



## Hydrogen Renewable Energy and Implementation of various hydrogen storage strategies

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### Abstract

Hydrogen is increasingly recognized as a critical element in the advancement and incorporation of renewable energy sources (RESs) in contemporary power systems. Serving as a key energy storage system (ESS), hydrogen plays a crucial role in ensuring stability and reliability within the power grid. With its notable energy density, substantial storage capacity, and rapid operational capabilities, hydrogen is swiftly becoming a favored option among ESSs. In a hydrogen energy system, hydrogen stored in the hydrogen storage system is transformed into direct current (DC) power by a hydrogen fuel cell during power shortages. Conversely, excess power from the grid is converted into hydrogen by an electrolyzer, which is then stored in the hydrogen storage system. These processes require the implementation of various systems to enable the connection of fuel cells and electrolyzers to the power grid, including power electronic converters and DC link regulation control systems. In this paper, we will have a comprehensive examination of the current challenges related to this source of renewable energy and the aspects of integrating hydrogen energy storage technologies into modern power grids. By focusing on the integration of renewable energy sources, this paper aims to assist researchers in a comprehensive understanding of the current state and future possibilities of hydrogen energy storage systems.

**Keywords:** Hydrogen, Renewable Energy, Energy Storage Systems, Control Systems



## Introduction

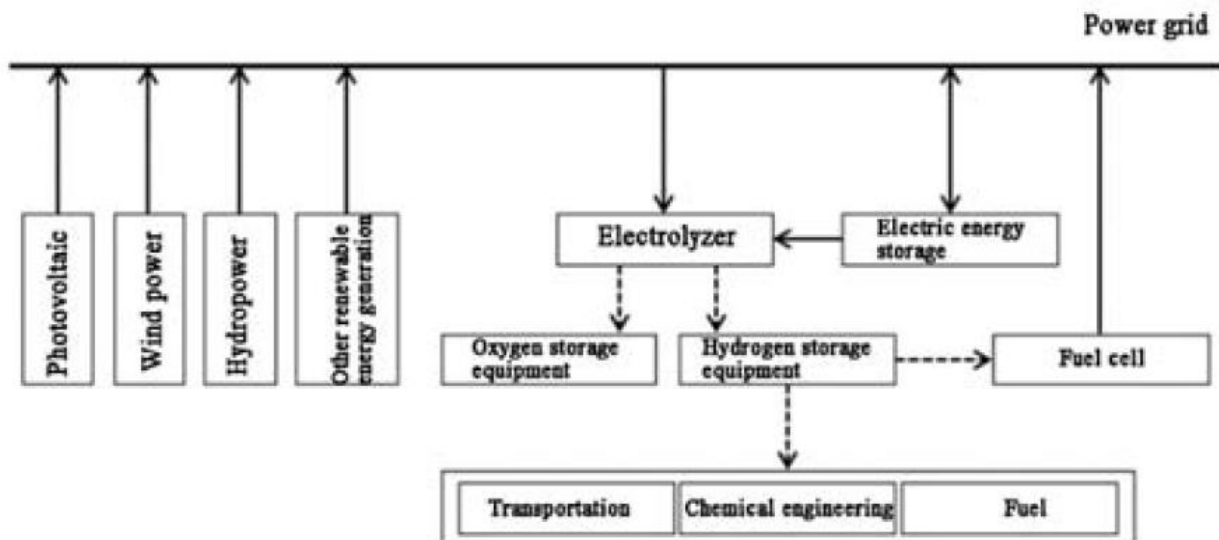
The integration of control systems in hydrogen energy storage systems holds significant importance in the realm of renewable energy technology and this can be a promising approach to tackle the climate change. As the world transitions towards a more sustainable energy future, the need for efficient and reliable energy storage solutions becomes increasingly crucial. Hydrogen energy storage systems offer a promising avenue for storing excess renewable energy and providing grid stability during periods of high demand or intermittent renewable energy generation. Reduction of CO<sub>2</sub> emissions from transportation, electricity generation, heating, and industrial sectors are few of the other benefits of such systems.

Therefore, storage systems play a pivotal role in enabling the seamless integration of renewable energy sources into the existing grid infrastructure. By regulating the control systems within these systems, we can optimize energy flow, enhance grid stability, and improve overall system efficiency. The utilization of different storage strategies present an opportunity to further enhance the performance of grid, enabling more precise and dynamic control over energy conversion and distribution.

Since there are a number of research papers done on the subject of energy storage systems and the control systems involved, it is crucial to gather all these information in a trackable single paper and categorizing each of the subjects with necessary data. The goal of this paper is to address this lack in the literature by providing a comprehensive review of the current state of knowledge on the topic, thus providing facilitated path to further researches and future endeavors.

