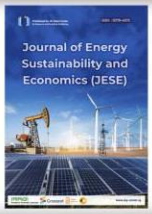
Al-Sibd Center
for Research and Scholarly Publishing

Journal of Energy Sustainability and Economics (JESE)

Journal Homepage : https://jese.srp-center.iq/



Green Hydrogen: Production Technologies, Challenges, and Role in Sustainable Energy Systems

F.A.Jassim [1], Salam K Hasoon[2], Ali.Kadhim[3],Hawra.M.Obaid

[1,2,3]: Department of Oil and Gas Engineering, College of Engineering, University of Warith Al-Anbiyaa, Karbala, 56001, Iraq.

Corresponding Author : ***fatima.ahmed@uowa.edu.iq***

Keywords:

Energy; sustainable; green hydrogen; water electrolysis; PEM and solid oxide;

Abstract

The increasing environmental impact of fossil fuel consumption has accelerated interest in sustainable energy carriers, with green hydrogen emerging as a key option for decarbonization. This review critically evaluates the current status of green hydrogen production technologies, including alkaline water electrolysis (AEL), proton exchange membrane electrolysis (PEMEL), anion exchange membrane electrolysis (AEMEL), and solid oxide electrolysis cells (SOECs). Reported system efficiencies range from approximately 60–70% for conventional alkaline systems to over 80% for advanced SOEC technologies under optimized conditions. Recent advances in electrocatalysts, membrane materials, and renewable energy integration have improved system performance; however, challenges related to capital cost, durability, scalability, hydrogen storage, and transportation remain significant barriers to large-scale deployment. The review further highlights emerging research directions, including hybrid electrolysis systems, artificial intelligence-assisted optimization, and advanced catalyst development. Overall, green hydrogen demonstrates strong potential to support deep decarbonization and long-term energy storage, although continued technological innovation and cost reduction are required for widespread commercialization

Introduction

The increased dependence on fossil fuels poses a significant challenge to future energy security due to resource depletion, price volatility, and severe environmental impacts (Figure 1). Simultaneously, the continuous rise in global energy demand and greenhouse gas (GHG) emissions has intensified the urgency to transition toward a net-zero carbon future [1]. Global climate commitments require substantial reductions in GHG emissions by 2030 and achieving net-zero targets between 2050 and 2070 [2]. As the energy sector accounts for approximately two-thirds of global GHG emissions, it plays a central role in this transition.

In response, many countries are actively restructuring their energy systems by promoting renewable energy sources in alignment with the Paris Agreement and the United Nations Sustainable Development Goals [3]. Within this context, green hydrogen has emerged as a key component of the global energy transition. Hydrogen can function as an energy carrier and a long-duration energy storage medium, enabling the integration of intermittent renewable energy sources into future energy systems (Figure 2). In addition, hydrogen offers a pathway for decarbonizing hard-to-abate sectors such as heavy industry, chemicals, steel production, and long-distance transportation, while also supporting energy security, economic development, and job creation (Figure 3).

Hydrogen is not a new energy carrier; however, its strategic importance in sustainable energy systems has significantly increased in recent years. Currently, global hydrogen production exceeds 120 million tonnes annually, accounting for approximately 4% of total global energy consumption. However, nearly 95% of this hydrogen is still produced from fossil fuel-based processes. Future projections suggest that hydrogen could contribute between 6–18% of global energy consumption by 2050, with renewable-based hydrogen potentially reaching 80 EJ annually. Moreover, up to 16% of global electricity generation may be required for hydrogen production by mid-century [4]. The declining cost of renewable energy further enhances the feasibility of green hydrogen production and its integration into power systems. Nevertheless, large-scale deployment remains dependent on technological advancements, cost reduction, supportive policies, and infrastructure development.

Despite its potential, green hydrogen production presents environmental considerations, particularly related to electricity demand and water consumption. These challenges highlight the importance of developing region-specific and resource-efficient production pathways. Furthermore, the transition toward hydrogen-based energy systems requires a holistic, system-oriented approach. Energy systems are complex, dynamic, and highly interdependent, and therefore traditional reductionist approaches are insufficient. Instead, integrated frameworks incorporating systems thinking, complexity science, and sustainability principles are essential to effectively address future energy challenges.Despite the growing number of review studies on hydrogen technologies, most existing literature focuses either on individual production methods, limited technical aspects, or broad hydrogen economy perspectives. A comprehensive and up-to-date comparative assessment of the four major green hydrogen production pathways—alkaline water electrolysis (AEL), proton exchange membrane electrolysis (PEMEL), anion exchange membrane electrolysis (AEMEL), and solid oxide electrolysis cells (SOECs)—in light of the most recent technological and scientific developments remains limited.

Accordingly, the novelty of this work lies in providing a systematic and critical review of the recent literature to identify the key technical and scientific limitations associated with these four green hydrogen production routes. This includes a focused analysis of efficiency, durability, scalability, cost constraints, and environmental performance. In addition, the review integrates recent advances in materials development, system design, renewable energy integration, hydrogen storage and distribution, and techno-economic evaluation. By doing so, this study provides a consolidated and updated perspective on current research progress and highlights priority areas for future research and industrial implementation.

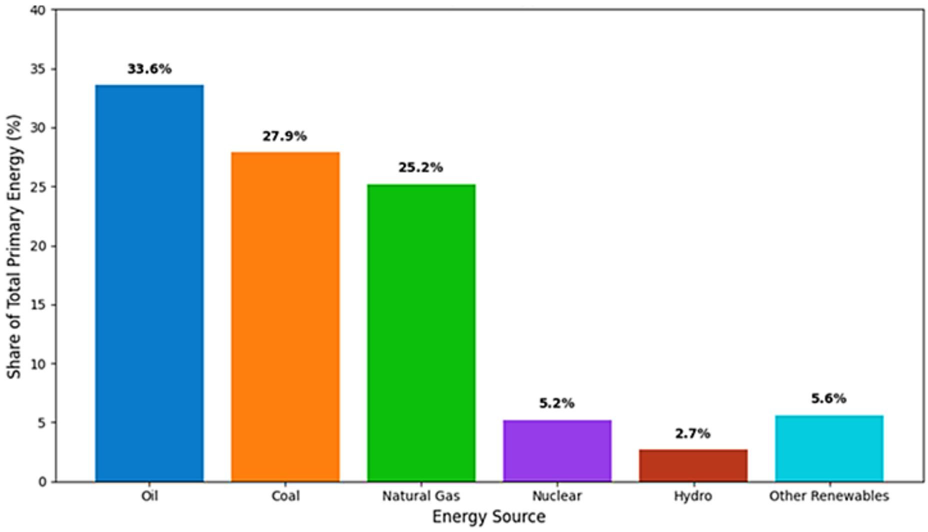


Figure 1 Global energy source shares in the world energy mix [4].

