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A Review of Environmental, Economic, and Application Aspects of Green Hydrogen Production Technologies

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ABSTRACT

Hydrogen (H_2) has gained significant attention as a sustainable energy carrier capable of addressing climate change and energy security concerns. This review provides a comprehensive evaluation of the hydrogen value chain, technical and economic viability, environmental significance, and technology readiness level (TRL) of each system, highlighting their advantages and limitations Despite rapid progress, the widespread adoption of green hydrogen is constrained by high production costs, durability challenges, and infrastructural gaps. The review concludes by identifying potential pathways to reduce levelized cost of hydrogen (LCOH), improving electrolyzer efficiency, and expanding the role of hydrogen in decarbonizing transportation and industrial sectors.

Key Terms: Climate change, environmental significance, green hydrogen, LCOH, sustainable energy.

1. INTRODUCTION

Hydrogen has emerged as a pivotal element in the transition towards a carbon-free energy system due to its high energy density, versatility, and environmental compatibility (Acar et al., 2019). Currently, global hydrogen production is dominated by fossil-based pathways, where nearly 95% is derived from steam methane reforming (SMR) and coal gasification, releasing substantial greenhouse gases (GHGs) into the atmosphere. Only about 5% of hydrogen is produced through water electrolysis using renewable energy sources, commonly referred to as green hydrogen (Ismael et al., 2025). Countries such as China, the United States, and members of the European Union have initiated large-scale hydrogen projects, with projections showing a rapid increase in global green hydrogen capacity by 2030 (Pingkuo & Junqing, 2024). However, the scalability and sustainability of these initiatives depend largely on advancing water electrolysis technologies, improving efficiency, and lowering production costs.

Among various hydrogen production methods, electrolysis-based systems such as Alkaline water electrolysis (AWE), Polymer Electrolyte Membrane Water Electrolysis (PEMWE), and Anion exchange membrane water electrolyzer (AEMWE) are at the forefront due to their ability to integrate with renewable energy sources. AWE has long been a mature and commercially available technology, but it suffers from lower efficiency and bulkier designs (Zeng & Zhang, 2010). PEMWE offers higher current density operation and compactness, but its dependence on expensive platinum group metal (PGM) catalysts significantly increases the cost (Feng et al., 2017). In contrast, AEMWE combines the benefits of both AWE and PEMWE, employing low-cost, non-PGM catalysts and polymer membranes, while still being at an early stage of development with a TRL of 2–3 (Mulk et al., 2024). These technological pathways represent the cornerstone for achieving affordable and scalable green hydrogen production in the near future.

The global H_2 production (including blue, gray, and green H_2) capacity of the leading countries is shown in Figure 1(a). Currently, China is leading the global H_2 production with a production capacity of around 33 $Mt.yr^{-1}$, followed by the United States, about 11 $Mt.yr^{-1}$ of H_2. Both Russia and Canada have a production capacity of nearly 6 and 4 $Mt.yr^{-1}$. Similarly, Germany, Netherlands, and Poland have a production capacity of around 3, 2, and 1 $Mt.yr^{-1}$, respectively. Spain, Italy, France, the UK, and South Korea have a production capacity of nearly 1 $Mt.yr^{-1}$. Apart from these countries, the Rest of the world has a total H_2 production capacity of around 11 Mt.yr-1(Dincer & Aydin, 2023) . Fig. 1(b) shows the top countries with the highest estimated green H_2 production by 2030. Various H_2 production methods including their advantages and disadvantages, process efficiency, and production cost, are reviewed in Table S1.

Beyond production, the utilization of hydrogen in the transportation sector is vital for reducing emissions from fossil-fuel-dominated systems, which contribute to nearly 17% of global GHG emissions (Yang et al., 2022). Hydrogen fuel cells (HFCs) offer higher efficiency and zero tailpipe emissions, whereas hydrogen internal combustion engines (H_2ICEs) provide a cost-effective transition pathway by utilizing existing engine technologies (Sari et al., 2024). Nevertheless, challenges such as NOx formation, infrastructure limitations, and cost barriers hinder their widespread adoption. Thus, advancing electrolyzer technology, reducing LCOH, and addressing storage and transport issues are essential for establishing hydrogen as a mainstream solution for decarbonization.

