A brief review on Hydrogen energy and state of the art of hydrogen storages (Part 1)

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List of Acronyms

FC	Fuel Cell
IEA	International Energy Agency
HES	Hydrogen Energy Storage
PEM	Polymer Electrolyte Membrane
PSO	Particle Swarm Optimization
CCS	Carbon Capture and Storage
GHG	Green House Gas
DGC	Dependable Generating Capacity
TNPC	Total Net Present Cost
LCA	Life Cycle Analysis
FCEV	Fuel Cell Electric Vehicle
NREL	National Renewable Energy Laboratory

Introduction

Energy is one of the most crucial components of life. After coal and oil, hydrogen plays a vital role as an energy carrier. Hydrogen has a lot of benefits which there are several options for producing, including the use of renewable energy sources (Lombardo et al., 2019) . Nowadays, Environmental issues related to global warming, climate change, and the need to reduce Carbon Dioxide (CO_2) emissions motivated the interest in searching for new technologies which overcome the effect and increased use of hydrogen, to develop the use of alternative fuels, and to the use renewable energies (Stern, 2018). There are a huge number of applications in which hydrogen can be used, as in road transport or space vehicles. Since hydrogen is the most energy-efficient element in the world and is available unlimited source on our planet also it is considered the cleanest energy source. Therefore, the storage of hydrogen plays an essential role in future transportation solutions for cars, trucks, and general transportation (Acar & Dincer, 2020).

Hydrogen Production

There are several ways to produce hydrogen. Hydrogen can be produced from both renewable technologies and fossil fuels. Most of the industrial hydrogen is produced from fossil fuels (natural gas, oil, and coal), while one important way for producing hydrogen from renewable energy is water electrolysis which occurs by solar cells, direct photocatalytic water, photobiological water splitting, or solar thermal processes represents a highly desirable, clean and abundant source of hydrogen. Although water electrolysis is efficient, it is an expensive technology. In water electrolysis, hydrogen is produced according to the following equations (Abdalla et al., 2018):

$2H_2O_{(liquid)} + \text{electricity} \rightarrow 2H_2 + O_2$

Reaction at the anode:

$H_2O \rightarrow 1/2O_2 + 2H^+ + 2e^-$

Reaction at the cathode:

$2H^+ + 2e^- \rightarrow H_2$

Hydrogen Storage

Hydrogen storage is the primary key to the use of hydrogen-powered vehicles. It can be clearly seen that the different cost and environmental issues for the power plant itself, storage, and the management of the storage system play an essential role in future hydrogen transportation options. Moreover, the availability of materials and the cost will be the most important issue for future operations. Hydrogen storage shows high technological challenges to be solved for commercial development. Among a wide variety of hydrogen storage possibilities such as liquid hydrogen, compressed hydrogen gas, and absorption and adsorption in metal hydrides, a group of novel materials has to be investigated (Broom et al., 2019).

Hydrogen storage materials

Hydrogen Storage has become a crucial issue as a problematic area because of the high demands on the performance of candidate materials. In this technology, the materials which are used should have the ability to absorb high quantities of hydrogen, able to sustain high pressures, absorb hydrogen in a reversible way, lightweight, and supply fast absorption and desorption. At this moment, it is vital to find out materials that are cost-effective and have a high performance in the long term (Lousada, 2020).

Hydrogen storage in Carbon Materials

Over the last decades, Carbon-based materials have become one of the most attractive solutions for hydrogen storage by considering these materials with low atomic weight and microporous nature that absorbs hydrogen molecules by van der Waal's forces at its surface. Some experiments which are done at Renewable Energy Laboratory illustrated that there is a maximum capacity for adsorption of hydrogen occurred on single-walled carbon nanotube. Moreover, hydrogen can be stored by absorption (metal hydrides and complex hydrides) and adsorption (carbon materials) (Mohan & Kumar, 2019). Compared to absorption, adsorption of hydrogen on carbon materials is more favorable in terms of storage capacity. The range of carbon nanostructures such as activated carbon (AC) and carbon nanotubes (CNTs) are examined to identify their hydrogen storage capacity. The binding energies of carbon-based materials can remain hydrogen at operational conditions without the need for high pressure and can be released after moderate heating, which is provided by various sources. Therefore, we can identify the suitable carbon materials for hydrogen storage application based on the hydrogen storage capacities, and materials can be chosen for future applications (Rivard et al., 2019).