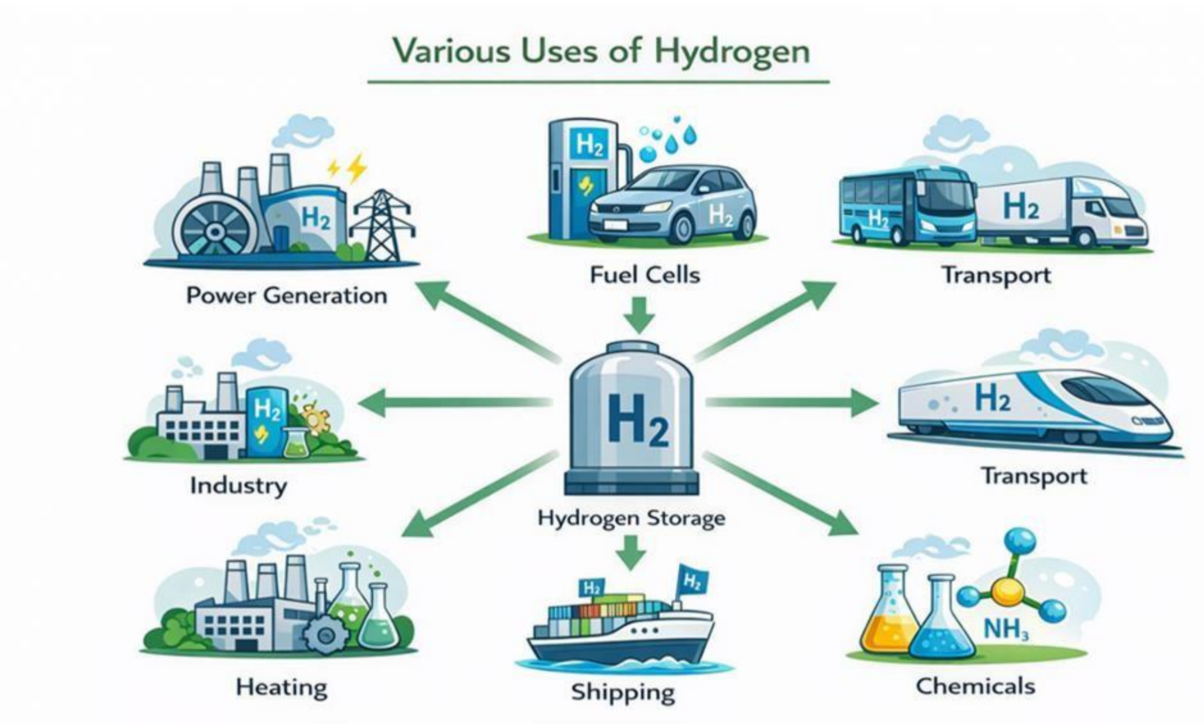


Figure 2 Overview of the diverse applications of hydrogen across energy, industrial, transportation, and residential sectors.

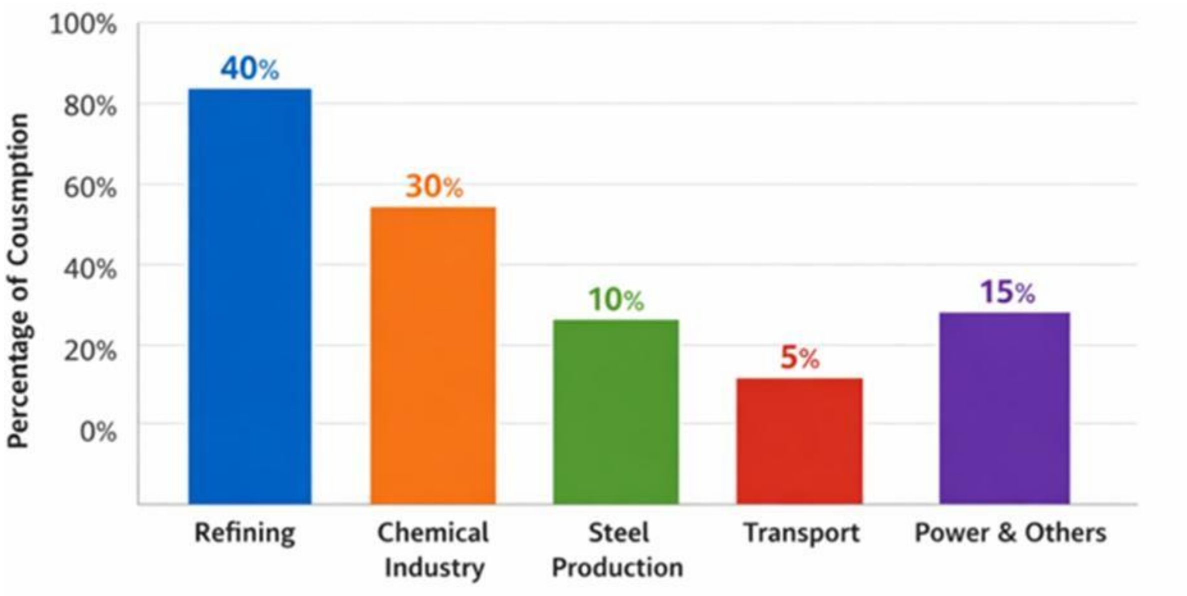


Figure 3 Distribution of Global Hydrogen Consumption by Sector [5].

Hydrogen Properties and Its Role in Future Energy Systems:

Hydrogen is a critical component of the global energy transition and an important pathway toward achieving carbon neutrality. Its growing importance stems from its versatility in a wide range of applications, particularly as a medium for energy storage and system integration of renewable energy sources. As hydrogen technologies continue to advance toward large-scale deployment, global interest has significantly increased, with many governments adopting hydrogen strategies to mitigate climate change and reduce greenhouse gas emissions [8].

Although hydrogen is the most abundant element in the universe, it is rarely found in its elemental form on Earth due to its high chemical reactivity, where it exists mainly in compounds such as water, hydrocarbons, alcohols, and biomass. Consequently, energy input is required to extract hydrogen, which defines its role as an energy carrier rather than a primary energy source [9].

From a physical and safety perspective, hydrogen is a colorless, odorless, and highly flammable gas. Its low ignition energy and wide flammability range raise important safety concerns, particularly in confined environments where leakage may lead to ignition or explosion risks. In addition, its small molecular size enables permeation through many metals, potentially leading to material degradation and hydrogen embrittlement in storage and transport systems [10].

In terms of energy characteristics, hydrogen possesses a high gravimetric energy density, with a higher heating value (HHV) of approximately 141.8 MJ/kg and a lower heating value (LHV) of around 120 MJ/kg at 298 K, significantly higher than conventional fuels such as gasoline (44 MJ/kg). However, its low volumetric energy density presents major challenges for storage and transportation, requiring much larger volumes compared to hydrocarbon fuels. For example, liquid hydrogen offers a gravimetric energy density about 2.4 times higher than liquefied natural gas, but requires approximately 2.8 times more storage volume [11]. Moreover, liquid hydrogen must be stored at extremely low temperatures (−253 °C at atmospheric pressure), which introduces additional technical and safety challenges, including boil-off losses and risks associated with cryogenic exposure [12][13].

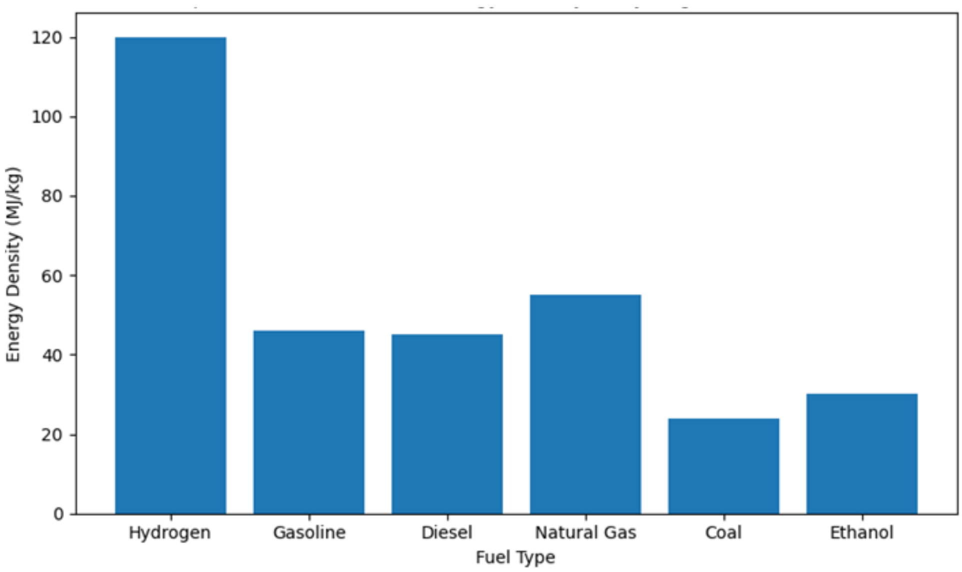


Figure 4 comparison of gravimetric energy density of hydrogen and other fuels [7].

