

# Report on the Hydrogen Energy Storage

*Mujgan Huseynli*

## Abstract

Hydrogen energy storage has garnered significant attention as a crucial component of sustainable energy systems, particularly for integrating renewable energy sources and addressing grid stability challenges. This paper provides a comprehensive overview of hydrogen energy storage, covering key aspects from production to utilization. Beginning with an introduction to the importance of energy storage in the context of renewable energy integration, the paper discusses various methods of hydrogen storage such as compressed gas storage, cryogenic storage, and material-based storage, highlighting their respective advantages and limitations. Furthermore, the concept of power-to-power storage, which involves converting electrical energy into hydrogen through electrolysis and reconvert it back to electricity using fuel cells or combustion engines, is explored in detail. The paper also addresses current challenges facing hydrogen energy storage, including technological constraints, infrastructure limitations, and cost considerations, and proposes potential solutions to overcome these challenges. Finally, future directions and research opportunities in hydrogen energy storage are discussed, emphasizing the role of innovation and collaboration in advancing this critical technology for a sustainable energy future.

**Keywords:** hydrogen storage, electrical storage system, fuel cell, electrolysis, challenges, future initiatives

## I. INTRODUCTION

Hydrogen storage is a key enabling technology for the advancement of hydrogen and fuel cell technologies in applications including stationary power, portable power, and transportation. Hydrogen energy storage is another form of chemical energy storage in which electrical power is converted into hydrogen. This energy can then be released again by using the gas as fuel in a combustion engine or a fuel cell. It is possible to power almost anything with hydrogen with numerous thermal chemical and electrical applications. Hydrogen is the lightest element – 14 times lighter than air. Because of its low density it is difficult to transport as a gas. Instead, it needs to be liquefied or converted into a denser form such as ammonia for transportation.

## II. ADVANTAGES & DISADVANTAGES

### ADVANTAGES

1. **High energy density:** Hydrogen has a high energy density by weight, making it an attractive option for energy storage. When compared to batteries, hydrogen can store more energy in a smaller and lighter package.
2. **Scalability:** Hydrogen energy storage systems can be scaled up or down to meet the needs of various applications, from small residential systems to large-scale grid storage.
3. **Long-term storage:** Unlike batteries, which can lose their charge over time, hydrogen can be stored indefinitely without significant energy loss. This makes it an ideal solution for long-term energy storage and seasonal energy balancing.
4. **Environmentally friendly:** When hydrogen is converted back into electricity, the only by-product is water, making it a clean and environmentally friendly energy storage solution.
5. **Grid stability:** Hydrogen energy storage can help stabilize the electrical grid by providing a buffer between supply and demand, reducing the need for peaking power plants and improving the overall efficiency of the grid.

### DISADVANTAGES

1. **Low Efficiency:** The process of converting electrical energy into hydrogen and back into electricity is not as efficient as other energy storage technologies, such as batteries. The round-trip efficiency of hydrogen energy storage is typically around 40 % to 50 %, while the round-trip efficiency of battery storage can range from 70 % to 90 % depending on the type of battery and its operating conditions.
2. **High capital costs:** The equipment required for hydrogen energy storage, such as electrolyzers and fuel cells, can be expensive, leading to higher initial capital costs compared to other energy storage solutions.
3. **Infrastructure:** The lack of existing hydrogen infrastructure, such as pipelines and refuelling stations,

can be a barrier to widespread adoption of hydrogen energy storage.

4. Safety concerns: Hydrogen is a highly flammable gas, and its storage and transportation require strict safety measures to prevent accidents.
5. Energy density by volume: Although hydrogen has high energy density by weight, its energy density by volume is relatively low. This means that large storage tanks or high-pressure systems are required to store hydrogen in a compact form.

### III. HYDROGEN STORAGE METHODS

Hydrogen storage is a critical component in enabling the practical utilization of hydrogen as an energy carrier for various applications. This section presents an overview of different hydrogen storage methods, including liquid storage, compressed gas storage, cryogenic storage, and material-based storage.

