Fuel cell cars with hydrogen production, storage, costs, efficiency and production model in manufacturing

Peijun Fang *

University of Central Lancashire, PRESTON, UK

* Corresponding Author Email: PFang@uclan.ac.uk

Abstract. Given the increasing global concern about climate change and environmental pollution, the development and application of clean energy have become particularly urgent. Hydrogen energy, with its high energy density and clean combustion characteristics, is widely regarded as the core of the future sustainable energy system. Although the wide application of hydrogen energy is constrained by life cycle cost and fuel safety. The primary elements influencing hydrogen's life cycle cost are its production, supply, market price, demand, storage, distribution, and cost of investment. The current hydrogen production, storage, and transportation technologies are summarized, including steam methane reorganization (SMR), wind and solar power generation, alkaline hydrolysis (AWE), high-pressure gas cylinders, low-temperature liquid hydrogen storage, ammonia compound hydrogen storage, methane compound hydrogen storage and hydrogen transportation. The article aims to provide a comprehensive perspective on the current situation and future development trends of hydrogen production and storage technology and provide suggestions for the sustainable progress of green hydrogen production and utilization.

Keywords: hydrogen energy, hydrogen production, hydrogen storage, efficiency, green hydrogen.

1. Introduction

Due to its high energy density and clean combustion characteristics, hydrogen is regarded as an essential component of contemporary sustainable energy systems. The main barriers to the widespread use of hydrogen right now are fuel safety perceptions and worries about total lifespan costs. Production, supply, market prices, demand, storage, distribution and investment are the main factors influencing lifetime costs. When considering expenses, the key factor affecting the cost of hydrogen is the characteristics of its source [1]. According to the International Energy Agency (IEA), the demand for hydrogen reached 94 million tonnes (Mt) in 2021, rising to levels seen before to the pandemic (91 Mt in 2019), and providing energy equivalent to roughly 2.5% of the world's total energy consumption [2]. To achieve truly clean hydrogen production, the concept of green hydrogen has emerged. This involves using renewable energy sources and water electrolysis technology to produce hydrogen. Moreover, due to the light and gaseous nature of hydrogen, its storage and transportation present a series of challenges. In Toyota's hydrogen production project, the team partnered with Emerson to develop a process orchestration layer integrated with systems like power meters, electrolyzers, fuel cells, refueling stations, solar and battery inverters, and monitoring instruments. Emerson's DeltaV software and automation solutions streamline the integration of necessary third-party systems for efficient hydrogen system operations. The implementation of DeltaV's DCS and SIS ensures safe operational controls, such as managing the cycling of hydrogen storage tanks to enhance their service life [2]. This article primarily summarizes current technologies for hydrogen production, storage, and transportation, including Steam Methane Reforming (SMR), wind and solar power generation, alkaline water electrolysis (AWE), high-pressure gas cylinders, liquid hydrogen in cryogenic tanks, ammonia compound hydrogen storage, methane compound hydrogen storage, and hydrogen transportation. Furthermore, numerous nations have concentrated on enacting eco-friendly energy regulations in order to achieve decarbonization and a sustainable environment. South Korea, for instance, introduced its second Climate Change Response Master Plan in 2019. This plan aims to reduce greenhouse gas emissions from 709.1 million tons in 2017 to 536 million tons by 2030, thereby fostering the development of a low-carbon and sustainable society [3].

This article aims to provide a comprehensive perspective on the status and future development of hydrogen production and storage technologies and to offer reasonable suggestions for the sustainable development of green hydrogen.

2. Grey hydrogen

Grey hydrogen currently constitutes the majority of hydrogen production. It is produced through steam methane reforming (SMR) or coal gasification processes that do not incorporate carbon capture, utilization, and storage (CCUS). The primary applications of grey hydrogen are in the petrochemical sector and ammonia manufacturing. Over the past 70 years, there has been a significant increase in demand for hydrogen for these two applications, as illustrated in Fig. 1. Annually, grey hydrogen is typically generated using approximately 2% of global coal resources and about 6% of the world's extracted natural gas [4].