Hydrogen production methods:

The literature has documented more than 100 hydrogen production methods, both present and under development. Approximately 70% of these technologies are based on steam methane reforming (SMR) of natural gas, and over 80% of them depend on the steam conversion of fossil fuels. These techniques have significant carbon dioxide emissions even if they are economically feasible and highly advanced in technology. Therefore, innovative low-carbon and carbon-free technologies such methane pyrolysis and seawater or water electrolysis that utilise renewable energy must be further researched and put into practice in order to minimise the carbon footprint of the production of hydrogen [14]. Around 55 million tonnes of hydrogen are produced annually globally, increasing at a rate of around 6% annually. A variety of feedstock's, such as natural gas, oil, coal, water, biomass, and industrial by-products, can be used to produce hydrogen. Nowadays, natural gas SMR accounts for almost half of the world's produced hydrogen, following with 30% from oil and naphtha reforming in chemical and refinery sectors, 18% from coal gasification, around 3.9% from water electrolysis, and just 0.1% from other sources. Although electrolysis and plasma-based technologies may attain great efficiency, they are often energy-intensive, which limits their large-scale deployment unless powered by renewable energy sources [15]. (table 1).

The four main phases of the hydrogen economy are production, storage, safety, and utilisation, In addition, hydrogen purification and compression must be considered as critical subsystems, and life cycle assessment (LCA) should be done when selecting any hydrogen production method. rather than focussing only on the location of production, this ensures that every aspect environmental effect of hydrogen is appropriately assessed [16].

Hydrogen production can be classified using a color-coded system based on the production pathway and its associated environmental impact [17]. The most commonly used categories include:

Grey hydrogen: Hydrogen is produced via steam methane reforming (SMR) of fossil fuels, primarily natural gas, without carbon capture. This process is highly carbon-intensive, emitting approximately 9–10 tonnes of CO_2 per tonne of hydrogen produced.

Blue hydrogen: Similar to grey hydrogen, blue hydrogen is produced from fossil fuels via SMR or autothermal reforming (ATR), but combined with carbon capture and storage (CCS). CCS can capture approximately 85–95% of CO_2 emissions; however, concerns remain regarding long-term storage stability and potential leakage.

Green hydrogen: Hydrogen is produced through water electrolysis powered entirely by renewable energy sources such as solar, wind, or hydropower. This pathway results in near-zero direct CO_2 emissions during production.

Brown hydrogen: Hydrogen is produced from coal gasification, where coal is converted into synthesis gas (syngas), followed by hydrogen separation. This process is highly carbon-intensive and results in significant CO_2 emissions released into the atmosphere.

Black hydrogen: Similar to brown hydrogen, it is also produced via coal gasification using black coal or lignite, with high associated CO_2 emissions and minimal environmental mitigation.

Turquoise hydrogen: Hydrogen is produced via methane pyrolysis, where methane is thermally decomposed into hydrogen and solid carbon (carbon black) at temperatures typically ranging from 600 to 1400 °C.

This pathway has the potential for near-zero CO_2 emissions if the required heat is supplied from low-carbon energy sources, and if solid carbon is stably stored or utilized. This allows for carbon storage in solid form and minimises CO2 emissions during production. To achieve full carbon neutrality, solid carbon must be stable over time, and the high-temperature process must use renewable energy [18]. The standard colour-coding method may be deception since it does not account for emissions throughout the whole life cycle, ignoring the fact pure green hydrogen is often viewed as the cleanest choice. Renewable technology, such as photovoltaic (PV) panels, has a significant impact on the environment during material collection, manufacture, and disposal at the end of its service life (approximately 30 years). Similarly, biomass-based hydrogen production during growth and thermochemical conversion may emit CH_4, CO_2, SO_x, and NO_x. While employing fossil fuels, blue hydrogen may occasionally demonstrate fewer overall emissions a result of effective carbon removal and less adverse environmental impacts. Life cycle assessment studies have shown that not all hydrogen methods produced using renewable resources are environmentally advantageous. For example, Al-Qahtani et al. (2021) reported that producing hydrogen using solar energy electrolysis has significant impact on the environment because of the potential of acidification and low efficiency of the system during PV panel development. This highlights the need to evaluate hydrogen production systems based on overall life cycle emissions rather than just their manufacturing process [19]. Han et al.(2021)To get around the limitations of traditional colour labels, a more advanced classification method based on a hydrogen cleanness index along with depth levels was developed. For instance, "80 green-4" suggests that hydrogen comes from renewable resources but is only 80% clean because of production-related emissions, whilst "4" indicates the existence of emissions from downstream and purification processes. Although promising, this method requires more work to establish suitable thresholds and weighting factors. Until 2020, fossil fuels contributed for more than 95% of the world's production of hydrogen, mainly via SMR, which produced 830 million tonnes of CO2 annually [20]. Water electrolysis and other renewable sources contributed to just 5% of the total production. This demonstrates unequivocally that the generation of hydrogen today is still largely dependent on carbon, underscoring the pressing need to scale up low-carbon and green hydrogen technologies (fig 4). Green hydrogen produced by water electrolysis using renewable energy sources is being seen as a critical option in the larger scheme of global decarbonisation. Wind and solar power are especially ideal because of their widespread availability and low cost. Furthermore, by combining electrolysis and energy from renewable sources, excess electricity could potentially be chemical stored as hydrogen, thereby contributing to the inconsistent nature of renewable power generation. In addition to functioning as an energy carrier, manufactured hydrogen may be utilised in industry, transportation, and power generation, cementing its place as a critical component of a low-carbon, sustainable energy system [21].

Table 1 Summary comparison between hydrogen production methods

Technology	Operating Conditions Temperature °C Pressure bar	Technical Features	Feed stock
Steam Reforming	700–850; Pressure: 3–25	Produces high-purity H_2; Catalyst prone to deactivation	CH_4
Gasification	800–900	High efficiency; Issues with catalyst and corrosion	Coal
Partial Oxidation	1150–1500	Produces high-purity H_2.	various hydrocarbon
PEM Electrolysis	50–80 ; Pressure: 15–30	Simple setup; High current density	H_2O
Alkaline Electrolysis	60–90 ; Pressure: 2–10	Low capital cost; No catalysts needed; Corrosive medium	H_2O
Solid Oxide Electrolysis	500–1000	High efficiency; Large system size	H_2O

Green Hydrogen as a Strategic Energy Carrier for Renewable Integration and Sustainable Development:

Green hydrogen plays a pivotal role in the transition to renewable energy and reducing reliance on traditional energy sources, and is gaining increasing recognition as a pathway to sustainable development and reliable energy systems. Green hydrogen is produced through the of excess renewable energy produced during times of high production and low demand into hydrogen, which can then be stored and used directly when demand outpaces supply (fig. 5). Global demand for green hydrogen will rise dramatically as nations investigate feasible ways for decreasing emissions in challenging sectors that need large amounts of energy, such as heavy manufacturing, chemical manufacture, transportation over long distances, and power generation. Green hydrogen's flexibility allows it to be used directly as a fuel or for combustion, processed into synthetic fuels In .response to this growing need, large-scale hydrogen production facilities are being developed worldwide, integrating sustainable energy sources with innovative electrolysis technologies [23]. In response to this growing need, large-scale hydrogen production facilities are being built around the world, combining renewable energy sources with innovative electrolysis technologies. These initiatives aim not only to demonstrate technical feasibility and reduce manufacturing expenses, but also to build the infrastructure necessary for hydrogen storage, transportation, and distribution, facilitating widespread use of hydrogen as a global energy source and managing energy supply and demand. Simultaneously, continuing developments in electrolysis performance, along with a constant drop in renewable energy costs, make green hydrogen more economically appealing. Integrating green hydrogen into present power and industrial systems could improve grid stability and energy distribution, improve energy security, and reduce dependence on import fossil fuels and other sources of high emissions and negative environmental impacts. The ability to provide seasonal and long-term energy storage is especially useful for power systems that rely significantly on changing renewable energy sources, enabling them to store excess energy during peak demand periods and use it when renewables are scarce[24]. As production grows and enabling rules and regulations are implemented, green hydrogen is expected to go beyond speciality applications to become the mainstream energy solution. Photoelectrochemical water splitting and plasma-assisted methods have demonstrated unique advantages in terms of sustainability and integration with renewable energy sources.

