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From Mechanisms to Efficiency Optimizations: A Research Progress of Hydrogen Production and Storage Techniques

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Abstract. Hydrogen energy is a promising clean energy solution to address growing energy demands and environmental challenges. This paper reviews hydrogen production methods, including water electrolysis — encompassing alkaline (AWE), proton exchange membrane (PEM), and solid oxide electrolysis (SOE) — as well as steam methane reforming (SMR). The analysis covers their respective efficiencies, environmental impacts, and potential optimization strategies such as catalyst development, thermal management, and system integration with renewable sources. Additionally, it examines hydrogen storage technologies, including high-pressure compressed gas, cryogenic liquefaction, and metal hydrides, highlighting their specific advantages and limitations in terms of energy density, safety, operational efficiency, and economic feasibility. The study emphasizes the crucial role of green hydrogen production using renewable electricity and explores recent advancements in materials, such as novel electrodes and absorbents, and process improvements aimed at enhancing efficiency, scalability, and long-term sustainability. The findings provide strategic insights into advancing hydrogen energy systems toward a low-carbon future by addressing technical and practical implementation barriers.

Keywords: Hydrogen production, Hydrogen storage, Green hydrogen, Renewable energy.

1. Introduction

Global population expansion continues to drive up energy consumption. Estimates indicate that the global population may approach 10 billion around the turn of the 22nd century [1]. Correspondingly, energy use in 2040 is anticipated to be 1.33 times higher than levels recorded in 2015 . Presently, the energy sector remains heavily dependent on combustion of fossil fuels—including petroleum, natural gas, and coal—which are not only finite but also contribute significantly to environmental degradation, such as global warming and sulfur emissions [2]. Transitioning to clean energy sources is therefore imperative for achieving carbon reduction and sustainable energy objectives [3]. Hydrogen energy has emerged as a promising candidate, owing to its high energy content and combustion without carbon emissions [4].

Hydrogen must be manufactured artificially through industrial processes, as it is not found in its pure form in nature like fossil fuels are. This paper discusses two primary production routes: electrolysis (powered by renewable electricity) and methane steam reforming. Additionally, storing hydrogen efficiently is critical for its broad application. Hydrogen can be retained using various

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strategies, primarily via compression into a gaseous state, cryogenic cooling to a liquid, or adsorption onto solid-state materials like metal hydrides and liquid organic carriers. The efficacy of a hydrogen-based energy system is largely a function of its production and storage efficiencies.

Regarding hydrogen generation, Pavlos Nikolaidis et al. differentiate between fossil-based methods (e.g., methane reforming) and renewable pathways (e.g., bio-hydrogen and electrolysis), underscoring the potential of green hydrogen—produced via renewable-powered electrolysis—as a zero-carbon solution pending improvements in electrolyzer efficiency. In storage, Muhammad R et al. outline major technologies such as high-pressure gaseous storage, cryogenic liquid hydrogen, and solid-state storage using metal compounds, also suggesting catalytic strategies to mitigate poisoning and enhance storage performance [5].

This paper provides a comprehensive review and critical assessment of techniques for generating and storing hydrogen, examining their advantages and limitations to suggest potential avenues for performance enhancement. For production, enhancements may involve catalytic material selection, process redesign, and advanced materials. In storage, innovations such as novel catalysts and optimized operational conditions are discussed.

2. Hydrogen production

The efficiency of hydrogen generation is governed by multiple variables, with the production process itself being the most influential. This section covers two leading production methods: water electrolysis using renewable energy and steam methane reforming. Renewable water electrolysis offers an environmentally benign route to produce hydrogen with virtually no carbon emissions when powered by clean energy. Meanwhile, steam methane reforming is the most extensively adopted method due to its technological maturity and capacity for large-scale industrial output.

2.1. Renewable water electrolysis

Electrolytic hydrogen production is based on the redox decomposition of water. The overall reaction is expressed as equation (1):

$$2H_2O \rightarrow 2H_2 \uparrow + O_2 \uparrow \tag{1}$$

Water is utilized as the raw material that decomposes into hydrogen and oxygen upon the application of an electrical voltage. At the cathode, reduction reactions take place, whereas oxidation occurs at the anode. Commonly deployed electrolyzer types encompass alkaline water electrolysis (AWE), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOE) [6]. While operational parameters and material specifications vary among these technologies, the core electrochemical process is universal. Notably, the reaction is endothermic, demanding an energy input of 237.13 kJ per mole. Consequently, external energy must be supplied to attain feasible reaction speeds and outputs in a practical timeframe. In electrolytic hydrogen production, energy is provided in the form of both electrical power and thermal energy. When the electricity originates from renewable sources, the hydrogen produced is classified as green hydrogen, ensuring a carbon-neutral lifecycle from generation to consumption. Therefore, the use of renewable energy for electrolysis is advantageous, as long as target efficiency levels are achieved.