## Hydrogen energy storage system structure

The hydrogen energy system typical structure is according to figure 1. In this figure, solid lines are electric energy transmission and dashed lines stand for gas transmission.

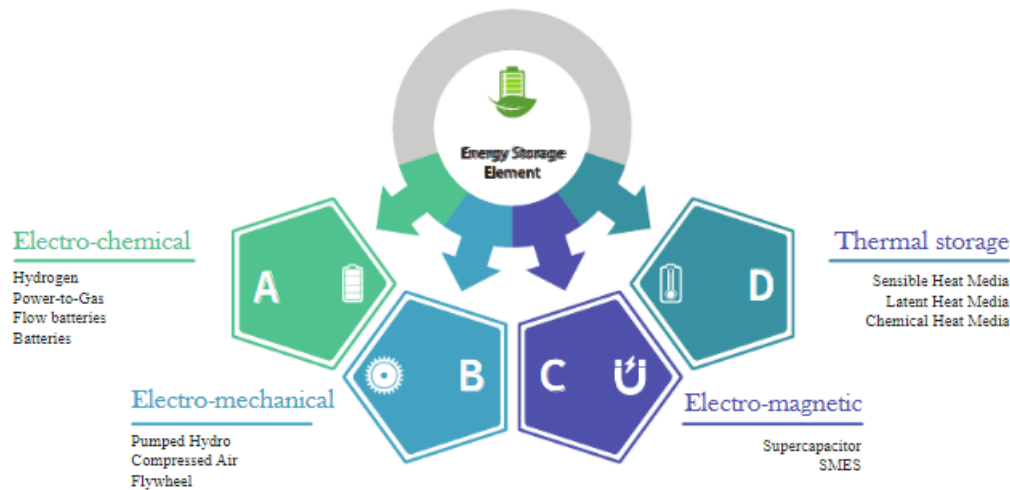


(Figure 1) Diagram of Hydrogen Energy System Structure

## Hydrogen Energy Storage Technologies

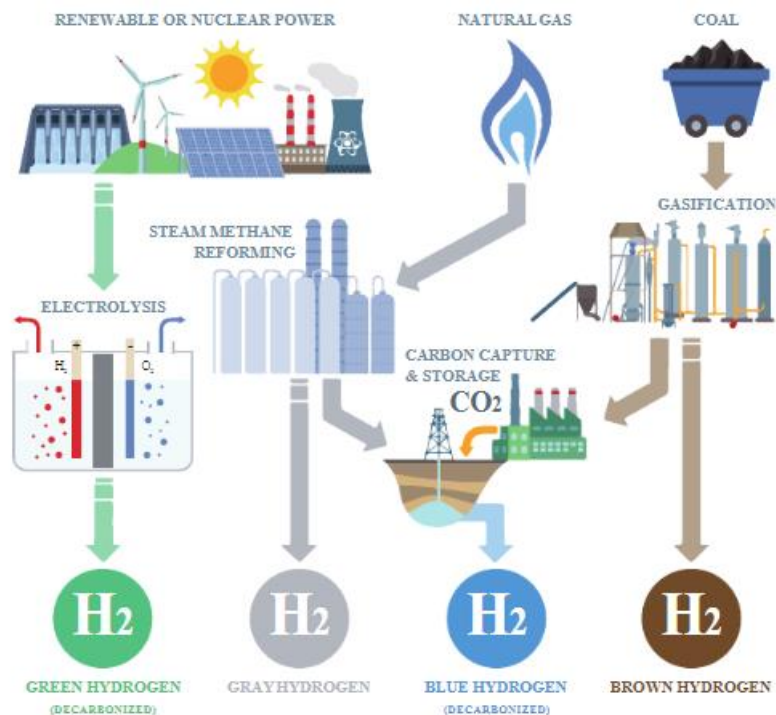
Around a third of the world's electricity will rely on intermittent renewable sources like wind and solar by 2040 [1]. This will require solutions for long-term and large-scale storage of electricity, with hydrogen production and storage being a promising technology.

There are several different types of energy storage systems, each with its own set of advantages and disadvantages. Fig. 2 shows different types of ESS used in the power system.