Water electrolysis to produce sustainable hydrogen:

Water electrolysis is a fundamental process for splitting water into its primary elements, hydrogen and oxygen, which produces hydrogen by using electric current. In theory, the electrolytic cell requires a thermal potential of 1.23 V -150v at to divide the two elements [22]. However, for practical applications, a higher potential of roughly required to break through the kinetic and ohmic resistance barriers within the electrolyser components. The primary reaction for water splitting is:

$$H_2O \rightarrow H_2 + 1/2\ O_2 \qquad (1)$$

This reaction divided into two half-reactions at the electrodes:

At the anode (oxygen evolution reaction, OER):

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \qquad (2)$$

$$4OH^- \rightarrow O_2 + 2H_2O + 4e^- \qquad (3)$$

At the cathode (hydrogen evolution reaction, HER):

$$4H^+ + 4e^- \rightarrow 2H_2 \qquad (4)$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \qquad (5)$$

Although this technology has been known for over two centuries, hydrogen produced using water electrolysis accounts for only 4% of total global hydrogen production. This percentage is low considering the technology's long history, primarily due to economic constraints. Additional challenges include the energy requirements of electrolysis, making the cost of the process variable depending on the cost of the electricity source and the high cost of the materials used in the cells [15].

Over time, several generations of water electrolysis technologies have been developed, which are generally classified into four main types based on the electrolyte solutions used in the cells, current density, and operating conditions (Table 2). Alkaline water electrolysis (AWE), anion exchange membrane electrolysis (AEM), proton exchange membrane electrolysis (PEM), and solid oxide electrolysis (SOEC) cells [25].

Alkaline water electrolysis (AWE) is one of the oldest and most mature electrolysis techniques. It is performed at relatively low temperatures, between 30 and 80°C, and the cell is constructed using concentrated alkaline electrolytes and nickel electrodes. While it boasts a long service life, it is limited by moderate current densities, corrosive electrolytes, and relatively low hydrogen purity.

To address these constraints, anion exchange membrane electrolysis (AEM) has emerged as a potential solution. AEM combines the advantages of alkaline and proton exchange membrane (PEM) systems by employing low-cost transition metal catalysts and less concentrated electrolytes, lowering overall process costs. However, this approach continues to have issues with stability of membranes and scale-up performance, preventing its applications. Solid oxide electrolysis (SOEC) cell technology, which operates at high temperatures (500–850°C) using steam, offers the advantage of integration with industrial processes. It utilizes heat to reduce electrical energy consumption, significantly improving reaction kinetics and overall efficiency, and eliminates the need for precious metals [26].

However, the long-term durability of cells and electrodes, in particular, and thermal stability remain key challenges for the widespread adoption of solid oxide electrolysis cells. Life cycle assessment research emphasise the sustainability benefits of green hydrogen. Wind-powered electrolysis produces the least CO_2-eq/kg H_2, while standard grid electricity releases around 30 kg CO_2-eq/kg H_2. Integration with photovoltaic systems enables for the direct conversion of solar energy into hydrogen, leading to total efficiencies of roughly 16%, however high prices and exergy inefficiencies now hinder broad use. Alternative solar-driven hydrogen production pathways, such as concentrated solar thermal thermolysis and thermochemical cycles, provide higher efficiency and lower costs by directly utilising high-temperature solar

heat for endothermic hydrogen generation, thereby improving the prospects for long-term large-scale green hydrogen production[27].

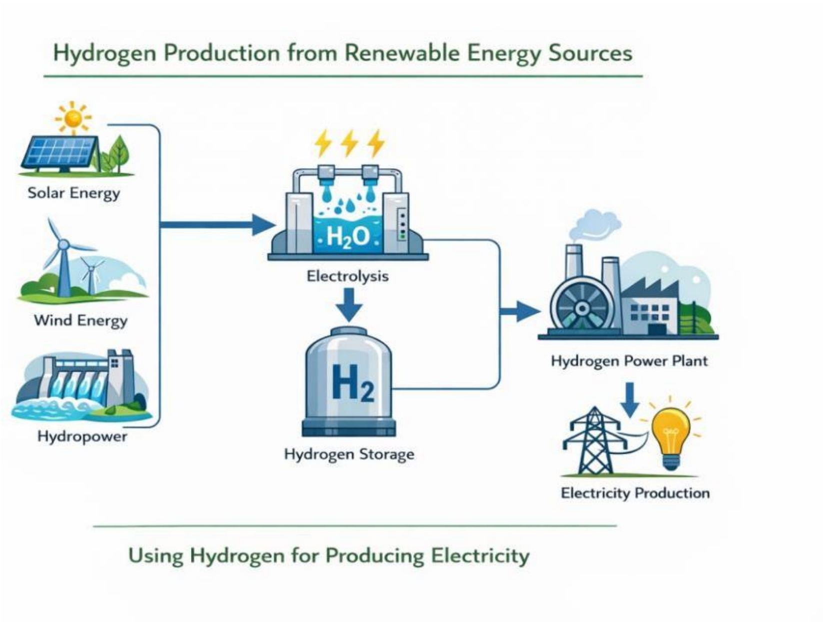


Figure 5 Cycle of hydrogen production from renewable energy and its utilization for electricity generation.

Table 2 Comparison between water electrolysis methods

Characteristic	Alkaline	AEM	PEM	Solid Oxide
Operating Temperature °C	70–90	40–60	50–80	700–850
Electrolyte	KOH/NaOH	DVB polymer + 1M KOH	Solid polymer (PFSA)	YSZ
Catalysts	Ni-based	Ni / NiFeCo alloys	Pt (HER), IrO_2 (OER)	Ni-YSZ, Perovskites
Current Density A/cm²	0.2–0.8	0.2–2	1–2	0.3–1
Voltage Range V	1.4–3	1.4–2.0	1.4–2.5	1.0–1.5
Efficiency %	50–78	57–59	50–83	≈89 (lab)
Lifetime (stack) h	≈60,000	>30,000	50,000–80,000	≈20,000
Development Status	Mature	R&D	Commercialized	R&D
Capital Cost (≈1 MW) USD/kW	≈270	Unknown	≈400	>2000

Alkaline water electrolysis Principles and Recent Developments:

Alkaline water electrolysis is an established process for producing hydrogen, with multi-megawatt facilities worldwide. Troostwijk and Diemann developed the method in 1789, and by 1939, the first large-scale industrial alkaline electrolyser with a capacity of 10,000 Nm^3 H_2 h^{-1} was in operation. By the early nineteenth century, over 400 industrial alkaline electrolyser units had been built for a number of industrial purposes. AWE is the most commercially demonstrated electrolysis method because to its durability, extended operating life, and cheap investment cost, generally ranging from 500 to 1000 USD kW^{-1}. System lifetimes can reach up to 90,000 hours[28].

Alkaline electrolysis systems typically operate at temperatures between 30 and 80 °C and use saturated alkaline electrolytes such as 5 M potassium hydroxide (KOH) or sodium hydroxide (NaOH). The electrodes are usually made of nickel-plated stainless steel, while the separators are made of asbestos or zirconia (ZrO_2). OH^- ions are transferred from the cathode to the anode via a porous membrane. Water molecules are reduced at the cathode into hydrogen gas and hydroxyl ions, which are then oxidised at the anode to create oxygen and water. This technique is very well adapted to large-scale hydrogen generation [29].

Alkaline electrolysis technology has many challenges, including a high cost. The restricted mobility of hydroxyl ions in the electrolyte leads to a low current density (0.1-0.5 A/cm²), posing a substantial technological difficulty. The use of very corrosive alkaline solutions also causes operational issues. Furthermore, potassium hydroxide rapidly absorbs carbon dioxide from the environment, becoming potassium carbonate (K_2CO_3) [30]. This process gradually reduces how easily ions can move at the electrodes and may clog or damage the tiny pores in the gas diffusion layers and membranes, which in turn lowers the efficiency of hydrogen production. Another issue is that the hydrogen produced is not perfectly pure, because small amounts of hydrogen and oxygen can leak through the membrane and mix. An alkaline electrolyzer is made up of a few key parts: a diaphragm or separator, gas diffusion layers that collect and distribute current, bipolar plates, and end plates. The electrolyte is usually made from materials such as crystalline zirconia or nickel-coated perforated stainless steel, while the gas diffusion layers are most often formed from nickel mesh or nickel foam. Bipolar plates are commonly manufactured from stainless steel or nickel-plated steel, as these materials provide a practical balance between affordability, good electrical conductivity, and resistance to corrosion [31].