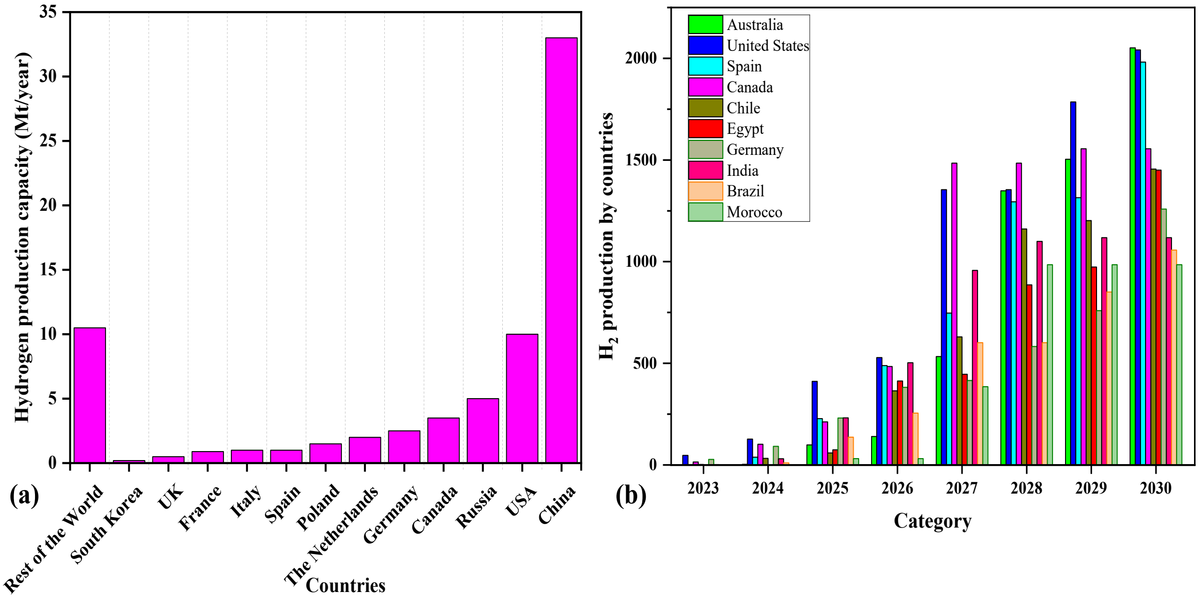


Figure. 1: (a) Hydrogen production capacity of different countries (Dincer & Aydin, 2023) (b) Top ten green H_2 production countries by 2030 (H.Insight).

While significant progress has been made in understanding the techno-economic and environmental aspects of AWE and PEMWE, literature on AEMWE remains scarce. Current studies have primarily focused on laboratory-scale demonstrations, leaving uncertainties regarding durability, scalability, and performance under real-world conditions (Kim et al., 2024) . Furthermore, comparative analyses of LCOH often overlook long-term material degradation, recycling issues, and integration with fluctuating renewable energy sources. These gaps necessitate further life cycle and environmental assessments along with the exploration of H_2 in ICEs to accelerate the commercialization of AEMWE and hydrogen-powered transport systems. Hence, the current review focuses on the hydrogen value chain with the cost comparison of different case studies on AWE, PEMWE, and AEMWE systems. Lastly, the techno-economic analysis, environmental aspects, technology readiness level (TRL), and future suggestions of the AEMWE system have been thoroughly discussed.

2. OVERVIEW OF THE HYDROGEN VALUE CHAIN

The H_2 value chain is broadly divided into four categories including the production of H_2, the storage, transportation, and utilization of H_2 as shown in Fig. 2. The bulk of the H_2 today (about 95%), is produced from fossil fuels without carbon capture and leading to severe global warming issues, and only 5% of the green H_2 is produced through water electrolysis using renewable energy sources (Hosseini & Wahid, 2016). Currently, the ongoing experiments in the UK and European countries are on the commercial viability of blending H_2 with CH_4 and distribution through the existing gas networks (Kotek et al., 2023). Most of the H_2 produced today is gray H_2, (the CO_2 emitted during the production of H_2 is not captured) and is used as a feedstock or by-product for other industrial processes such as heating, electricity generation, and fueling various modes of transportation (e.g., buses, trucks, heavy-good vehicles, and maritime shipping and aviation) (Hassan & El-Amary, 2025).