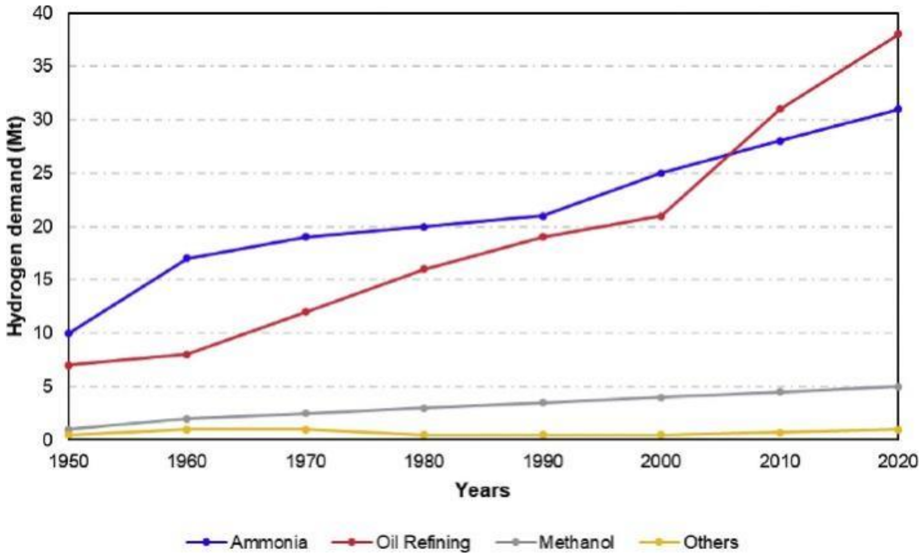

Figure 1. Global demand for hydrogen has developed during the past 70 years [5]

However, the SMR technology produces a significant amount of carbon dioxide during the conversion of methane to hydrogen. To reduce the CO_2 emissions from hydrogen production by SMR, carbon capture is crucial. The Sorption Enhanced Steam Methane Reforming (SE-SMR) technology reacts methane and water in the presence of a catalyst and a CO_2 sorbent to produce hydrogen and calcium carbonate. This process can be carried out in an integrated carbonator and reformer, achieving in-situ CO_2 capture, thus producing low-carbon and high-purity hydrogen. The overall reaction of the SE-SMR process can be simplified to the following equation.

$$CH_4 + 2H_2O + CaO = CaCO_3 + 4H_2 \quad (1)$$

In the above reaction, CO_2 is captured as solid calcium carbonate instead of being emitted as a gas into the atmosphere. This process helps to reduce the carbon footprint associated with hydrogen production. SE-SMR process typically operates at temperatures between 550 and 650 degrees Celsius and at a pressure of about 25 bar to reduce the energy penalty for hydrogen compression. In this way, the SE-SMR technology can produce high-purity hydrogen at lower energy consumption, and compared to the traditional SMR technology, which requires multiple shift reactors and subsequent purification steps, the SE-SMR technology has a higher hydrogen yield and methane conversion rate [6].

3. Green hydrogen

Using renewable energy sources such as solar and wind to produce hydrogen is classified as green hydrogen. This process involves several stages: first, harnessing solar and wind energy to generate electricity; second, conducting alkaline water electrolysis (AWE); and finally, storing and extracting pure hydrogen [7]. The installation of energy storage devices is crucial for enhancing system stability, as solar energy may not always be available, even on overcast days. Multigenerational systems provide effective, cost-efficient, environmentally friendly, and sustainable solutions to this challenge. Furthermore, Fig. 2 illustrates the entire procedure.