(Figure 2) Range of Storage Technologies

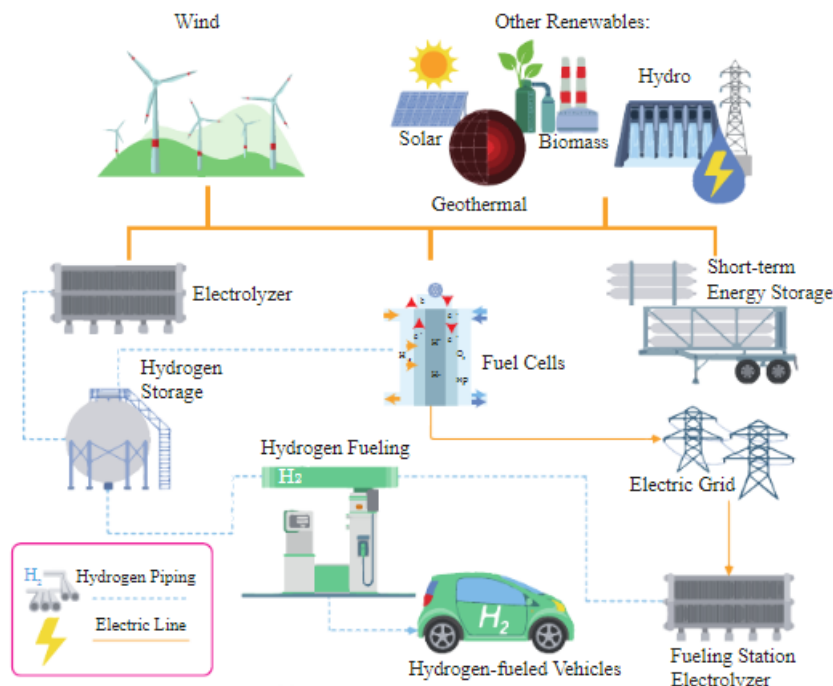
Hydrogen functions as an electrochemical energy storage system (ESS), serving as an energy carrier rather than an energy source. Its utilization spans diverse applications such as electricity generation, transportation, and industrial processes, leveraging its attributes of cleanliness, abundance, and renewability. While it is widely recognized as a promising solution for carbon reduction, the alignment of hydrogen's environmental benefits with this objective relies on factors such as the feedstock employed and the intended end-use application. In a study conducted by [2], the authors proposed a concept for categorizing produced hydrogen based on its quality. Fig. 3 illustrates the color grading system employed to categorize different production methods. Green and blue hydrogen represents the most desirable categories in terms of achieving carbon neutrality. Green hydrogen gives impetus to the researchers to make an application in power systems. In the power system, hydrogen can be used as a way to store excess electricity from RESs, such as wind and solar, which can then be converted back into electricity when it is needed [3].



(Figure 3) Hydrogen Color Categories

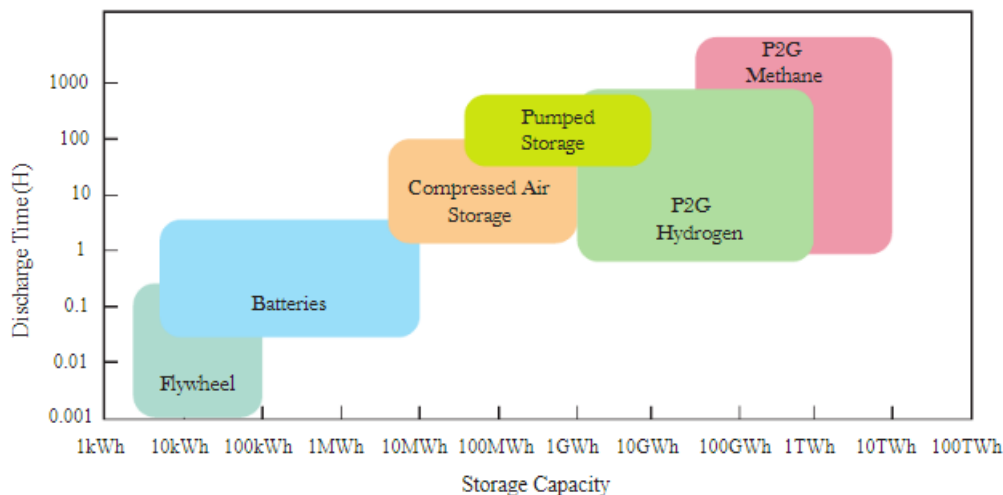
The community-level regional energy systems in figure 4, that integrates electrical, thermal, and hydrogen interactions, involving low-rise single houses, rooftop PV systems, hydrogen vehicles, a hydrogen station with an

electrolyzer, a local power grid, and hydrogen pipelines can accelerate the transformation process toward a carbon-neutral residential community [4].



(Figure 4) A Community based of hydrogen modern network

Another essential parameter to consider is the discharge time and capacity of different energy storage systems, as demonstrated in figure 5.



(Figure 5) Relation between the discharge time and storage capacity of various energy storage technologies

### Hydrogen energy storage systems as renewable energy

There are various ways in which hydrogen can be stored for later use. The most common method so far is as compressed gas. Another method is to store it as a liquid at very low temperatures. Hydrogen can also be stored through physisorption, which is physical adsorption on the surface of a solid material, or chemisorption using metal hydrides [4]. However, Compressed gas storage and metal hydride storage are the most relevant storage methods for stationary power systems. Storing hydrogen as compressed gas is currently the most widespread method. The compression process typically uses 20% of the energy content in the hydrogen [5]. Advantages with storing hydrogen as compressed gas is that it is relatively simple from a technical viewpoint and the cost is relatively low. Disadvantages

include relatively low system energy density compared to systems based on fossil fuels and safety issues related to the high pressure.