In addition, regional disparities in resource endowments, electricity prices, and infrastructure readiness significantly influence the adoption and cost competitiveness of green H_2 production (e.g. higher electricity costs and scarcity of grid capacity in some regions hinder green H_2 deployment) (Hassan & El-Amary, 2025). Countries endowed with abundant, low-cost renewables are better placed to produce green H_2 economically, while others remain reliant on fossil-based pathways. Moreover, international cooperation and standardization are increasingly critical: the development of global H_2 trade corridors, harmonized safety and certification protocols, and common contract structures (e.g. GHG intensity standards, trading rules) are viewed as essential to unlock scale, reduce transaction costs, and build investor confidence in cross-border H_2 markets (Marouani et al., 2023). To that end, organizations such as ISO have already published a technical specification (ISO/TS 19870) for assessing the emissions of the H_2 supply chain, and regional alliances (e.g. the European Clean Hydrogen Alliance) are pushing for harmonised hydrogen standards to support large-scale deployment (Gallegos, 2024). These coordinated efforts are expected to accelerate the expansion of H_2 infrastructure and promote its adoption across diverse sectors.

Nevertheless, the effectiveness of the H_2 value chain is hindered by the energy-intensive process of production and storage, as well as the substantial expenses and infrastructural difficulties involved in scaling up. Moreover, though H_2 holds promise in substantially reducing emissions, particularly when generated from sustainable sources, its economic feasibility and safety issues regarding storage and transportation require additional technological progress along with robust regulatory frameworks to fully exploit its potential in the energy transition.

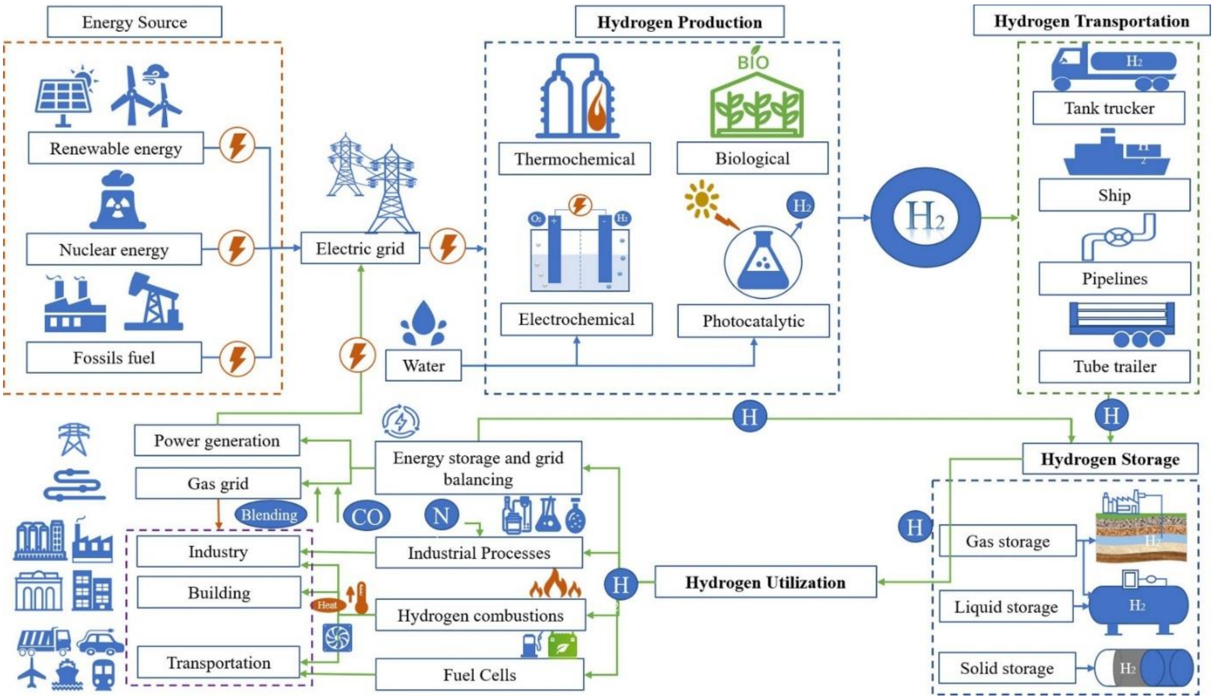


Figure. 2: Hydrogen value chain. Adapted with permission from Ref. (Zhang et al., 2024) Copyright 2023, Elsevier.