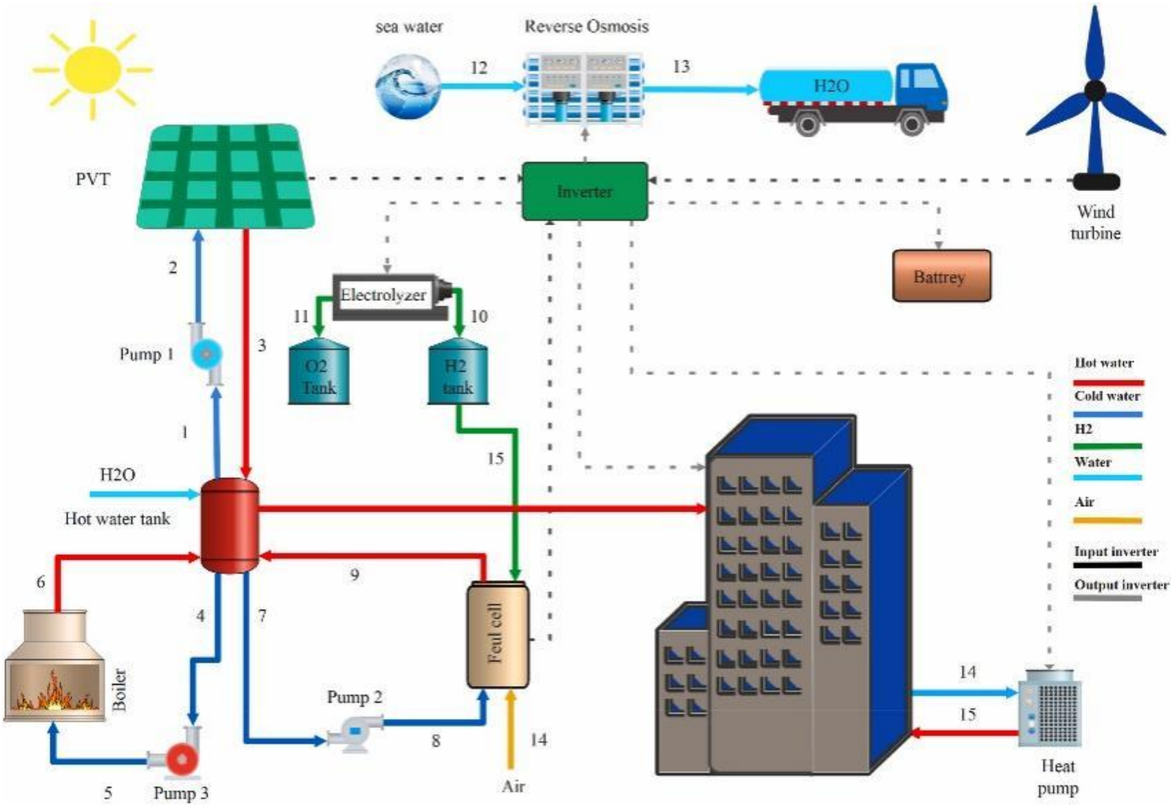

Figure 2. System flow chart of AWE [5]

3.1. System workflow

Solar power is transformed into electrical and thermal energy via photovoltaic/thermal (PV/T) systems. The electrical energy serves to fulfill the building's power requirements, whereas the thermal energy is utilized for water heating or is directly fed to heat pump systems. Wind energy conversion, such as wind turbines, capture kinetic energy from wind to produce electricity, supplementing solar power and ensuring system functionality during periods of insufficient or absent solar irradiation. Heat pumps modulate the indoor temperature in accordance with the building's thermal demands for heating and cooling, employing electrical energy in the process. Fuel cells, when solar and wind energies are not sufficient, generate electricity and thermal energy by harnessing stored hydrogen, thus ensuring the uninterrupted operation of the integrated energy system.

3.2. System optimization

The system is optimized using the Response Surface Method (RSM) to determine the optimal angles, quantity of solar panels, quantity of wind turbines, fuel cell electricity, and heat pump cooling and heating capacities. The optimization goals include keeping the Predicted Mean Vote (PMV) within the optimal range and reducing life cycle expenses, boiler fuel use, and overall electricity consumption.