Activated carbon (AC)

Activated carbon is a form of processed carbon comprising graphite crystallites and amorphous carbon. It can be produced from carbonaceous material through dry distillation, in which pore volume can be increased by thermal or chemical activation. The hydrogen adsorption on these materials depends on SSA (specific surface area) and pore volume. It shows that AC is obtained by chemical and physical processes of natural materials such as wood, peat, and coal. Activated carbon is cheap and available material for industrial purposes. Therefore, it is interesting to use this material for hydrogen storage applications. The potential for storage in this form of carbon is determined by the microstructure of the material. Activated carbon is a bulky carbon with a high surface area of 500-2500 $m^2\ g^{-1}$ able to adsorb hydrogen in the microscopic pores. Macropores with a diameter of 100-200 nm are the widest pores in the activated carbon. As it can be seen, the adsorption process on this surface is negligible, and the same as mesopores, they act as transporting channels. The storage capacity of hydrogen on activated carbon is different based on temperature and pressure, which seems that by decreasing temperature and pressure, the storage capacity will be increased (Samantaray et al., 2019).

Carbon nanotubes (CNT)

The storage capacity of CNTs depends on their structure, geometry, operating pressure, and temperature. Inside, outside, between the tube, and between shells are the possible hydrogen sites. One of the main benefits of CNTs is carbon structure which can make the correlation between theoretical prediction and experimental data. The porous structure of CNT improves hydrogen storage capacity in the inner and outer surfaces (figure 1). Therefore, CNT has become one of the favorable nanostructures for hydrogen storage. Moreover, structural types have a significant impact on adsorption, which affects the amount of hydrogen stored in the system. It can be seen that thermal treatments on carbon nanostructures useful for improving hydrogen storage capacities, while higher storage capacities can be achieved at lower temperature and higher pressure (Rajaura et al., 2018).

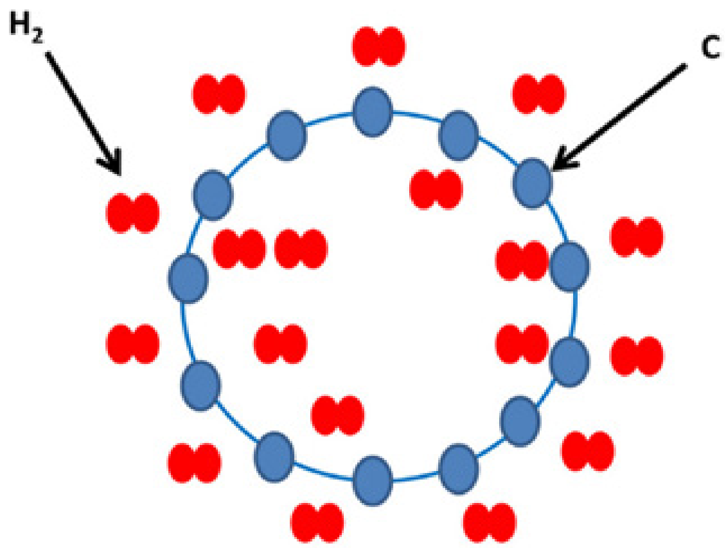


Figure 1: Absorption of hydrogen in Carbon Nanotube (Abdalla et al., 2018).