Researchers are continuously working to improve the performance of alkaline electrolysis systems, with much of the effort focused on increasing current density and reducing unwanted gas crossover. This includes developing better electrode materials that lower electrical resistance, as well as designing more effective membranes and separators that last longer and operate more efficiently. At the same time, linking alkaline electrolyzers with renewable energy sources such as wind and solar power is increasingly viewed as a realistic and effective way to reduce carbon emissions and lower the overall cost of producing hydrogen. Recent developments in hierarchical membrane architectures, functionally graded porous electrodes, and improved flow-field configurations have significantly improved ion transport, gas separation efficiency, and electrolyte distribution. At the same time, advanced bubble-control techniques—such as surface engineering and the application of external fields—have reduced gas-related transport resistance. Looking ahead, the development of smart interfacial systems that combine responsive materials, integrated sensing technologies, and AI-enabled digital twins offers new opportunities for real-time transport regulation and predictive optimization. This review consolidates recent advancements and identifies future research directions, highlighting the importance of integrated material-to-system design strategies to achieve durable, high-efficiency, and cost-effective hydrogen production. [32][33].

To enhance the performance and reduce its energy input, Recent studies on PV-assisted alkaline electrolysis demonstrate that integrating photovoltaic arrays with AWE systems through DC/DC converters and maximum power point tracking (MPPT) significantly enhances energy efficiency, stabilizes operation under fluctuating solar input, and reduces overall specific energy consumption for hydrogen production [34].

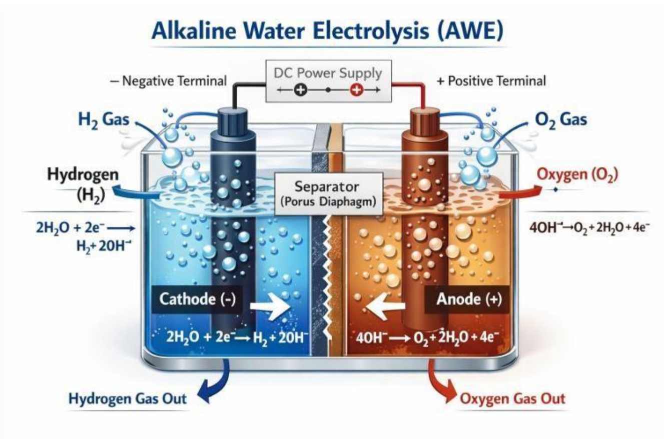


Figure 6 Alkaline Water Electrolysis (AWE) cell.

Anion exchange membrane water electrolysis Principles and Recent Developments:

Anion exchange membrane water electrolysis, or AEMWE, is a relatively new way to produce green hydrogen—and it's quickly becoming one of the most exciting options out there. What makes it attractive is that it combines the reliability of basic alkaline electrolysis with the compact, efficient design of proton exchange membrane (PEM) systems—but without the high cost[35].

While the chemistry is similar to alkaline electrolysis, AEMWE swaps the liquid electrolyte and porous separator for a solid anion exchange membrane. It might sound like a small change, but it makes a huge difference. As a result, the system is simpler and more compact, enabling ions to move more easily and operating under far less alkaline conditions.

One of the biggest advantages of AEMWE is its flexibility. compared to PEM systems, that require cost noble metals, AEMWE can use low transition metals like as nickel, iron, and cobalt. It can additionally rely on pure water or lightly alkaline solutions, as instead of the more concentrated and caustic electrolytes used in typical alkaline systems. This combination of properties lowers costs and reduces corrosion, making AEMWE particularly desirable for future industrial applications [36].

However, achieving the industrial objective of around 100,000 hours will require more work.

Electrons flow through an external circuit to keep the process going. At the anode, the hydroxyl ions react to form oxygen and water, releasing electrons back into the circuit. It's similar to alkaline electrolysis, but the solid membrane gives better control over ion movement and system design.

An AEM electrolyzer has several key components: the anion exchange membrane, catalyst-coated electrodes, gas diffusion layers, bipolar plates, and end plates. Popular commercial membranes include Sustainion®, Fumasep®, and Fumatech. The catalysts are usually low-cost transition metals, which work well for both hydrogen and oxygen production. Gas diffusion layers are often nickel foam, nickel mesh, or carbon cloth. Bipolar plates are usually stainless steel or nickel-coated steel, chosen for their good conductivity and resistance to corrosion [37].

Right now, AEMWE is mostly used in labs and small commercial setups. Two main challenges slow its wider adoption: limited lifetime and relatively high production costs. Back in 2020, producing hydrogen using AEM technology cost around $1,279 per kilowatt. The goal for 2050 is to bring this below $300 per kilowatt, which will require stronger membranes, more stable catalysts, and more efficient systems overall [38].

Encouragingly, continuous and measurable advancements are being achieved in this field. New catalysts and electrode designs are already improving performance. For example, three-dimensional NiFeOOH electrodes on carbon fiber supports show excellent oxygen evolution activity, low energy losses, and strong long-term stability. In some cases, these electrodes even outperform commercial IrO_2 catalysts, operating at lower voltages and higher efficiency. Similarly, Cu–Co–P catalysts on carbon paper deliver strong hydrogen evolution, rivaling noble-metal-based systems[39].

Recent developments in anion exchange membrane water electrolysis (AEMWE) have primarily concentrated on refining membrane electrode assembly (MEA) configurations to deliver commercially relevant efficiency and long-term stability. Significant progress has been achieved at the component level, including the introduction of earth-abundant, nonprecious metal catalysts, the development of AEMs exhibiting enhanced ionic conductivity and improved alkaline durability, and the design of gas diffusion layers (GDLs) with hierarchical pore structures to facilitate efficient mass transport [40].

Performance enhancement is strongly linked to advanced interfacial engineering within the MEA, where optimized integration of catalyst layers (CLs), AEMs, and GDLs minimizes ionic and charge-transfer resistances while reducing the risk of mechanical separation. A notable advancement is the emergence of ordered, defect-free electrode architectures. These designs employ strategies such as ionomer-integrated structures to create continuous ion-transport networks, or in situ catalyst growth directly on AEM surfaces to form vertically aligned triple-phase boundaries. Such structured assemblies significantly improve catalyst utilization, decrease voltage losses at industrially relevant current densities, and enhance durability under differential-pressure operation. Moving forward, translating these ordered configurations into scalable manufacturing processes will be essential to connect laboratory-scale material innovations with large-scale industrial implementation [41]. Research is also exploring completely noble-metal-free catalysts, like $Cu_{0.5}Co_{2.5}O_2$ and materials derived from metal–organic frameworks (MOFs). These can handle high current densities while remaining stable over time. Meanwhile, advances in membrane design are pushing the technology forward. New anion exchange membranes based on poly(fluorenyl-co-aryl piperidinium) show excellent ion conductivity and chemical stability, enabling record-breaking current densities—up to 7.68 A cm^{-2} at 2 V with noble-metal catalysts and over 1.6 A cm^{-2} with noble-metal-free catalysts—while staying stable for more than 1,000 hours

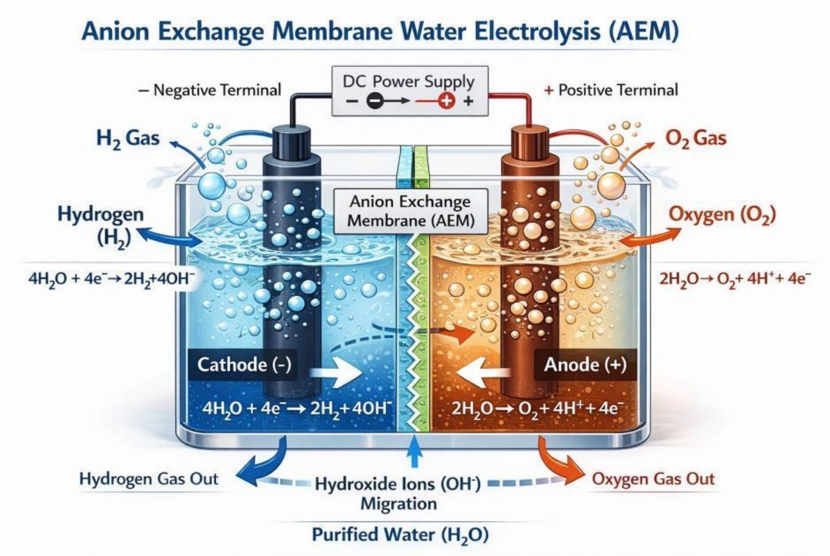


Figure 7 Anion exchange membrane water electrolysis cell

Proton Exchange Membrane Electrolysis, Principles and Recent Developments:

Proton exchange membrane (PEM) water electrolysis was developed to solve some of the problems of traditional alkaline systems. The idea was first suggested by Grubbs and later brought to life by General Electric in 1966.PEM electrolysis is closely related to PEM fuel cells, using a special polymer membrane that lets protons pass through while keeping everything else separate. In practice, deionized water flows through the membrane, protons move across it, and electricity drives the reaction that splits water into hydrogen and oxygen [42].