2. TECHNO-ECONOMIC, ENVIRONMENTAL ASESSMENT, AND TECHNOLOGY READINESS LEVEL (TRL) OF GREEN H_2 DEVELOPMENT TECHNOLOGIES

The cost of green H_2 is determined by numerous aspects, including production technology (e.g., AWE, PEM, Solid oxide electrolysis cells (SOEC), AEM, and photocatalysis), location (access to green electricity), and the lifetime of the available facility. The assembly and operation of electrolyzers have high production costs and energy requirements (Xiang et al., 2021). Green H_2 now costs between 2.28–7.39 \$.kg–1 H_2 produced. To reduce the high cost of the electrolysis process, optimal materials for producing electrolytic cells must be identified, as well as a large-scale electrolysis supply chain must be established (Yu et al., 2021). The other factor affecting the overall cost of green H_2 production is the cost of the renewable electricity needed for the electrolysis process. Green H_2 will become a viable and economical option by minimizing the cost of electricity and enhancing the efficiency of current electricity production technologies (Ayodele & Munda, 2019). The production of green H_2 using wind power is still a costly alternative since the infrastructure of wind energy technologies has significant capital costs. The weather conditions, namely the wind direction, air pressure, temperature, and speed, affect the wind power which ultimately increases the H_2 production cost (Babarit et al., 2018). Although solar energy is the most abundant and long-lasting energy source, its intermittent nature is a challenging issue. The lifetime and recycling of solar cells and requirements of additional components in photovoltaic (PV) further increase the cost of the H_2 production (Ahmed et al., 2022). This section will discuss the cost analysis of different green H_2 production technologies such as AWE, PEMWE, and AEMWE in detail.

Shin et al. (2023) analyzed the economical evaluation of both AWE and PEMWE using three types of renewable energy sources including offshore wind, onshore wind, and onshore PV energy system located in different areas of South Korea. The results of the electrolysis systems simulation based on the power input and actual renewable energy generation data for a year with a 1-h sample time were used to calculate the accurate efficiency of H_2 production. A wind power generation prediction model developed through machine learning techniques produced the offshore wind power generation data. Using cost data for system components, the levelized cost of H_2 (LCOH) for each case was computed, and sensitivity analysis was used to examine the effect of each price component on LCOH. As shown in Figure3 (a), the LCOH of offshore wind AWE and PEMWE system was 11.85 and 12.60

\$.kg^{-1}, respectively. Similarly, for the onshore wind AWE and PEMWE system, the LCOH was 7.25 and 8.51 \$.kg^{-1}, respectively as shown in Figure 3 (b). The LCOH of PV based AWE and PEMWE system was 11.77 and 13.44 \$.kg^{-1}, respectively as shown in Figure 3 (c). To summarize, the lowest LCOH of 7.25 \$.kg^{-1} was obtained for the onshore wind powered AWE system while the highest LCOH of 13.44 \$.kg^{-1} was obtained for the PV-PEMWE system. Furthermore, it was observed that the capacity factor of RE has a major impact on LCOH, followed by the operating or capital expenditures of the renewable power plant. The operating conditions and H_2 production efficiency of both the electrolysis systems are shown in Table 1.

Table 1. Operating conditions and H_2 production efficiency of AWE and PEMWE systems Shin et al. [32]

Operating condition & optimum performance	**AWE**	**PEMWE**
Pressure (bar)	1.0	30
Temperature (°C)	60	55
Electrolyte (wt%)	KOH (30%)	---
Current density (Acm^{-2})	0.66	1.18
Stack efficiency (%)	75	75
System efficiency (%)	73.3	73.6
H_2 production efficiency (%)		
Offshore wind	77.4	77.17
Onshore wind	78.3	77.7
Onshore PV	81.2	80.54