3.3. Alkaline water electrolysis

An aqueous solution of water and 25-30 weight percent potassium hydroxide is usually used as the electrolyte in the well-known AWE technology. Nevertheless, alternative electrolytes, such as sodium hydroxide and sodium chloride, have also been utilized. The liquid electrolyte allows ions to move between electrodes. Although it is not used up in the reaction, other system losses require that it be frequently replaced. The current used in commercial alkaline electrolyzers is typically between 100 and 300 mA/cm². Equations (2) and (3), respectively, depict the reactions for the alkaline anode and cathode. Oxygen (OH-) ion transport is demonstrated by the reactions [8].

$$4OH^- \rightarrow O_2 + 2H_2O \tag{2}$$

$$2H_2O \quad + 2e^- \rightarrow H_2 + 2OH^- \tag{3}$$

4. Hydrogen storage

4.1. High-pressure gas cylinders

Hydrogen has a density of only 0.089 kg/m³ at standard atmospheric pressure and room temperature, which results in a large volume under normal conditions, making it unfavorable for storage and transportation [9]. Compressed hydrogen at high pressure is the most often utilized hydrogen storage technique. In addition to being a highly established technology, hydrogen compression provides high rates of hydrogen filling and release [10]. Incredibly high pressures of up to 700 bar or 1000 bar may be demanded in automotive applications.

Such high pressure not only poses challenges for the materials and design of hydrogen storage tanks but also increases the costs of manufacturing and operation. The hydrogen density rises from 0.1 g/L to 40 g/L as pressure rises from 1 bar to 700 bar, and as a result, the energy volumetric density rises from 0.0033 kWh/L to 1.32 kWh/L. A particular kind of hydrogen storage tank has improved gravimetric performance by using a polymer liner rather than a metallic one in order to cater to the car industry. Following the polymerization process, the carbon fiber reinforced polymer, or CFRP, has enough mechanical qualities and can function as the principal load-bearing component. Because composite filament woven technology is lightweight, strong, and has sufficient resistance to fatigue and corrosion, it has the potential to enhance storage performance [11]. Composite filament wound technology will work with military, aerospace, hydrospace, and automotive applications because of these properties. As a result, the automobile sector will see an acceleration of hydrogen's commercialization.

4.2. Cryo-compressed hydrogen storage

In the context of high-pressure hydrogen storage, at 70 MPa at room temperature, gaseous hydrogen has a relatively low density of 39.1 kg/m³. In comparison, liquid hydrogen has a density of 71.0 kg/m³ at a cryogenic temperature of 20 K and a relatively low pressure of 0.4 MPa. Still, it is crucial to note that gaseous hydrogen, when stored above 15 MPa and near its liquefaction temperature, can achieve a higher density than liquid hydrogen. This finding highlights the importance it is for maximizing pressure and temperature parameters in order to achieve the usefulness of hydrogen storage equipment. Yanxing as well as others have delineated an optimal range for temperature and pressure that maximizes hydrogen storage density, independent of the ortho-to-para-hydrogen conversion [12]. The identified range spans from 35-110 K in temperature and 5-70 MPa in pressure, generating concentrations of hydrogen ranging from 60.0 to 71.5 kg/m³.

These parameters are pivotal for achieving high-performance hydrogen storage capabilities. To quantitatively assess the efficiency of hydrogen storage systems, Yanxing et al. proposed two critical indices: ψ, which correlates hydrogen density with the power consumed per unit, and ω, which represents the ratio of the system's total power consumption to the heat of hydrogen's combustion. The ω values for liquid hydrogen (LH2) and compressed hydrogen (CcH2) storage systems are found to be maximized at 35% and 25%, respectively. CcH2, with its enhanced ψ values, stands out as a favorable option for hydrogen storage due to its efficiency. Despite the potential advantages of compressed hydrogen storage, such as higher attainable densities under specific conditions, these systems encounter notable challenges. They are particularly susceptible to heat leakage, which is a more pronounced issue compared to conventional gaseous hydrogen (CGH2) and liquid hydrogen

(LH2) systems. Furthermore, the power consumption of compressed hydrogen systems exceeds that of CGH2, and the risk of hydrogen embrittlement poses a significant threat to the structural integrity of pressure vessels, potentially leading to severe degradation.

