technique that is extensively used in a range of functional applications. In 2010, this technique has been used by approximately 80% of the 215 active hydrogen refueling stations around the world. Though this method is uncomplicated and inexpensive, it has its own flaws. CGH_2 is low volumetric density, which renders it less often used in practice. Although the present hydrogen storage tanks can withstand pressures of up to 70 MPa, their hydrogen density is only 39.1 kg/m^3. Because volumetric density does not rise proportionately to pressure, increasing volumetric density alone via pressurization is very difficult (Yanxing et al., 2019).

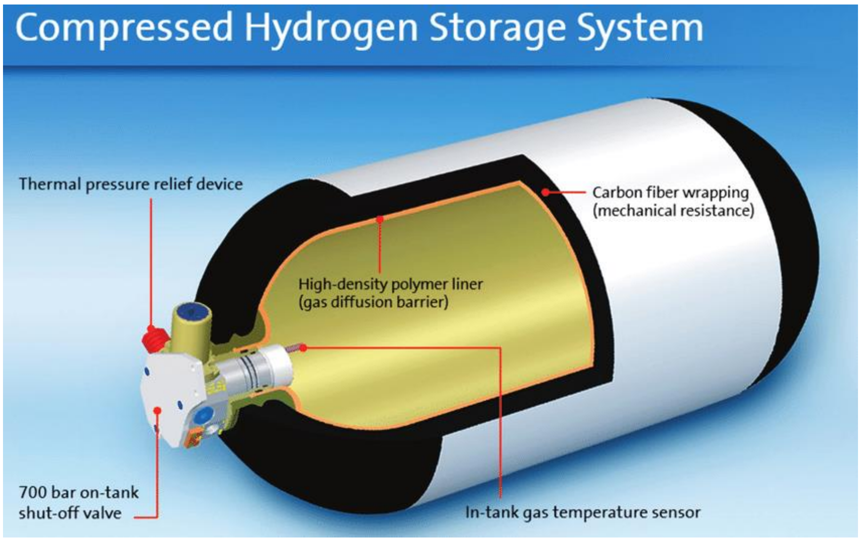

Figure 4. Type IV 70 MPa compressed gaseous hydrogen vessel (Eberle & Helmolt, 2016).

Material-based Hydrogen Storage

Among hydrogen storage techniques, physical-based are found to be closer to commercial feasibility, while materials-based have strong potential. Materials based hydrogen storage has demonstrated the ability to increase the density of hydrogen by a factor of more than twice that of liquid hydrogen, resulting in hydrogen densities of up to 21.1 MJ/L hydrogen (Scott McWhorter et al. 2011). After complete development and commercialization, these materials can accumulate high quantities of hydrogen and can be easily dispense when required.

Although much of research has been performed in this regard, to date, materials with high hydrogen storage capacities under the required conditions set by the United States Department of Energy (USDOE) have not been achieved. The USDOE target is to provide adequate hydrogen storage for onboard light-duty vehicle, material-handling equipment and portable power applications (https://www.energy.gov/eere/fuelcells/hydrogen-storage).

Hydrogen storage materials can be of different types: (i) dissociative material in which molecular hydrogen is dissociated into hydrogen atoms, which occupy interstitial sites (ii) material with chemically bound hydrogen; and (iii) materials that adsorb molecular hydrogen, wherein molecular hydrogen is attached to the surface by weak interactions such as van der Waals force or physisorption.

These materials should be able to store large amounts of hydrogen in gravimetric and/or volumetric manners, dispense hydrogen under mild temperature and pressure conditions, and offer easy handling of hydrogen and should be inexpensive when compared with other techniques (Gurwinder Singh et al. 2023). Materials such as metal hydrides, Pd-based catalysts, ammonia (NH_3) and NH_3 boranes are commonly used chemisorption materials whereas materials including nanoporous carbons, MOFs and porous polymers are generally employed physisorption materials (Gurwinder Singh et al. 2023, El Sayah, Z. et al 2016, Rusman, N. A. A. et al. 2016, D.P. Broom et al. 2019, Dundar Tekkaya et al. 2016). Although porous materials can potentially achieve the targets for hydrogen storage set by the USDOE, most of the studies are conducted at very low temperatures and/or under high pressures. Thus, continuous research and development of new materials for both chemisorption- and physisorption-based storage of hydrogen is crucial for realizing the full potential of these materials on a commercial scale.

In conclusion, hydrogen storage technology has come a long way. Investigating in all directions need to be continuous in order to find the best system for each application. In the end, the objective to deliver genuinely decarbonized societies will depend on the most appropriate hydrogen storage method for each application. The ability to pick and choose the best hydrogen storage technology will be based not only on technical requirements, but also on its economic feasibility.

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