Wood cellulose

Hydrogen storage has become one of the most significant candidates for a future energy storage medium, while there are some technological challenges in both production and storage. Therefore, it is vital to search for abundant, non-toxic, lightweight, and environmentally friendly materials. From a sustainability perspective, wood cellulose would be an ideal storage material because of its physical-chemical properties, lightweight, and wide availability. Wood cellulose has the ability availability. Wood cellulose has the ability to absorb H_2 through the physisorption process with the interaction of the van der Waals, which involved the O-atoms of the D-glucose rings. The H_2 molecules absorb onto the cellulose through interactions with O-atoms. These reactions lead to dispersion forces between the H_2 molecules. Since the interactions between H_2 and cellulose happen through non-bonding electron pairs of the O-atoms of D-glucose, so the interactions with H_2 are stronger for cellulose than the physisorption of H_2 in materials that consist of carbon atoms. Moreover, it can be seen that by increasing the temperature, the more energetic vibrations of the lattice disturb the dispersion interaction between H_2 molecules and the O-atoms of D-glucose, which lead to less favorable at the highest temperature compared to the lowest. Additionally, by increasing temperature, the reactions of absorption become less favorable, which illustrated that hydrogen absorption could be driven by pressure and desorption can be driven by temperature. In the end, it is obvious that hydrogen storage capacity could be increased by physical-chemical transformations of wood cellulose, such as an expansion of the lattice and doping, and wood cellulose has become an interesting material for investigations on its potential as a hydrogen storage medium (Lousada, 2020).

Metal Hydrides

Metal hydrides are well-known as efficient and low-risk material for the hydrogen storage system. One of the most attractive and important options is energy storage through the reversible storage of hydrogen in metal hydrides which can be employed by fuel cells. Due to the thermodynamic features of metal hydrides, these materials open up the chance to develop a new hydrogen storage technology. Therefore, storage systems consist of metal hydrides and high-pressure have become a realistic solution for hydrogen storage on fuel cell vehicles. Metal hydrides are an excellent choice for hydrogen storage due to their safety, good hydrogen gravimetric density, and excellent volumetric density. Since they have a lower weight and less volume, they can release hydrogen at low pressures and temperatures (Bellosta von Colbe et al., 2019). The main reason which can make metal hydrides surpass other materials in the hydrogen storage system is the ability of metal hydrides to absorb and desorb hydrogen either at room temperature or through heating of the tank, which is gained attention as a promising H_2 storage material.

Furthermore, the safety aspect of metal hydrides makes them more efficient due to the fact that during severe accidents, there are no fire hazards from hydrogen release because hydrogen will remain within the metal structure. In the end, it can be clearly seen that metal hydrides play an important role in the hydrogen storage system because metal hydrides can be used not only as a potential storage hydrogen materials, but also it can be used for the production of complex hydrides in future (Abdalla et al., 2018).

Electrical Energy Storage Classification

Several methods to store energy exist. A selection of the leading energy storage technologies is presented below:

1. Mechanical storage technologies save energy in different forms of potential or kinetic energy.
2. Thermal storages convert electricity to heat, which is then stored in different types of materials.
3. Batteries are a group of electrochemical storage solutions.
4. Supercapacitors are advanced capacitors with higher energy storage capacity than conventional capacitors and can discharge over more extended periods.
5. Chemical storage can provide storage services over various timeframes, depending on the specific application. Chemical storage enables cost-effective separation of the power and the energy elements in an energy storage utilization. So, it allows for a more straightforward adaptation to the changing storage needs over time. Chemical storage is mostly based on hydrogen generation, at least as a first level. The hydrogen produced can be further processed according to the needs of, for example, ammonia, methane or methanol, or other chemicals used in the industry. When the hydrogen is used for producing methane, it is commonly called SNG, as methane is the main energy-carrying content in natural gas. In such circumstances, carbon may come from CO2 captured from large combustion plants such as power stations or industrial plants.