4.3. Ammonia compound hydrogen storage

Ammonia in liquid form is distinguished by its exceptional volumetric hydrogen density, which attains 121 kg-H_2/m³-approximately 1.7-fold that of liquid hydrogen at 70.8 kg-H_2/m³. This elevated capacity for hydrogen storage within a given volume is a significant advantage for liquid ammonia. Furthermore, liquid ammonia can be maintained at a relatively modest pressure of 0.99 MPa at 25°C, contrasting favorably with the pressures exigent for compressed hydrogen storage. This pressure requirement reduction may translate into enhanced safety profiles and reduced infrastructure complexities. Nevertheless, the physical density of liquid ammonia, at 600 kg/m³, surpasses that of both compressed and liquid hydrogen, potentially imposing greater mass burdens during storage and transportation processes. Methanol emerges as a competitive hydrogen storage medium, with an energy density of 20.1 MJ/kg, which exceeds that of ammonia at 18.6 MJ/kg. However, methanol's hydrogen content, both in terms of gravimetric (12.5 wt%) and volumetric (99 kg-H_2/m³) metrics, falls short of ammonia's respective figures of 17.8 wt% and 121 kg-H_2/m³. The synthesis of methanol, which incorporates CO_2, and its decomposition, which emits CO_2, present environmental challenges due to the carbon footprint associated with these processes. Additionally, the reformation of methanol can generate carbon monoxide (CO), a compound that is detrimental to the catalysts commonly utilized in fuel cells, thereby potentially abbreviating the operational lifespan of such cells. This propensity for catalyst poisoning is a critical technical hurdle that must be addressed to enhance the viability of methanol as a hydrogen storage solution [13].

The ejection of hydrogen from ammonia demands an extensive energy input of 30 kJ/mol-H_2, contrasting with the minimal energy required for the regasification of liquid hydrogen at 0.90 kJ/mol-H_2. This energy-intensive nature of ammonia decomposition underscores the need for efficient strategies to optimize the overall energy balance, especially when high-purity hydrogen is essential for end-use applications. In such cases, additional processes for hydrogen purification become necessary, further complicating the energy efficiency of ammonia-based hydrogen storage systems. Conversely, hydrogen in both compressed and liquid forms offers the advantage of delivering high-purity hydrogen with greater energy efficiency, presenting a more straightforward and less energy-intensive approach for hydrogen utilization. When assessing hydrogen storage mediums, it is crucial to consider not only the storage capacity but also the energy costs associated with each stage of the hydrogen supply chain, from production and storage to distribution and end-use [13].