These electrolyzers operate at relatively low temperatures, around 30 to 80 °C, yet they can reach high current densities of 1 to 2 A cm^{-2} and produce hydrogen and oxygen with incredible purity—up to 99%. Compared with alkaline systems, PEM devices are faster because of the highly active platinum catalysts and the acidic environment, which helps hydrogen form more efficiently. They're also safer and more compact since they avoid harsh alkaline solutions and take up less space.Because of these benefits, PEM electrolysers are being used at megawatt scales for industrial hydrogen generation and transportation. Modern systems can run continuously for around 60,000 hours with minor performance loss, with a long-term goal of roughly 100,000 hours[43].

The most major barrier, however, is cost. PEM electrolysers require expensive noble metals, titanium components, and coated bipolar plates, therefore the initial expenditure is significant. The method separates water into hydrogen and oxygen using two half-reactions. Water molecules are oxidised at the anode, producing oxygen gas, protons, and electrons.. Protons flow through the membrane to the cathode, while oxygen bubbles away. Electrons flow across an external circuit to meet protons at the cathode, resulting in hydrogen gas. This system separates the gases, resulting in ultra-pure hydrogen, which is perfect for applications that need the greatest purity [44].

A PEM electrolyser consists of several important components. The membrane electrode assembly has a proton exchange membrane with catalyst layers on both sides.[30] Common commercial membranes include Nafion®, Fumapem®, Flemion®, and Aciplex®. Nafion® is the most widely used because it combines excellent proton conductivity, chemical stability, mechanical strength, and the ability to handle high current densities. Catalysts are usually noble metals: IrO_2 at the anode for oxygen production and carbon-supported platinum at the cathode for hydrogen. While effective, these materials are expensive—especially iridium, which is rare. For example, a 10 MW PEM electrolyzer operating at 1 A cm^{-2} might need around 15 kg of iridium, costing several million dollarsThe anode is commonly made of porous titanium or titanium mesh because it resists corrosion, whereas the cathode is usually made of carbon fabric. Bipolar plates, often titanium plated with platinum or gold, enhance conductivity and prevent corrosion, but they can amount for over half of the entire cell cost [45].

Even though PEM systems are commercially mature, there’s still room for improvement to bring costs down and make them more sustainable. In 2020, hydrogen production costs with PEM electrolyzers ranged from $700 to $1,400 per kilowatt, with the goal of reducing this to below $200 per kilowatt by 2050To achieve this, it will be necessary to reduce or replace platinum group metals with less expensive alternatives, remove pricey coatings on bipolar plates, create new materials for current collectors, and improve membrane performance.. Making the membrane thinner also helps efficiency: for instance, a Nafion® 117 membrane at 180 µm causes about a 25% efficiency loss at 2 A cm^{-2}, while cutting it to 20 µm reduces losses to roughly 6% [46].

Research is pushing the limits of catalyst design. On the cathode side, new structures such as platinum nanowires on ultrathin titanium supports minimise overpotentials and consume up to 15 times less platinum while maintaining excellent efficiency. Non-noble metal catalysts are also attracting interest. Various materials, including MoS_2-based heterophase structures, titanium-doped molybdenum phosphide, cobalt phosphides, graphene-encapsulated NiMo alloys, and biomass-derived carbon-supported MoS_2, are stable in acidic environments and effectively produce hydrogen. Some of these have previously demonstrated competitive performance in single-cell PEM electrolysers [47].

On the anode side, researchers are focused on reducing iridium use while maintaining strong oxygen evolution activity and long-term stability. Advanced designs like Ir-decorated WO_x nanorods, IrRu-coated WO_3 nanoarrays, IrO_2 on nitrogen-defective carbon nitride, and IrGa core–shell structures deliver high activity with less noble metal and excellent durability. Some systems now reach current densities above 4 A cm^{-2} at relatively low voltages, with iridium loadings below 0.12 mg cm^{-2}—a major step toward cutting costs.

Notwithstanding its advantageous operational characteristics, PEM electrolysis encounters scaling obstacles owing to elevated capital expenditures linked to noble metals and intricate membrane production. Additional examination of cost-reduction strategies, including non-precious metal catalysts and membrane advancements, might enrich the discourse. Empirical deployment data could further elucidate PEM's function in distributed hydrogen systems and its suitability for decentralized energy markets [48]. The major limitation of the production technologies is the trade-off between efficiency and cost. PEM offers superior efficiency but is hindered by high costs and material concerns, while AW is more cost-effective but less efficient. SO offers excellent efficiency but faces scalability and material degradation issues. Emerging research on hybrid systems combining these technologies may mitigate some of these limitations in the future.

One common approach to improving water and thermal behavior in the membrane electrode assembly (MEA) is the inclusion of a microporous layer (MPL) between the catalyst layer and the GDL. Studies have shown that MPLs with high porosity can reduce liquid water saturation and thus mitigate flooding, enhancing PEMFC performance. However, excessively thick MPLs can have adverse effects, as increased thickness may hinder mass transport. In addition, incorporating an MPL has been found to promote a more uniform internal temperature distribution, likely due to an increased effective thermal conductivity across the MEA [49].

Beyond component-level modifications, active control strategies are increasingly recognized as vital for managing the coupled humidity and temperature fields in real time. Although conventional proportional–integral–derivative (PID) controllers remain widely used, advanced control methods such as model predictive control (MPC) and fuzzy logic have shown strong potential. In recent years, extensive research has examined the feasibility and techno-economic viability of advanced thermal management strategies aimed at enhancing PEMFC system efficiency. Thermal management in PEMFCs generally involves two main approaches: implementing effective cooling techniques to maintain the fuel cell within its optimal operating temperature range, and recovering waste heat to enhance overall system performance. Significant progress in both areas has been achieved through collaborative efforts from academic researchers and industrial practitioners.

In recent years, artificial intelligence (AI) has demonstrated significant effectiveness in accelerating the research and development of advanced electrode materials. Machine learning approaches—including artificial neural networks (ANNs), convolutional neural networks (CNNs), deep neural networks (DNNs), generative adversarial networks (GANs), support vector machines (SVMs), and genetic algorithms (GAs)—have been widely employed to predict, design, and optimize porous architectures, compositional tuning, catalyst distributions, and surface properties in Proton Exchange Membrane Fuel Cells [50].