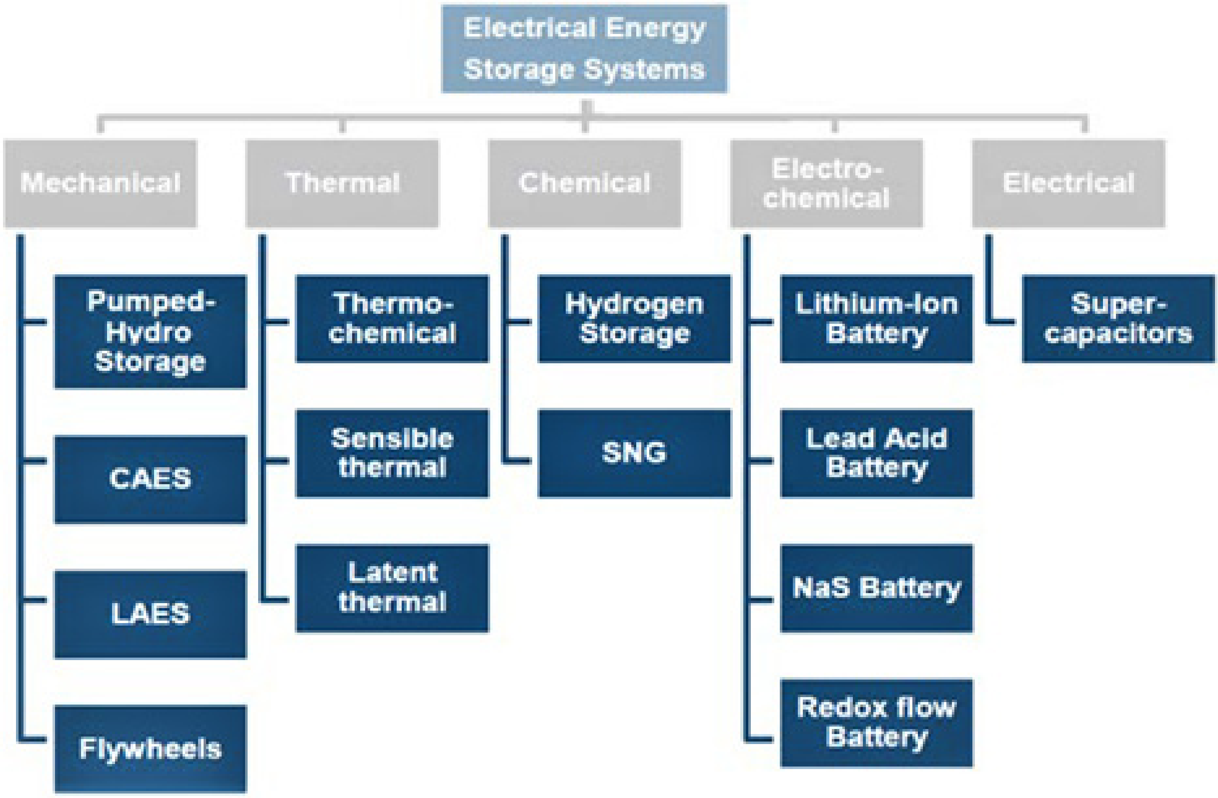
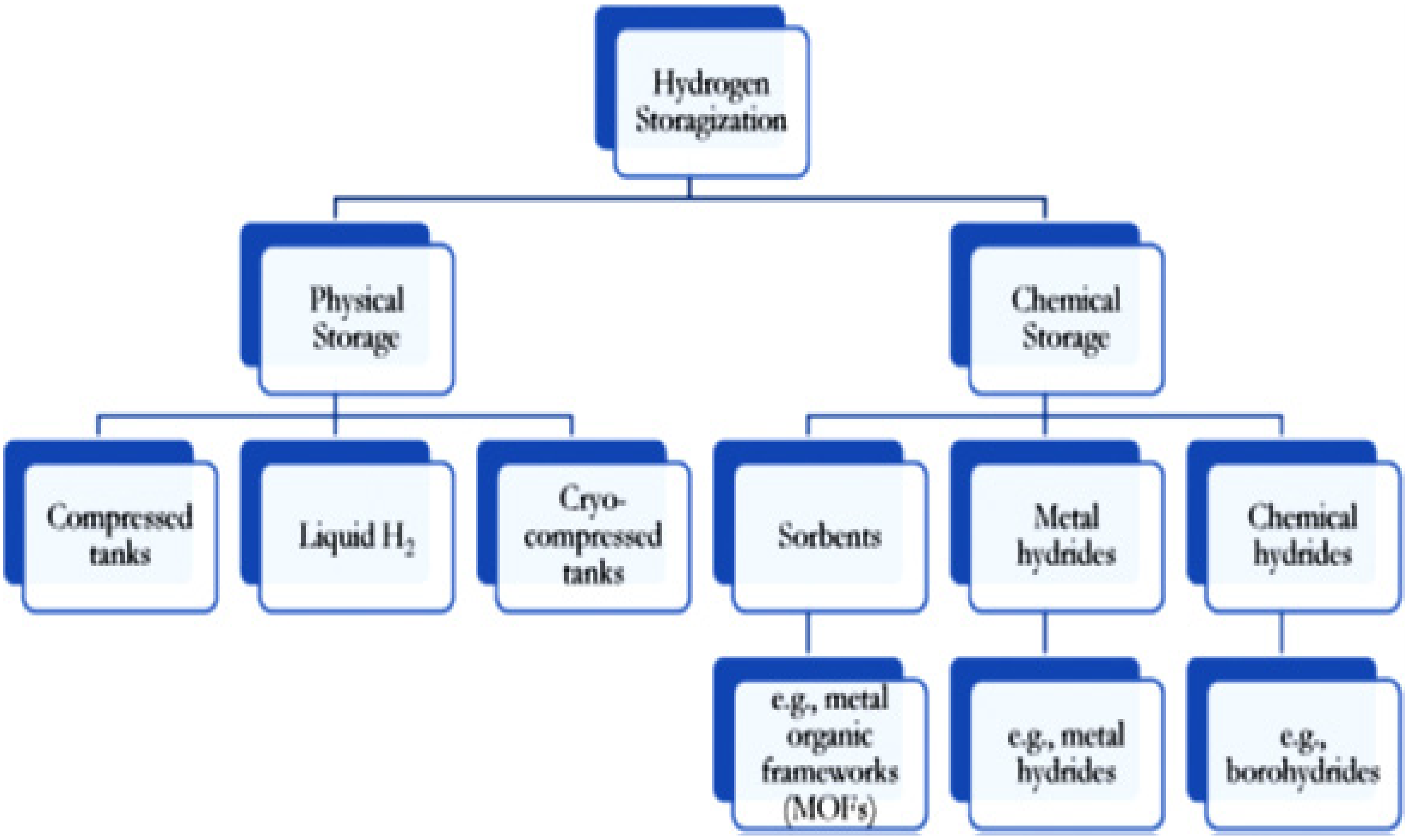