Hassan, Sameen, et al. (2023) evaluated the cost analysis of a large-scale AWE H_2 production plant using 1.5 and 2.0 MW wind turbine (WT) and solar PV power plant. An experimental dataset of one year was recorded that showed solar irradiance and wind speed with a one-minute precision. The carbon footprint study was carried out to standardize the performance assessment method for RE-based H_2 production systems, like the electrolyzer capacity fulfilled by WT and solar PV power plants. As shown in Fig. 3(d), the annual H_2 production was 8014 kg with an electrolyzer capacity of 0.25 MW for WT power plant. The rate of H_2 production was increased with the increase in electrolyzer capacity. The maximum H_2 production using WT power plant was 11963 kg. yr^{-1} with the electrolyzer capacity of 1.50 MW. Similarly, for solar PV power plants, the minimum H_2 production rate was 23955 kg. yr^{-1} with the electrolyzer capacity of 0.25 MW. Similar to WT power plant, the H_2 production rate was increasing by increasing the electrolyzer capacity using solar PV power plant. The maximum H_2 production was 94432 kg. yr^{-1} having electrolyzer capacity of 2.0 MW. As shown in Fig. 3(e, f), by using WT power plant the cost of green H2 produced from electrolysis was about 8.87 \$.kg^{-1} and by using solar PV power plant, the cost of green H_2 production was about 6.33 \$.kg^{-1}.

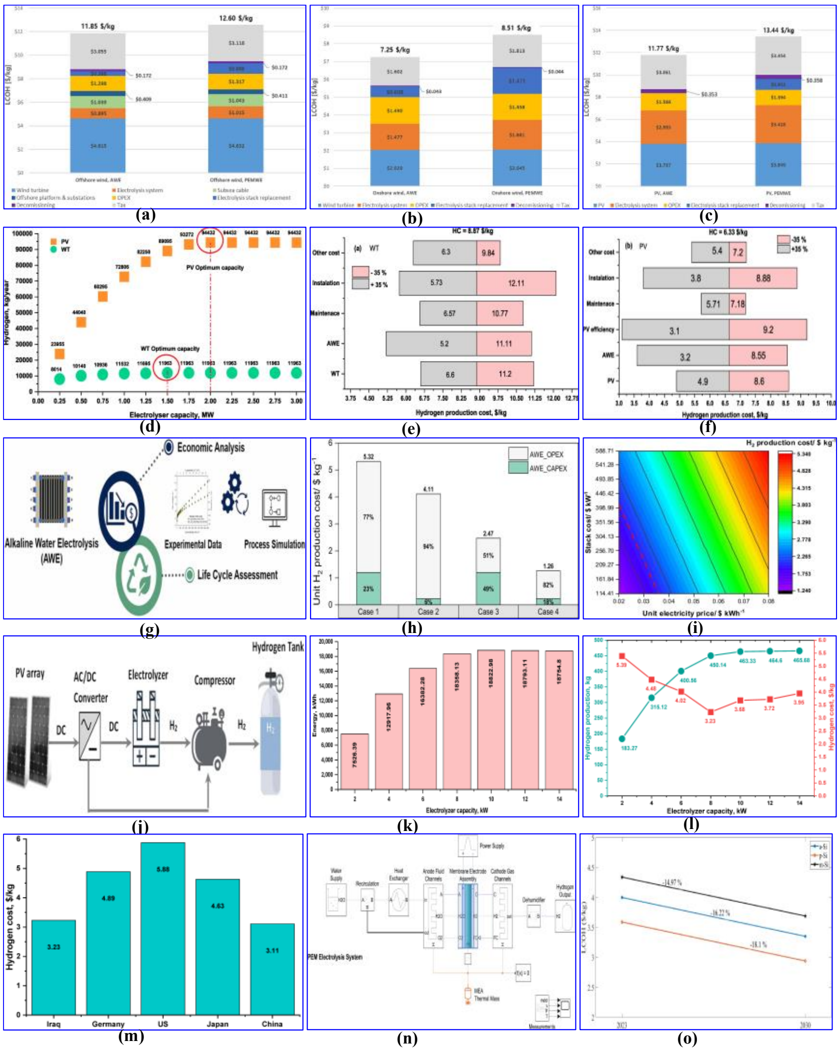
Lee et al. (2021) conducted the techno-economic and environmental evaluation of green H2 production using AWE with the experimental data from the advanced AWE system of the Korea Institute of Energy Research (KIER) to evaluate the potential of technology. The schematic diagram of AWE used in their study is shown in Figure 3 (g). They have categorized their study based on the four different Cases from (Case 1-4). Case 1 covered the highest stack of 588.7 \$. kW^{-1} and 0.08 \$. kWh^{-1} unit cost of electricity whereas case 2 considers the lowest stack cost of 114.4 \$.kW^{-}with highest electricity cost. Similarly, Case 3 considers the highest stack and minimal electricity cost of 0.02 \$. kWh^{-1}, While Case 4 consists of both minimal stack and unit electricity cost. The resulting hydrogen production from cases 1 to 4 were 5.3, 4.1, 2.47, and 1.2 \$.kg^{-1}, respectively, indicating the lowest H_2 production cost of 76.3% for Case 4 compared to Case 1. The H_2 production cost of Case 3 was 53.6% lower than Case 1. For Case 2, the H_2 production cost was 22.7% lower than Case 1, as shown in Figure 3(h). Moreover, from Figure 3(h), it can be observed that the electricity price is the main economic restriction which affects the unit H_2 production cost, with the stack cost being the next most influential. Furthermore, as seen in Figure 3 (i), a scenario analysis was carried out to determine the impact on the unit H_2 production cost of the range in unit electricity and stack costs affect the hydrogen production cost per unit in their study. The necessary unit electricity price and stack cost are below than 0.035 and 406 \$.kW^{-1}, respectively, when compared to the unit H_2 production cost of less than 2 \$.kg^{-1} by the conventional H_2 production method such as steam methane reforming (SMR) as shown by the red dashed line in Figure 3 (i). The specifications of the AWE stacks from the KIER are shown in Table 2. Thus, the technological advancements of AWE resulting in the reduced stack and unit electricity cost could accelerate the development of a green H_2 society. Additionally, CO_2 emissions for the years 2021, 2030, 2050, and renewable Korean electricity mix scenarios were found to be 30.7, 17.4, 7.04, and 3.12 kgCO$_2$-eq kgH$_2$$^{-1}$, respectively. These results showed that both the 2050 Korean electricity mix scenario and the renewable scenario have a smaller carbon footprint than the traditional H_2 production technology (11.5 kgCO$_2$-eq kgH$_2$$^{-1}$).