Hydrogen can also be stored as a liquid. This increases the volumetric energy density significantly compared to storing it as a compressed gas. Liquid hydrogen has a volumetric energy density of 2.2 kWh/L, while compressed hydrogen gas contains 1.3 kWh/L at 700 bar and 0.8 kWh/L at 350 bar. However, the volumetric energy density of liquid hydrogen is less than 40% of the volumetric energy density of liquified natural gas (LNG), which is 5.8 kWh/L [4]. Disadvantages with liquid hydrogen are the energy required for liquefaction, hydrogen boil-off and very costly storage systems. The consequence of the boil-off issue is that liquid hydrogen is only considered for applications where hydrogen is used relatively quickly after loading (e.g. transport applications with frequent re-filling opportunities) and it is not a good choice for long-term energy storage in stationary power systems.

Physisorption is another method for storing hydrogen. The hydrogen gas molecules are adsorbed onto the surface of a solid material, and then released as gas when hydrogen is needed for use, for example in a fuel cell. The materials most commonly used to adsorb the hydrogen gas are carbon-based materials and metal organic frameworks [5]. While many of these materials are the subject of promising research, they have not been deployed on a commercial scale and none of the projects reviewed in this article uses/used physisorption to store hydrogen. Advantages with hydrogen storage through physisorption includes low system complexity, low pressure and fairly non-expensive materials. Disadvantages include relatively low hydrogen density on carbon and the low temperatures required [6].

Finally, hydrogen can also be stored through chemisorption in metal hydrides. This is a process where hydrogen gas is absorbed and stored in a metal powder, either a pure metal or a metal alloy. Heat is released when the hydrogen gas is absorbed in the metal hydride material and heat must be applied for the metal hydride to release the hydrogen again. A drawback with the metal hydride storage method for some of the materials is that the hydrogen bonds so strongly to the metal hydride that relatively high temperatures are needed to release the hydrogen again, for example more than 650 °C in the case of lithium. However, an advantage is that some of these materials have very high gravimetric hydrogen capacities, e.g. 18 wt% for LiBH<sub>4</sub> [5].

### Economy Efficiency Analysis of Hydrogen Energy systems

Construction cost is a crucial investment before the operation of a hydrogen energy system [7]. Cost of water electrolysis equipment, hydrogen storage equipment and fuel cell are of these items to consider. Electrolyzer cost is of the factors to consider. If unit construction cost of electrolyzer is  $C_1$  and size is  $P_s$ , construction cost is  $C_d$  of electrolyzer:

$$(1) C_d = C_1 \times P_s$$

The cost of hydrogen storage equipment is another criteria in which the system applies hydrogen storage at high pressure and the equation is as below:

$$(2) C_c = C_p \times P_{\max} + C_r \times Q_{\max}$$

Another factor to consider is fuel cell cost. Assuming that the unit construction cost of a fuel cell system is  $C_2$  and system capacity is  $P_1$ , the equation to calculate construction cost is  $C_d$  as follows:

$$(3) C_d = C_2 \times P_1$$

Running costs as well as the maintenance and management costs are other factors that should not be neglected. The proportion of management and maintenance costs according to table 1 are as below:

Table 1. Proportion of maintenance and management costs

	Electrolyzer	Hydrogen storage	Fuel cell
Proportion	4%	1%	4%

### Conclusions

This article has taken a deep dive into the different areas of hydrogen energy storage systems. Various studies focusing on power electronics, control systems and energy management strategies for energy systems with hydrogen storage were reviewed. The focus of the review was to provide an overview of the recent developments and current state-of-

the-art within hydrogen-based systems and to present the advantages as well as challenges connected to the real-world implementation of hydrogen as an energy storage technology. Results from the projects and papers reviewed in this article show that hydrogen storage systems are technically feasible in many different situations, including large-scale industrial power-to-gas facilities, large commercial/public buildings, residential houses, as well as micro-scale mobile systems. Both the overall energy efficiency of the system and the lifetime of the various components increase significantly when a hybrid system is used. However, there are considerable challenges that need to be dealt with before these systems can be implemented on a commercial scale. The costs of a hydrogen-based system are still high. On the positive side, the predicted increase in demand for long-term energy storage could lead to mass production of the various components of hydrogen storage systems. The economies-of-scale effect from this is predicted by many to significantly reduce the cost of these components and systems in the coming decades. It remains to be seen whether this reduction will be large enough to make them a commercially attractive option for energy storage in future power systems.

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