#### Liquid Storage:

Liquid hydrogen (LH<sub>2</sub>) storage involves storing hydrogen gas at extremely low temperatures, typically below -253°C (-423°F), to liquefy it. LH<sub>2</sub> offers high energy density per unit volume, making it suitable for applications with stringent space constraints, such as aerospace and long-range transportation. However, maintaining the low temperatures required for liquid hydrogen storage poses technical challenges and necessitates energy-intensive cooling processes.

#### Compressed Gas Storage:

Compressed gas storage involves storing hydrogen gas at high pressures, typically ranging from 350 to 700 bar (5,000 to 10,000 psi), to increase its energy density. This method is commonly utilized in fuel cell vehicles and stationary storage systems. Compressed hydrogen tanks, composed of lightweight, high-strength materials such as carbon fiber composites or metal alloys, withstand the high pressures. While compressed gas storage offers relatively high energy density per unit volume, it necessitates robust safety measures to prevent leakage or rupture of the storage tanks.

#### Cryogenic Storage:

Cryogenic hydrogen storage entails storing hydrogen gas at very low temperatures, like liquid storage, but without liquefying it. Instead, hydrogen gas is stored in insulated tanks at cryogenic temperatures, typically below -253°C (-423°F), to maintain its high energy density. Cryogenic storage offers advantages in terms of energy density and safety compared to liquid storage, as it eliminates the need for complex

liquefaction processes and mitigates the risk of hydrogen boil-off. Nonetheless, cryogenic storage systems necessitate robust insulation and cooling systems to sustain the low temperatures.

#### Material-Based Storage:

Material-based hydrogen storage methods involve chemically or physically absorbing hydrogen molecules onto the surface or within the structure of solid materials. These materials encompass metal hydrides, complex hydrides, carbon-based materials, and nanostructured materials. Material-based storage holds promise for high hydrogen storage capacities and reversible hydrogen uptake and release kinetics. However, challenges persist in achieving high storage capacities at ambient conditions, enhancing hydrogen uptake and release kinetics, and ensuring the stability and durability of storage materials.

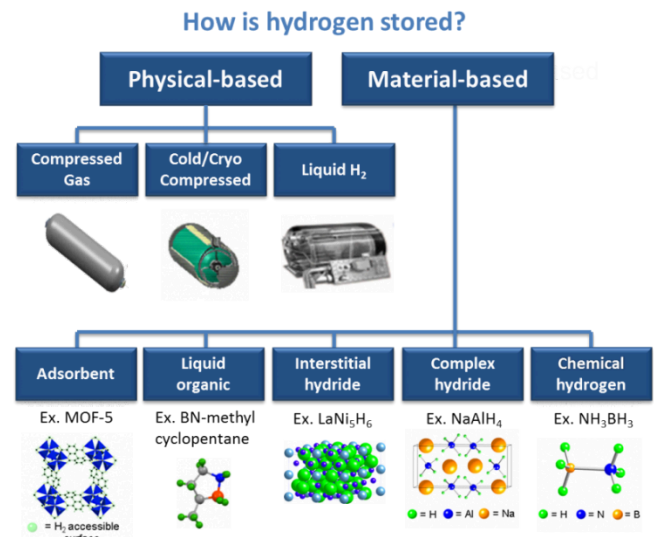
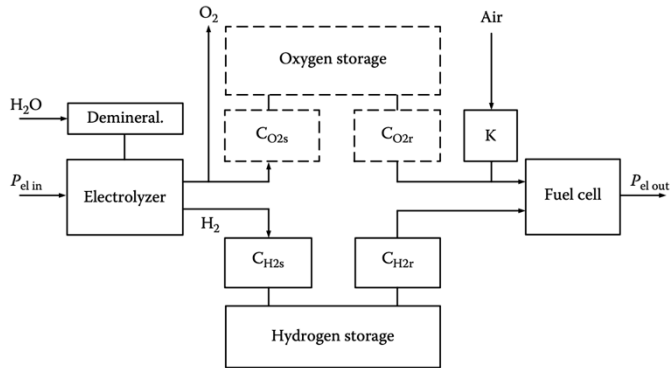