Table 2: Specifications of the AWE stacks from KIER (Lee et al., 2021)

Parameter	Value	Unit
Gross system power	1.27	MW
H_2 production rate	519	kgd^{-1}
Stack power	1.03	MW
Pressure	2.9	bar
Temperature	353	K
Active area (single cell)	0.07	m^2
KOH Concentration	30	wt %
Potential	1.8	V
Current density	1.0	Acm^{-2}
Power density	1.8	Wcm^{-2}
Faradaic efficiency	82	%
Cell efficiency	82	%
Cells per stack	200	cells

Hassan, Abdulrahman, et al. (2023) analyzed a PV energy system designed to feed a PEMWE system for H_2 production to examine the optimum size of the electrolyzer. Experimental meteorological data was used to analyze the electrolysis system installed in Baghdad, the capital city of Iraq. The proposed PEMWE system for H_2 production using PV solar energy is shown in Figure 3 (j). The 12 kWp PV array was installed at the site with the optimum yearly tilt angle. Several electrolyzes ranging in capacity from 2 to 14 kW were examined to evaluate the efficiency of the system. The simulation was carried out using MATLABTM by considering the duration of the project from 2021 to 2035. The annual energy provided by the installed PV system at 4313 operating hours was 18,892 kWh, and the obtained H_2 production cost ranges from 5.39 to 3.23 $\$.kg^{-1}$. As shown in Fig. 3(k), the minimum energy consumption of 7526.39 kWh was obtained for the 10 kW electrolyzer capacity. The energy consumption gradually increased by increasing the electrolyzer capacity to 10 kW and then gradually decreased by further increasing the electrolyzer capacity. The energy consumption at the electrolyzer capacity of 4, 6, 8, and 10 kW was found 12917.96, 16382.28, 18358.13, and 18822.98 kWh, respectively. Furthermore, the energy consumption at 12 and 14 kW was obtained 18793.11 and 18754.8 kWh, respectively. The drop in energy consumption at high electrolyzer capacity was due to the drop in system efficiency, as the capacity of the electrolyzer did not match the capacity of the PV array. As shown in Figure 3(l), the rate of H_2 production increased with an increase in electrolyzer capacity; however, the corresponding H_2 cost decreased. The maximum and minimum H_2 production cost of 5.39 and 3.23 $\$.kg^{-1}$ was obtained for the electrolyzer capacity of 2 and 8 kW, respectively. The H_2 production cost of the PV solar based PEMWE system was compared with different electrolysis technologies located in Germany, US, Japan, and China as shown in Figure 3(m). The cost of the green H_2 production obtained in their study was cheaper than that of the mentioned electrolysis technologies (Okonkwo et al., 2021).