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2.1.1. Alkaline Water Electrolysis (AWE)

AWE is a well-established technology that employs alkaline solutions (e.g., 20–30% NaOH or KOH) operated at 60–80°C. Energy consumption ranges between 4.5–5.5 kWh/Nm³, with current densities typically under 400 mA/cm², resulting in relatively low efficiency (~60%) [7]. Its slow dynamic response and reliance on stable electrical input make integration with intermittent renewables challenging. Several upgrades have been proposed: three-dimensional porous electrodes (e.g., nickel foam) can increase active surface area and facilitate bubble release; nanoparticle catalysts help reduce overpotential and enhance specific surface area. Heat recovery systems preheat feedwater using waste heat, and advanced sealing techniques enable pressure differentials of 3–10 bar between electrodes, elevating current density to 500–600 mA/cm² [8]. Despite these improvements, the theoretical efficiency of AWE remains capped near 70% [9].

2.1.2. Proton Exchange Membranes (PEMs)

The PEM electrolysis employs perfluorosulfonate membranes and operates at 60–80°C, with typical efficiencies of 60–70% and energy consumption of 4.0–4.5 kWh/Nm³. Its rapid response makes it suitable for variable renewable sources [10]. Key optimization strategies include developing low-iridium or iridium-free catalysts (e.g., using chalcogenides or spinel oxides) with high activity and durability, and implementing ultrathin films with protective layers to enhance efficiency and safety. These advances can elevate peak efficiency to 91.3% [10].

2.1.3. Solid Oxide Water Electrolysis (SOE)

The SOE operates at high temperatures (700–1000°C) and consumes 3.5–4.5 kWh/Nm³, with 30–50% of the energy supplied as heat. Electrical efficiency can reach 85–95%, approaching 100% with heat recovery [10, 11]. However, the high operating temperature and long heat-up times hinder compatibility with variable renewables. Optimization efforts include AI-assisted real-time adjustment of voltage and temperature, predictive maintenance to avoid degradation, and development of intermediate-temperature electrolyzers (500–700°C) using materials such as doped lanthanum gallate to reduce thermal stress and extend system life [8, 11]. Nevertheless, continuous cycling remains detrimental to durability, and renewable adaptability is still limited.

2.2. Steam Methane Reforming (SMR)

Steam methane reforming involves the catalytic reaction of methane with steam to produce hydrogen and carbon oxides (CO or CO_2). The primary reforming step is given by equation 2:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{2}$$

This endothermic reaction requires high temperatures (850–900°C) and elevated pressure (3.5 MPa) [5,12]. Side reactions such as the water-gas shift equation 3, methane cracking equation 4, and carbon gasification equation 5 may occur under varying conditions and catalysts [12]:

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{3}$$

$$CH_4 \rightarrow C + 2H_2 \tag{4}$$

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$$C + H_2O \rightarrow CO + H_2 \quad (5)$$

The main catalyst is nickel, which is the core active component of industrial SMRs and has excellent catalytic activity for CH_4 cracking and steam reforming reactions [13,14]. Nickel is very abundant, inexpensive and more economical than precious metals (e.g. Rh, Pt) [15]. However, the disadvantages of nickel metal catalysts are still significant and most of the major efficiency limitations also come from the catalyst nickel. At high temperatures (>700°C) and low water-to-carbon ratios, the nickel surface is susceptible to methane cracking (4), leading to carbon build-up covering the active sites [16]. Sulphides such as H_2S in the feed gas can form stable NiS with nickel, poisoning the catalyst and thus irreversibly deactivating it [17]. Another disadvantage is the low efficiency of heat transfer Conventional heating methods (e.g. external combustion furnaces) lead to significant thermal gradients in the reactor and energy wastage, so that neither the productivity nor the heat return is very high (energy conversion efficiency is only 1.75%) [18]. For improving the overall reaction efficiency, improving the catalyst material and usage is definitely a good way to optimise production efficiency in multiple dimension

The $Ni_{60}Co_{40}$ catalyst was prepared by impregnating nickel nitrate and cobalt nitrate solutions (Ni:Co = 60:40) using a balanced adsorption method, followed by drying at 80°C. The catalyst was then calcined at 450–750°C in flowing air for 1 hour and subsequently reduced with hydrogen at 900°C for 5 hours. The optimal loading amount was determined to be 30 wt%, and the particle size distribution was optimal at 600°C calcination temperature (20–35 nm) [19]. The $Ni_{60}Co_{40}$ catalyst significantly improves resistance to poisoning through alloy design, as the electronic effects of cobalt weaken the binding of sulphur species to active sites [18].To address the issue of low heat transfer efficiency, radio frequency induction heating technology is used to generate heat directly inside the catalyst particles [14]. Eliminating the thermal gradient of traditional heating can increase energy efficiency from 1.75% to 16%. Carbon deposits can be synergistically addressed by inhibiting methane cracking with cobalt and optimising particle size (20–35 nm) [17]. At the same time, in multiple cycle tests (using 180 catalysts, ten times the original amount, at a temperature of 740°C), the CH_4 conversion rate remained stable at 80% with no activity decay (the catalyst has excellent anti-poisoning properties) [18].

