Hydrogen Storage: Status, Advances and Outlook

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Introduction

For the last centuries, the world's energy needs have been met primarily by burning fossil fuels. However, the long-term consequences of relying on these energy sources have become increasingly evident, leading to geopolitical conflicts, the emission of harmful greenhouse gases, air pollution, and the depletion of finite resources. The adverse effects of climate change, such as rising temperatures, extreme weather events, and ecosystem disruption, are already being felt, underscoring the urgent need for action to mitigate future catastrophic impacts.

The transition away from fossil fuels is not just essential for environmental health but also critical to ensuring geopolitical stability and energy security. However, renewable energy sources, such as wind, solar, and hydropower, which are key to achieving the global decarbonization, also have limitations, primarily their intermittent nature. The availability of solar and wind energy depends on weather conditions, time of day, and seasonal cycles, creating mismatches between energy supply and demand. This variability presents challenges for maintaining a stable and reliable energy system, which is where energy storage comes into play.

Energy storage systems are essential for managing the fluctuations in renewable energy generation. Storage technologies can store excess energy during periods of high availability and release it when demand exceeds supply. These systems can take many forms, including batteries, pumped hydro storage, and chemical storage in the form of hydrogen.

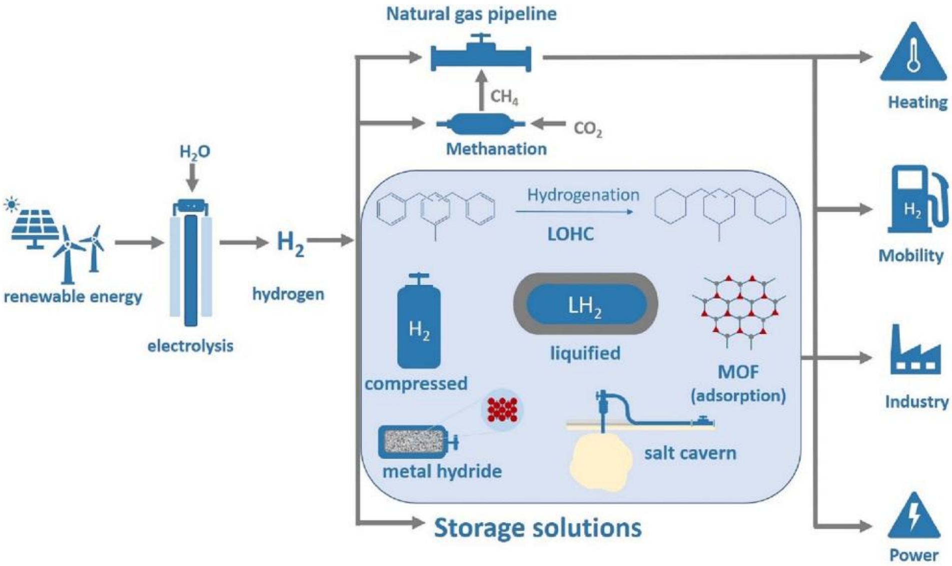

Figure 1: Hydrogen production from renewables via electrolysis, different storage possibilities and subsequent utilization for heating, mobility, industry and power. Adapted from: [1]

Especially green hydrogen offers a promising solution as a clean, sustainable energy carrier. It can be produced through electrolysis, where electricity from renewable sources like wind or solar is used to split water into hydrogen and oxygen (see Figure 1). On the demand side, hydrogen can be used as a carbon-neutral fuel for mobility, power generation and heating or as a chemical in various industrial applications. Thereby efficient hydrogen storage and transport are key to link the production and demand. Although hydrogen has the highest energy density per unit mass of any fuel, its low volumetric mass density at ambient temperature and pressure correspondingly results in a low energy density per unit volume. This makes efficient hydrogen storage across different applications an open challenge.[1]

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Methods

Hydrogen can be stored in various forms (Figure 1), each with specific advantages, drawbacks, and technical challenges. In this work, a comparative analysis was carried out to evaluate compressed gaseous hydrogen (CGH_2) against liquid hydrogen (LH_2), cryo-compressed hydrogen (cCH_2), and material-based storage options such as metal hydrides, adsorption storage and liquid organic hydrogen carriers (LOHCs) [2]. The assessment focused on storage density, economic factors, operating pressure and temperature, efficiency, system complexity and scalability. The methodology combines a comprehensive literature review with years of own hands-on experience in hydrogen storage simulation, testing, and implementation into real-life applications, ensuring that the evaluation reflects both theoretical performance and practical applicability. The current state-of-the-art as well as research advances will be presented.

Summary of Hydrogen Storage Technologies

CGH_2 is the current state-of-the-art and most widely used hydrogen storage technology. While even at high pressures up to 700 bar, its gravimetric and volumetric capacities are modest compared to some other hydrogen storage technologies, it benefits from simpler infrastructure, established standards, and broad operational experience with high-pressure gases. Replacing steel type I pressure vessels with aluminium and polymers (type III/IV) to improve gravimetric capacity for mobile applications is possible, but comes at higher specific tank costs and challenges regarding carbon-fibre recyclability. Steel tanks remain the most cost-effective option for small- to medium-scale, while further research is needed on sustainable tank materials, optimized filling procedures and efficient refuelling infrastructure.[2]

LH_2 and cCH_2 provide significantly higher storage densities and are therefore attractive for heavy-duty mobility and aviation. However, their overall storage efficiency is reduced by high energy demand for cooling and liquefaction, boil-off losses and the need for complex cryogenic infrastructure. Despite the increased complexity, the specific costs per kg hydrogen stored of the cryogenic vessels are roughly comparable to type III/IV CGH_2 tanks.[2]

Material-based storage concepts, such as adsorption on the surface of porous materials such as activated carbon (AC) or metal-organic frameworks (MOFs), and solid-state storage via absorption in metal hydrides (MH), promise high storage capacities. AC/MOFs require cryogenic temperatures (77 K) for optimal performance, and as such the technology currently remains at lab-scale. Research efforts aim to increase the operating temperatures. MH on the other hand see first commercial applications as stationary storage at moderate pressure and temperature conditions (e.g. 10-70 °C, 10-30 bar), but suffer from high material costs, low gravimetric capacity and challenging thermal management. Lastly, LOHCs combine high capacities with liquid-fuel handling infrastructure but depend on high temperatures for hydrogenation, expensive catalysts and often toxic materials.[2]

Outlook

In the short- to mid-term, hydrogen storage will be dominated by technologies that are already commercial or close to market such as CGH_2 and LH_2. From an economic and infrastructure perspective, CGH_2 and, where geographically available, large-scale underground hydrogen storage currently represent the most realistic backbone of a scalable hydrogen economy. At the same time, it is clear that no single storage technology can serve all applications. Stationary systems, long-distance transport, seasonal storage and onboard vehicle storage each impose different requirements on storage density, cost, efficiency, safety and infrastructure. This underlines the need for continued research and development across the entire portfolio of storage solutions. A coordinated, application-driven technology mix, rather than a one-size-fits-all solution, will be essential to enable a flexible, resilient and cost-effective hydrogen-based energy system.

References

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