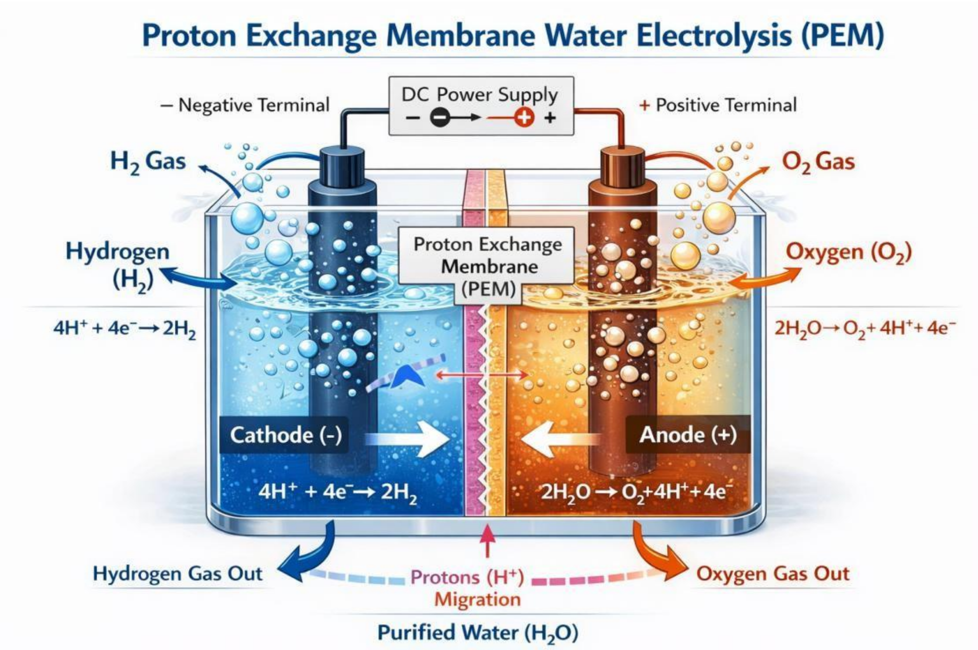


Figure 8 Proton exchange membrane (PEM) water electrolysis cell

High-Temperature Solid Oxide Electrolysis: Principles and Technological Advancements:

Solid oxide electrolysis is a potential way of producing green hydrogen. It combines renewable energy sources with thermal sources in a variety of industries, olid oxide electrolysis cells (SOECs) offer a cut-ting-edge approach to hydrogen production by convert-ing electrical energy into chemical energy through high-temperature electrochemical reactions. Originally developed in the 1970s by General Electric and Brookhaven National Laboratory, with subsequent en-hancements by Dornier in Germany, SOECs operate at elevated temperatures ranging from 500°C to 850°C. This high temperature helps minimise the supply of electrical power used during electrolysis, reducing the total cost and enhancing both thermodynamics and reaction kinetics . However, the high temperature increases electrode degradation. Solid oxide electrolysis (SOEC) cell technology is gradually moving from laboratory research to early stages of commercial application and actual hydrogen production[51].

SOECs avoid the use of precious metal catalysts, relying instead on robust ceramic materials. The electrolyte is typically yttria-stabilized zirconia (YSZ), valued for its thermal and chemical stability as well as high ionic conductivity under SOEC conditions. Nickel-YSZ composites are commonly employed as cathodes, while the anode is often made of perovskite materials like lanthanum strontium cobalt ferrite (LSCF) or lanthanum strontium manganite (LSM), both known for superior electrical and ionic conductivity [52]. In the SOEC process, water vapor is reduced at the cathode to generate hydrogen and oxygen ions (O^{2-}). These ions migrate through the dense YSZ electrolyte to the anode, where they are oxidized to form molecular oxygen and release electrons. While the technology ex-hibits excellent efficiency, its commercial deployment has been hampered by long-term durability challenges. Most SOEC systems currently demonstrate lifespans of around 20,000 hours—well below the target of 100,000 hours necessary for cost-effective operation [45]. Recent research has concentrated on improving SOEC performance through innovative cell designs and new material formulations. For example, cathode alternatives such as $Ni_{1-x}Cd_xO$-SDC composites have demonstrated high catalytic efficiency and thermal stability [53]. New cobalt-free perovskites, like $Ba_{0.97}Nd_{0.03}FeO_{3-\delta}$, offer promising electrical perfor-mance with reduced thermal expansion. Hybrid SOEC architectures—such as those in-corporating $BaZr_{0.1}Ce_{0.7}Y_{0.1}Yb_{0.1}O_{3-\delta}$—enable dual conduction of protons and oxygen ions, leading to higher current densities and improved fuel flexibility. Further enhancements have come from oxygen electrode research, such as Mn-doped $La_{1.5}Sr_{0.5}NiO_{4+\delta}$, which has shown stable operation for over 145 hours with signifi-cant current density gains. Layered perovskites like $Pr_2NiO_{4+\delta}$, modified with cobalt to im-prove structural resilience, have also shown promise in enhancing long-term durability [54]. Studies on materials like $Pr_{0.6}Sr_{0.4}CoO_{3-\delta}$ continue to explore failure mechanisms caused by impurities and phase instability, guiding future materials design and operational strategies . To make SOECs commercially viable, current research is focused on extending operational life, reducing degradation rates, and decreasing system costs. Achieving cost targets below $200/kW by 2050 will require continued innovations in perovskite development, cell configuration, and the integration of renewable energy inputs for sustainable high-efficiency hydrogen production at scale. Researchers in academia and industry are actively working to improve the efficiency and durability of the cell electrodes. One of the most significant advantages of this technology is its very high efficiency; in the long term, electricity consumption for hydrogen production is expected to decrease to around 200 kWh per kilogram of hydrogen or even less. However, achieving this goal requires significant progress in improving the conductivity of the cell electrodes, enhancing their durability, and reducing costs through effective integration with renewable energy sources [56].

Recent research has focused heavily on developing electrode materials and cell design. For hydrogen electrodes, composite materials with improved defect chemistry have demonstrated higher catalytic activity and better stability under high-temperature operating conditions. These electrodes are also capable of operating at relatively low cellular potentials while maintaining stable performance across a wide range of vapor concentrations. Solid oxide In this context, developing efficient fuel catalysts with high electrocatalytic activity and long-term stability is crucial for improving the performance of solid oxide fuel and electrolysis cells in electrochemical energy storage and conversion applications. Oxide-based catalysts have been extensively investigated as alternatives to conventional Ni-based fuel electrodes due to their superior structural stability and strong resistance to carbon deposition (coking), particularly under carbon-containing fuels such as in CO_2 electrolysis [57].

A novel strategy has recently been proposed to enhance oxide electrocatalyst performance through nanoparticle exsolution combined with improved electronic conductivity. In this approach, an A-site deficient perovskite, $Sr_{0.95}Ti_{0.3}(Fe_{0.9}Ru_{0.1})_{0.7}O_{3-\delta}$ (STFR), was coupled with $Sr_2Fe_{1.5}Mo_{0.5}O_{6-\delta}$ (SFM) to form a composite electrode. The STFR phase generated in-situ exsolved Fe–Ru nanoparticles, providing highly active catalytic sites, while the SFM phase enhanced electron transport pathways, thereby significantly boosting overall electrode activity. When applied to an LSGM electrolyte-supported cell, the Fe–Ru exsolved STFR–SFM composite electrode demonstrated outstanding electrochemical performance, surpassing previously reported metrics. It achieved a peak power density exceeding 1.5 W cm^{-2} in fuel cell mode, current densities above 1.75 A cm^{-2} at 1.3 V in steam electrolysis mode, and more than 2.15 A cm^{-2} at 1.3 V in direct CO_2 electrolysis mode at 800 °C [58].

Doping and strain engineering are effective strategies for improving the electrical conductivity of electrode materials in solid oxide electrolysis cells (SOECs). Elemental doping introduces aliovalent cations into the crystal lattice, creating oxygen vacancies and enhancing charge carrier concentration, which increases both ionic and electronic conductivity. For example, substituting transition metals at the A- or B-site of perovskite structures can optimize defect chemistry and improve catalytic activity. Meanwhile, strain engineering—achieved through lattice mismatch, thin-film growth, or compositional gradients—modifies bond lengths and orbital overlap within the crystal structure. This structural distortion can enhance charge mobility and oxygen ion transport by lowering activation energy barriers. Together, controlled doping and strain effects provide a powerful approach to tailoring transport properties, boosting electrode performance, and improving the overall efficiency of SOEC systems [59].