Figure 1. Methods of storing Hydrogen

### IV. ELECTRICAL STORAGE SYSTEM BASED ON HYDROGEN

An energy storage system (ESS) or power-to-power storage system utilizing hydrogen involves the use of a water electrolyzer and a fuel cell for intermediate conversions. To increase the volumetric energy density, hydrogen and oxygen conditioning systems are necessary. Figure below illustrates the key components of such a system: the electrolyzer, hydrogen storage, and fuel cell. A hydrogen conditioning device (CH<sub>2</sub>s) is positioned between the electrolyzer and the storage reservoir, as well as between the storage reservoir and

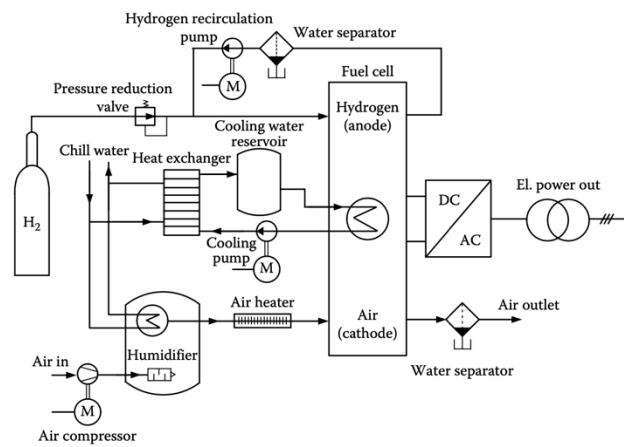
the fuel cell (CH<sub>2</sub>r). The electrolyzer also generates oxygen, typically stored separately. The oxygen path is indicated with a dotted line as many modern fuel cells utilize ambient air for oxidation, represented by an air compressor (K). Conditioning blocks (CO<sub>2</sub>s, CO<sub>2</sub>r) are included for the case of using stored oxygen. Compressors or liquefiers typically serve as conditioning devices for the storage process (CH<sub>2</sub>s, CO<sub>2</sub>s), while simple relief valves are used for recovery conditioning (CH<sub>2</sub>r, CO<sub>2</sub>r). The conditioning processes become more complex when solid storage of hydrogen in the form of metal hydrides is employed.



**Figure 2. Structure of a storage system based on Hydrogen**  
**Efficiency of the fuel cells**

The energy efficiency of fuel cells is gauged by comparing the useful energy output, typically measured as electrical energy generated, to the total energy input, which is the energy stored in the fuel. Fuel cells generally exhibit energy efficiencies ranging from 40% to 60% when operated under ideal conditions with hydrogen and oxygen inputs.

In real-world applications, many fuel cells, particularly proton exchange membrane (PEM) fuel cells, utilize ambient air as the oxygen source, drawn in by an air compressor. In such systems, the energy consumption of the air compressor and other auxiliary components like air humidification, hydrogen recirculation, and cooling pumps must be factored into efficiency assessments, as depicted in Figure below.



**Figure 3. Fuel Cell System**

To mitigate the power demand of the air compressor, various strategies can be employed, such as adjusting the air flow rate based on the electrical output power.

In essence, the efficiency of fuel cells for hydrogen storage involves considering not only the conversion of hydrogen into electrical energy but also the efficiency of auxiliary components and processes involved in the overall system.

### Renewable ESS with Hydrogen Fuel Cells

Electrical storage of hydrogen involves a series of steps to convert electrical energy into hydrogen gas, store it efficiently, and convert it back into electricity when required. Firstly, electrolysis is employed, where electrical energy is utilized to split water molecules into hydrogen and oxygen gases. This process occurs within an electrolyzer, comprising two electrodes submerged in water and separated by an electrolyte. Hydrogen gas produced at the cathode is then collected and stored in tanks or cylinders, often under high pressure or cryogenic conditions to enhance its energy density. Various storage methods such as compressed gas storage and cryogenic storage are utilized, along with solid-state storage using metal hydrides or chemical storage using hydrogen carriers. Subsequently, when electricity is needed, the stored hydrogen gas is fed into a fuel cell along with oxygen from the air. In the fuel cell, hydrogen reacts with oxygen to generate electricity, releasing water vapor as a byproduct. The generated electricity can be distributed to power electrical devices, appliances, or grids, providing a flexible and efficient means of storing and utilizing electrical energy.