Figure 2. Electrical Energy Storage Classification

Modern electrolysers (i.e., units where electricity splits water into hydrogen and oxygen through the process called electrolysis) used for hydrogen production have fast response times and are currently installed in multi-megawatt sizes. The produced hydrogen can be stored in a variety of ways, from small cylinders or tanks to extensive underground storage facilities. The hydrogen and derived chemicals produced could feed gas turbines, fuel cells or combustion engines to generate electricity or used as feedstock in industrial processes.

Hydrogen Storagization

Hydrogen is a promising energy carrier that could efficiently address the challenges associated with renewable, green energy and material resources such as irregularity and discontinuity in supply. That being said, as a smart energy solution for a sustainable future, hydrogen energy systems must be robust and reliable from source, system, to service which is only possible with safe, effective, affordable, and available hydrogen storage systems. Therefore, Storagization is a key smart energy solution when transitioning a sustainable future with hydrogen options. Various storagization options for hydrogen energy systems is presented in Fig. 10 (Ibrahim and Canan, 2018).



Comparison of discharge time vs capacity of energy storage technologies

Despite this growth, battery storage has limitations in terms of storage capacity and is not suitable for every application, as shown in Figure 11. long-term storage, which will be required for seasonal backup or as energy security reserves in the absence of fossil fuels, will require different technology. As mentioned, hydrogen storage has the

As mentioned, hydrogen storage has the potential to fulfil this role; therefore, the future grid is likely to be one where hydrogen plays a significant and crucial role alongside various other storage technologies. In terms of recourse attribute, Hydrogen storage technology can be considered as a DGC (Dependable Generating Capacity) (Ibrahim and Canan, 2017).