5. Conclusion

This article provides a comprehensive review of hydrogen energy as a clean energy source, examining its current status and challenges in production, storage, cost, efficiency, and manufacturing models. Amid growing global concern over climate change and environmental pollution, hydrogen, with its high energy density and clean combustion characteristics, is regarded as a key component of future sustainable energy systems. In terms of production, the article discusses the transition from grey hydrogen, produced through traditional methods such as Steam Methane Reforming (SMR), to green hydrogen, which is generated using renewable energy sources and water electrolysis technologies. The importance of reducing greenhouse gas emissions and improving production efficiency is emphasized. Particularly, the case study of Toyota's hydrogen production project demonstrates how advanced process orchestration layers and automation solutions can achieve efficient hydrogen production and sustainable system operations. Storage technology is another critical area for the application of hydrogen energy. The article analyzes various storage methods, including high-pressure gas cylinders, cryogenic liquid storage, and ammonia compound storage, discussing their characteristics in terms of energy density, safety, cost, and environmental impact. It is specifically pointed out that although liquid ammonia storage has advantages in terms of volumetric energy density, it requires a significant energy input to release hydrogen, indicating the need for further optimization of hydrogen storage and release processes. The article also employs the Response Surface Method (RSM) for optimization studies on hydrogen energy systems, aiming to minimize Consumption of boiler fuel, overall electricity consumption, and life cycle expenses and to maintain an ideal thermal comfort index. Through multi-objective optimization, the best system design parameters are identified, providing a scientific basis for the design and operation of hydrogen energy systems. Finally, the article highlights the key role of hydrogen technology in achieving sustainable energy transformation and offers sensible suggestions for promoting the development of the hydrogen economy. By thoroughly analyzing the current situation, challenges, and future development directions of hydrogen production and storage technologies, the article provides valuable references for both academia and industry, promoting the advancement and application of hydrogen energy technologies.

References

[1] Tashie-Lewis, B. C., & Nnabuife, S. G. Hydrogen production, distribution, storage and power conversion in a hydrogen economy-a technology review. Chemical Engineering Journal Advances, 2021, 8: 100172.

[2] IEA. Hydrogen demand is growing, with positive signals in key applications. Retrieved on September 15, retrieved from https: //www.iea.org/reports/global-hydrogen-review-2022/executive-summary.

[3] Emerson Exchange. Interconnection and Visualization of Toyota's Hydrogen Production Plant. Retrieved on September 15, retrieved from https: //emersonexchange365.com/worlds/china_/f/controlandsafetysystemchina/10239/thread.

[4] Le, T. T., Sharma, P., Bora, B. J., et al. Fueling the future: A comprehensive review of hydrogen energy systems and their challenges. International Journal of Hydrogen Energy, 2024, 54: 791 - 816.

[5] Ajanovic, A., Sayer, M., Haas, R. The economics and the environmental benignity of different colors of hydrogen. International Journal of Hydrogen Energy, 2022, 47: 24136 - 24154.

[6] Midilli A, Kucuk H, Topal ME, et al. A comprehensive review on hydrogen production from coalgasification: challenges and Opportunities. Int J Hydrogen Energy 2021, 46: 25385e412.

[7] Yan, Y., Manovic, V., Anthony, E. J., et al. Techno-economic analysis of low-carbon hydrogen production by sorption enhanced steam methane reforming (SE-SMR) processes. Energy Conversion and Management, 2020, 226: 113530.

[8] Dezhdar, A., Assareh, E., Agarwal, N., et al. Transient optimization of a new solar-wind multi-generation system for hydrogen production, desalination, clean electricity, heating, cooling, and energy storage using TRNSYS. Renewable Energy, 2023, 208: 512 - 537.

[9] John T., George S., Margaret K. et al. Renewable hydrogen production. National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, 2007, CO 80401 - 3393, U.S.A.

[10] Usman, M. R. Hydrogen storage methods: Review and current status. Renewable and Sustainable Energy Reviews, 2022, 167: 112743.

[11] Hassan, I. A., Ramadan, H. S., Saleh, M. A., et al. Hydrogen storage technologies for stationary and mobile applications: Review, analysis and perspectives. Renewable and Sustainable Energy Reviews, 2021, 149: 111311.

[12] Yanxing Z, Maoqiong G, Yuan Z, et al. Thermodynamics analysis of hydrogen storage based on compressed gaseous hydrogen, liquid hydrogen and cryo-compressed hydrogen. Int J Hydrogen Energy 2019; 44 (31): 16833 - 40.

[13] Aziz, M., Wijayanta, A. T., Nandiyanto, A. B. D. Ammonia as effective hydrogen storage: A review on production, storage and utilization. Energies, 2020, 13: 3062.