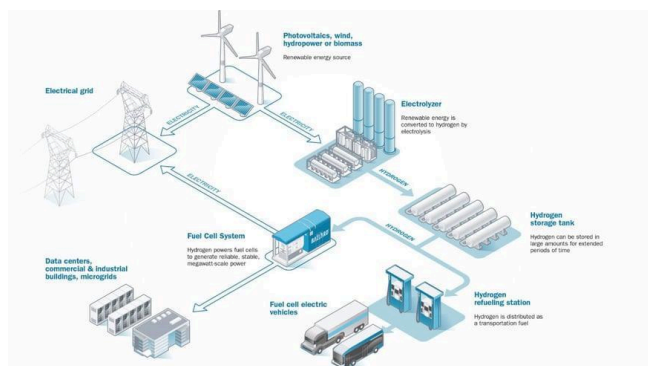


Figure 4. ESS of Hydrogen

## V. CURRENT STATUS & FUTURE APPLICATIONS

### Current Projects - Installed Cost

HESS consists of three major components:

- Charging system includes electrolyzer modules, BOP, water-handling units, mass flow controllers, electrolyzer management system, compressor, and rectifier.
- The discharging system is comprised of stationary fuel cell modules, BOP, gas-handling units, blowers, mass flow controllers, fuel cell management system, and inverter.
- The storage system typically includes pipes or a cavern. Electrolyzer hardware capital costs consist of stacks and BOP.

The life of the BOP is expected to be 20-25 years, corresponding to the life of compressors and air and fuel delivery systems (Purchasing, Undated; Rundle, 2012), while the life of the electrolyzer depends on operating profile. The capital costs for hydrogen systems, along with EPC and O&M costs, are project-specific and can vary substantially. Bidirectional usage for hydrogen is not limited to electricity generation by fuel cells; gas turbines or engines can also be used. Though there are various hydrogen technology configurations, the one included in this report is a stationary bidirectional HESS that uses a PEM electrolyzer, a salt cavern for storage, and stationary fuel cells. Cost estimates and projections for this technology were based on extensive literature review and analysis reported in Information on response time capability was provided from the literature regarding dynamic modeling and validation of electrolyzers.

Table 1 below provides breakdown for a 100 MW, 10-hour HESS system, calculated from the estimates

provided in Hunter et al. (In Press) with additional cost components and adjustments described previously.

Category	Cost Component	Low 2020 Values	Low 2030 Values	Moderate 2020 Values	Moderate 2030 Values	High 2020 Values	High 2030 Values
PEM electrolyzer	Capital cost (\$/kW)	1,353	393	1,503	437	1,653	481
	Rectifier cost (\$/kW)	117	84	130	94	143	103
	Compressor cost (\$/kW)	35	35	39.3	39.3	43	43
Storage	Storage (\$/kWh)	2	1.69	3.66	3.09	10	8.45
	Storage DOD (%)	70%	70%	70%	70%	70%	70%
	Effective storage (\$/kWh)	2.86	2.4	5.23	4.44	14.29	12.10
Stationary fuel cell	Capital cost (\$/kW)	1,188	854	1,320	949	1,452	1,044
	Inverter (\$/kW)	60	41	67	45	74	50
C&C (\$/kW)		1.35	0.95	1.5	1.06	1.65	1.16
Grid integration (\$/kW)		18	15	19.89	16.3	22	18
<b>Grand total (\$/kW)</b>		<b>2,793</b>	<b>1,440</b>	<b>3,117</b>	<b>1,612</b>	<b>3,488</b>	<b>1,824</b>
<b>Grand total (\$/kWh)</b>		<b>279</b>	<b>144</b>	<b>312</b>	<b>161</b>	<b>349</b>	<b>182</b>