Achour et al. (2023) investigated the production and cost of H_2 production through PEMWE powered by three different PV technologies including monocrystalline (m-Si), polycrystalline (p-Si) and amorphous (a-Si) located in Morocco. The proposed block model of PEM fuel cell system is shown in Figure 3 (n). Therefore, a performance evaluation of the aforementioned PV solar systems was carried out using data gathered during 6 yr operation to determine the suitable PV system for H_2 production in the climate conditions of the mountains. Additionally, the degradation rate of each technology and its effect on H_2 production and cost have been investigated. According to the results obtained, the lowest degradation rate of 0.28% was found for p-Si, followed by m-Si and a-Si (0.41 and 0.75%). Important metrics such as the levelized cost of energy (LCOE) and the levelized cost of hydrogen (LCOH) have also been identified. According to the obtained results, p-Si technology has the lowest LCOE and LCOH (0.021 and 3.59 $\$.kg^{-1}$, respectively), followed by a-Si technology (0.027, 4 $\$.kg^{-1}$, respectively), and m-Si (0.032, 4.34 $\$.kg^{-1}$, respectively), as shown in Table S2. Consequently, the findings showed that p-Si is the most cost-effective and advantageous technology for H_2 production in the observed moderate environment. Figure 3 (o) shows a comparison of the actual and expected LCOH of PEMWE powered by PV solar system. Green H_2 will become an economically feasible option when the cost of renewable power and electrolyzer units decreases. The forecasted CAPEX of PEMWE (excluding installation) is expected to reduce to 380 $ by 2030 (Yates et al., 2020).



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

(j) (k) (l)

(m) (n) (o)

Figure. 3. LCOH cost components in (a) offshore wind (b) onshore wind and (c) onshore PV water electrolysis system. Adapted with permission from (Shin et al., 2023) Copyright 2023, Elsevier. (d) Annual H_2 production using AWE system at the specific capacities of wind and solar power plant. Sensitivity analysis of H_2 production cost using (e) wind turbine and (f) solar PV power plant. Adapted with permission from Ref. (Hassan, Sameen, et al., 2023) Copyright 2023, Elsevier. (g) Schematic representation of green H_2 production using AWE system. (h) Percent distribution of H_2 production cost for Cases 01–04. (i) Scenario analysis of H_2 production cost based on unit electricity and stack cost. Adapted with permission from Ref.(Lee et al., 2021) Copyright 2021, Elsevier. (j) Schematic representation of the proposed PEMWE system using solar energy. (k) Annual energy consumption of the electrolyzer at various capacities. (l) Annual H_2 production by the electrolyzer and H_2 costs at different capacities. (m) Comparison of the H_2 production cost of the current study with other countries. Adapted with permission from Ref.(Hassan, Abdulrahman, et al., 2023) (n) Schematic representation of the proposed PEMWE system. (o) Prediction of LCOH for 2030 using PEMWE system. Adapted with permission from Ref. (Achour et al., 2023) Copyright 2023, Elsevier.

3. Conclusion and recommendation

Hydrogen holds immense potential as a clean and sustainable energy vector, capable of enabling deep decarbonization across industries and transportation. Electrolysis technologies remain central to this transition, with AWE and PEMWE offering proven pathways, while AEMWE presents a promising low-cost alternative still in its developmental stage. Despite the advantages, widespread deployment is hindered by high LCOH and infrastructure challenges. In the automotive sector, both fuel cells and H_2ICEs show promise, though efficiency, emissions control, and economic competitiveness must be addressed. Future research should focus on material innovation, scale-up strategies, and integration with renewable energy systems to achieve cost targets below \$2/kg H_2, as recommended by the U.S. DOE. By bridging these gaps, hydrogen can evolve from a niche energy carrier to a mainstream enabler of global net-zero goals.

4. Appendix

Appendix A contains supplementary materials related to the study.

5. ACKNOWLEDGEMENT

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