3. Hydrogen storage

After hydrogen is produced, storing it is also an important step that needs to be considered. Currently, the predominant approaches for hydrogen storage involve compression, cryogenic liquefaction, and metal hydride absorption. This article will introduce the working principles of these three methods and summarise improvements in efficiency for each method.

4. Compressed hydrogen technique

High-pressure vessels, constructed from steel, aluminum, or carbon fiber composites, and underground cave storage are the two predominant techniques for retaining hydrogen in a compressed state. High-strength materials (such as steel, aluminium, or carbon fibre composite materials) are often required to manufacture hydrogen storage containers [20]. For compressed gases, the storage rate is fast, and there is almost no loss of hydrogen after release. However, the inner walls of the container must withstand high pressure (700 bar), which poses a risk of leakage. Hydrogen has a low storage density, resulting in insufficient volumetric hydrogen storage capacity . To improve the feasibility of this method, this paper reviews the following methods. First,

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lightweight, high-strength carbon fibre composite materials are used to replace traditional materials, reducing weight and improving impact resistance [20]. In addition, combining compressed hydrogen with liquid hydrogen for storage utilises the high density of liquid hydrogen to compensate for the volume deficiency of compressed hydrogen, while also reducing evaporation losses.

4.1. Liquefied hydrogen technique

The advantage of liquefied hydrogen gas lies in its use of low-temperature liquefaction to increase volume energy density (four times that of gaseous hydrogen), but it requires special insulated containers (such as double-layer vacuum insulated tanks) to reduce heat transfer. In addition, the liquefaction process consumes a significant amount of energy, accounting for approximately 30% of hydrogen's functionality [20]. Continuous cooling to maintain hydrogen liquefaction also requires energy. Current optimisation schemes mainly focus on improving container insulation efficiency. The use of new insulation materials (such as aerogels) helps reduce heat penetration and integrates pressure release devices [20].

4.2. Metal hydride storage

The principle of metal hydrogen compounds is to store hydrogen by forming metal hydrides through reversible chemical reactions between metals or alloys and hydrogen gas. Taking magnesium-based hydrogen storage alloys as an example, the theoretical hydrogen storage capacity reaches 7.6 wt%. Its core reaction is equation 6:

$$Mg + H_2 \rightleftharpoons MgH_2 \tag{6}$$

The process utilises vacant positions in the metal lattice to accommodate hydrogen atoms. However, this method also has significant shortcomings. First, in terms of dehydrogenation, the required temperature is extremely high, as pure MgH_2 requires temperatures above 300°C for dehydrogenation. Moreover, hydrogen diffusion in metals is limited, resulting in relatively slow hydrogen absorption and desorption rates. The current main optimisation strategies involve alloying (e.g. Mg_2Ni), nanostructuring, and adding catalysts to optimise thermodynamic and kinetic properties, thereby achieving more complete desorption, faster rates, and lower temperature requirements.

5. Conclusion

This survey offers a methodical evaluation of hydrogen generation and storage techniques, critiquing the merits, challenges, and possible improvements for different systems. such analysis provides critical insights for advancing low-carbon and sustainable energy systems. In production, water electrolysis (AWE, PEM, SOE) and steam methane reforming (SMR) are the dominant approaches. Green hydrogen from electrolysis is ideal for zero-carbon emissions but requires efficiency gains. AWE is mature yet inefficient (60%), but can reach 70% with porous electrodes and heat recovery. PEM offers rapid response and up to 91.3% efficiency, though it depends on precious metal catalysts. SOE achieves the highest efficiency (near 100%) but is constrained by high temperatures and limited renewable compatibility. SMR has low base efficiency (1.75%), but using $Ni_{60}Co_{40}$ catalysts and induction heating can boost energy efficiency to 16%, alongside improved resistance to poisoning and coking.

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For storage, compressed hydrogen offers fast charging but suffers from leakage risks and low energy density—issues partly addressed by composite materials and hybrid storage with liquid hydrogen. Liquefied hydrogen has high energy density but high energy costs; novel insulators like aerogels can reduce heat influx. Metal hydrides provide high storage density but require high temperatures and exhibit slow kinetics; alloying, nanotechnology, and catalysts can markedly improve performance.

In summary, continued optimization of hydrogen production and storage is essential for improving efficiency and reducing costs. Future work should prioritize catalyst development, process optimization, and new materials to enable large-scale adoption of hydrogen energy and support global sustainable energy goals.

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