Table 1. Costs by Component for a 100 MW, 10-hour HESS System

### Projects and initiatives driving the hydrogen industry in future

The hydrogen industry is being driven forward by numerous notable projects and initiatives that aim to advance the production, storage, distribution, and utilization of hydrogen. These projects and initiatives are crucial for realizing the full potential of hydrogen in the future energy landscape. Here are some noteworthy examples:

- **European Clean Hydrogen Alliance:** Launched as part of the European Commission's Hydrogen Strategy, the European Clean Hydrogen Alliance brings together industry stakeholders, governments, and civil society to accelerate the development of a sustainable hydrogen economy in Europe. It aims to support the deployment of hydrogen technologies across various sectors and facilitate investment in hydrogen projects.
- **H2@Scale (United States):** H2@Scale is a U.S. Department of Energy initiative that focuses on advancing hydrogen technologies to enable large-scale production, storage, and utilization of hydrogen in multiple sectors. The initiative promotes collaborative research and development efforts, including projects related to hydrogen production, transportation, and utilization in industries and power generation.
- **Hydrogen Energy Supply Chain (Japan):** Japan's Hydrogen Energy Supply Chain (HESC) project aims to establish a global hydrogen supply chain through the production, transportation, and utilization of liquefied hydrogen. The project involves collaboration between government, industry, and academic partners to demonstrate the feasibility and viability of a large-scale hydrogen supply chain.

- **HyDeal Ambition:** HyDeal Ambition is a European initiative that aims to deploy 100 gigawatts (GW) of solar-powered electrolyzers by 2030, producing low-cost hydrogen for various applications. The project aims to leverage renewable energy, economies of scale, and long-term supply agreements to drive down the cost of green hydrogen and accelerate its market adoption.
- **Gigastack (United Kingdom):** The Gigastack project in the United Kingdom aims to demonstrate the feasibility of low-cost, zero-carbon hydrogen production using large-scale alkaline electrolyzers. The project focuses on deploying gigawatt-scale electrolysis systems powered by renewable energy sources to produce cost-competitive green hydrogen.
- **NorthH2 (Netherlands):** NorthH2 is a consortium of companies, including Shell, Gasunie, and Groningen Seaports, aiming to develop a large-scale green hydrogen value chain in the Netherlands. The project aims to utilize offshore wind farms to produce hydrogen through electrolysis, with the goal of scaling up production to approximately 4 GW by 2030.

contribute to reducing carbon emissions and achieving global energy goals.

## REFERENCES

- Rufer, A. Energy Storage Systems and Components (2018). Taylor and Francis Group, LLC
- Segev, R. (2020). Optimizing Renewable Energy Storage with Hydrogen Fuel Cells  
<https://blog.ballard.com/powergen/renewable-energy-storage>
- Gregus, N. (2022). Everything you need to know about Hydrogen Energy Storage  
<https://goenergylink.com/blog/hydrogen-energy-storage/>
- 2020 Grid Energy Storage Technology Cost and Performance Assessment [Final - ESGC Cost Performance Report 12-11-2020.pdf \(pnpl.gov\)](#)

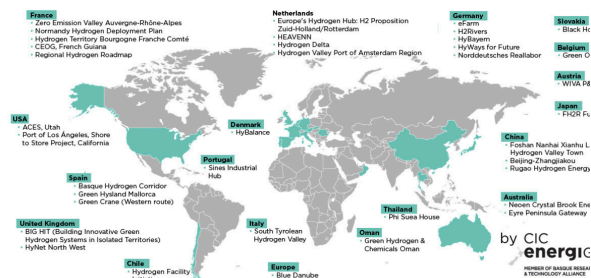


Figure 5. Worldwide ongoing and future projects

## VI. CONCLUDING REMARKS

In conclusion, hydrogen energy storage stands at the forefront of renewable energy solutions, offering a promising pathway to a sustainable future. Its capacity to store and release energy efficiently, the potential for large-scale application across various sectors, and its environmental friendliness position it as a key player in the transition towards clean energy. Despite facing challenges like high production costs, storage difficulties, and the need for specialized infrastructure, ongoing technological advancements and decreasing costs are steadily paving the way for hydrogen to become a viable, widely used energy storage medium. The successful integration of hydrogen energy storage could significantly