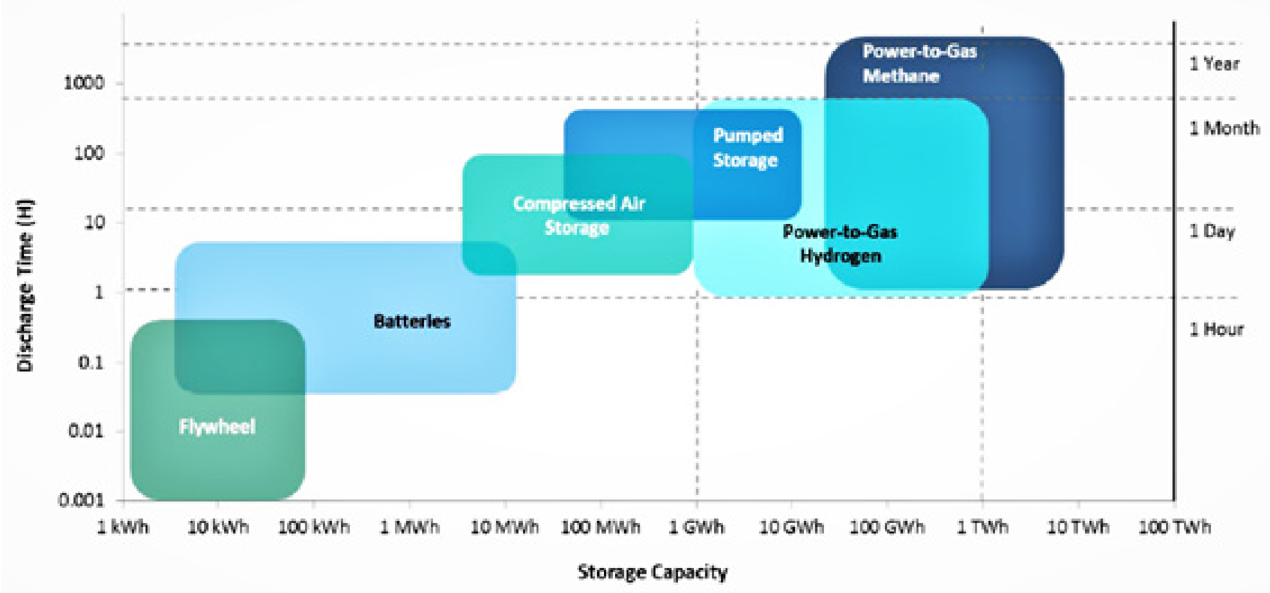


Figure 4. Hydrogen Storagization.

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References

1. Lombardo, L., H. Yang, and A. Züttel, Study of borohydride ionic liquids as hydrogen storage materials. Journal of Energy Chemistry, 2019. 33: p. 17-21.
2. Stern, A.G., A new sustainable hydrogen clean energy paradigm. International Journal of Hydrogen Energy, 2018. 43(9): p. 4244-4255.
3. Acar, C. and I. Dincer, The potential role of hydrogen as a sustainable transportation fuel to combat global warming. International Journal of Hydrogen Energy, 2020. 45(5): p. 3396-3406.
4. Abdalla, A.M., et al., Hydrogen production, storage, transportation and key challenges with applications: A review. Energy Conversion and Management, 2018. 165: p. 602-627.
5. Broom, D.P., et al., Concepts for improving hydrogen storage in nanoporous materials. International Journal of Hydrogen Energy, 2019. 44(15): p. 7768-7779.
6. Lousada, C.M., Wood cellulose as a hydrogen storage material. International Journal of Hydrogen Energy, 2020. 45(29): p. 14907-14914.
7. Mohan, M., et al., Hydrogen storage in carbon materials—A review. Energy Storage, 2019. 1(2): p. e35.
8. Rivard, E., M. Trudeau, and K. Zaghib, Hydrogen Storage for Mobility: A Review. Materials, 2019. 12(12).

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