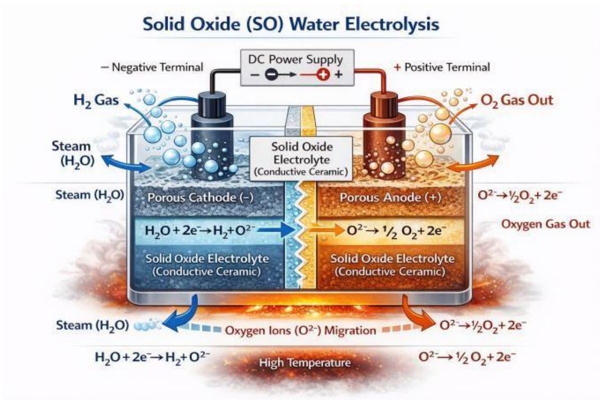


Figure 9 solid oxide water electrolysis cell

Economic Challenges in Green Hydrogen Production:

Hydrogen production faces distinct challenges with electrolysis. In the case of electrolysis, the process re-quires significant amounts of electricity to split water molecules into hydrogen and oxygen.[34] To achieve green hydrogen, this electricity must come from renewa-ble sources like solar or wind, which can be both variable and costly. This reliance on renewable energy, along with the need for advanced electrolyzer technology, makes electrolysis an expensive option. Current costs for pro-ducing green hydrogen via electrolysis are approximately two to three times higher than hydrogen from traditional fossil fuels, limiting its competitiveness in the energy market. Economic assessments of green hydrogen production using water electrolysis consistently demonstrate that energy costs are the most important factor in determining the adjusted cost of hydrogen. Electricity is frequently responsible for more than 60% of overall production costs because it is the principal energy input in the electrolysis process [47]. While conventional energy sources, such as coal and nuclear power, provide electricity at lower adjusted costs, their high greenhouse gas emissions raise serious concerns about their long-term sustainability. In contrast, renewable energy sources are increasingly favored, even with their current high costs, due to their alignment with global carbon emission reduction targets, and are expected to become more competitive as technologies mature and their deployment expands [48].

As a consequence, hydrogen produced by electrolysis using renewable energy sources remains more costly than hydrogen sourced from fossil fuels. Reported adjusted hydrogen prices varied substantially, from US$3.41 to US$16.01/kg for solar-powered systems and from US$5.27 to US$8.01/kg for wind-powered systems, with hybrid renewable energy systems often fall within these ranges. Local factors have a substantial impact on hydrogen production costs, in addition to the energy source used. Variations in sun irradiance and wind availability have a direct influence on power generation and electrolysis working hours, making green hydrogen's profitability extremely reliant on geography [49].

The choice of electrolysis technology also has a significant impact on the overall economic viability of the system. Proton exchange membrane (PEM) electrolyzers coupled with wind power typically achieve hydrogen cost values (LCOH) between US$5 and US$9.37/kg, while alkaline water electrolysis (AWE) systems tend to exhibit slightly higher costs, ranging from US$7.47 to US$7.6/kg [50]. The cost of solid oxide electrolysis (SOEC) cell technologies currently ranges in a similar cost range of approximately US$6–9.2/kg, but they offer strong long-term potential, with projections indicating that costs could fall to around US$2/kg by 2050 [51].

Table 3 Comparison of Hydrogen Production Technologies: Cost, Efficiency, and Scalability

Parameter	Alkaline Electrolysis (AEL)	Proton Exchange Membrane (PEM)	Solid Oxide Electrolysis (SOE)
Production Cost (USD/kg H_2) $	3–6	4–7	2–5
Capital Cost (USD/kW)$	500–1,000	1,200–2,000	2,000–3,500
Operating Cost (USD/kg H_2) $	2–4	3–6	1.5–3
Efficiency (%)	60–80	55–75	70–90
CO_2 Emissions (kg CO_2/kg H_2)	0 (if renewable energy used)	0 (if renewable energy used)	0 (if renewable energy used)
Maturity	Commercially mature	Emerging commercial	Pilot/early-stage commercial

Scalability	High	Medium	Low
Energy Source	Electricity (Renewable/Non)	Electricity (Renewable/Non)	Electricity + Heat
Feedstock Cost Dependence	Electricity cost	Electricity cost	Electricity cost
Application	Industrial, large-scale	Small to medium-scale	Industrial

Conclusion

Hydrogen is increasingly recognized as a strategic energy carrier for achieving deep decarbonization and enabling the transition toward sustainable energy systems. Although hydrogen provides important benefits such as long-duration energy storage and enhanced integration of variable renewable energy sources, the current global hydrogen supply remains dominated by fossil-fuel-based production pathways, significantly limiting its environmental advantages.

Green hydrogen produced via renewable-powered water electrolysis represents the most viable long-term pathway for low-carbon hydrogen production. Among the available technologies, alkaline water electrolysis (AEL) remains the most commercially mature and cost-effective option, while proton exchange membrane electrolysis (PEMEL) offers higher efficiency, rapid response, and superior hydrogen purity, making it suitable for dynamic operation with renewable energy systems. In contrast, anion exchange membrane electrolysis (AEMEL) is still at an early developmental stage but shows promising potential for reducing system cost by enabling the use of non-precious metal catalysts. Solid oxide electrolysis cells (SOECs) demonstrate the highest theoretical efficiency due to high-temperature operation; however, their industrial deployment is still constrained by durability limitations, thermal management challenges, and material degradation.

From an economic perspective, the levelized cost of green hydrogen is primarily governed by electricity prices, which highlights the critical role of scaling up low-cost renewable energy infrastructure. In addition, system integration, operational stability, and lifecycle performance remain key factors influencing overall feasibility.

Future research should prioritize improving catalyst durability, reducing membrane and stack degradation, enhancing system efficiency under variable renewable conditions, and developing hybrid and integrated electrolysis systems. Moreover, advances in large-scale hydrogen storage, transportation infrastructure, and techno-economic optimization are essential to support commercialization.

Acknowledgment

The authors gratefully acknowledge the contributions of colleagues and research staff whose insightful discussions and technical assistance greatly supported the execution of this study. Their collective support was instrumental in advancing the quality and completion of this research.

Declarations:

The authors declare no competing financial or non-financial interests

References.

[1] Younis, O., Hussein, A. K., Attia, M. E. H., Aljibori, H. S. S., Kolsi, L., Togun, H., Ali, B., Abderrahmane, A., Subkrajang, K., & Jirawattanapanit, A. (2022). Comprehensive review on solar stills—latest developments and overview. *Sustainability*, *14*(16), 10136.

[2] Niu, Y., Mohammed Merza, A., Ibraheem Kadhem, S., Tawfeq, J. F., Soon JosephNg, P., & Gheni, H. M. (2023). Evaluation of wind-solar hybrid power generation system based on Monte Carlo method. *International Journal of Electrical and Computer Engineering (IJECE)*, *13*(4), 4401. https://doi.org/10.11591/ijece.v13i4.pp4401-4411

[3] An, Q., Basem, A., Alizadeh, A., Al-Rubaye, A. H., Jasim, D. J., Tang, M., Soheil Salahshour, & Rozbeh Sabetvand. (2024). The effect of initial temperature and oxygen ratio on air-methane catalytic combustion in a helical microchannel using molecular dynamics approach. *Case Studies in Thermal Engineering*, *54*, 104062–104062.

[4] Seck, G. S., Hache, E., Sabathier, J., Guedes, F., Reigstad, G. A., Straus, J., ... & Cabot, C. (2022). Hydrogen and the decarbonization of the energy system in europe in 2050: A detailed model-based analysis. *Renewable and Sustainable Energy Reviews*, *167*, 112779.

[5] Goltsov, V. (2001). From hydrogen economy to hydrogen civilization. International Journal of Hydrogen Energy, 26(9), 909–915.

[6] Tarhan, C., & Çil, M. A. (2021). A study on hydrogen, the clean energy of the future: Hydrogen storage methods. Journal of Energy Storage, 40, 102676.

[7] Dash, S. K., Chakraborty, S., & Elangovan, D. (2023). A brief review of hydrogen production methods and their challenges. Energies, 16(3), 1141.

[8] Anser, M. K., Ali, S., Umair, M., Javid, R., & Tayab, M. (2025). Optimizing hydrogen integration in vehicle fuel systems for sustainable development: a step towards economic decarbonization. International Journal of Hydrogen Energy, 98, 321-333.

[9] Akpasi, S. O., Smarte Anekwe, I. M., Tetteh, E. K., Amune, U. O., Mustapha, S. I., & Kiambi, S. L. (2025). Hydrogen as a clean energy carrier: advancements, challenges, and its role in a sustainable energy future. *Clean Energy*, *9*(1), 52-88.

[10] Hassan, Q., Algburi, S., Sameen, A. Z., Jaszczur, M., & Salman, H. M. (2024). Hydrogen as an energy carrier: properties, storage methods, challenges, and future implications. *Environment Systems and Decisions*, *44*(2), 327-350.

[11] Dash, S. K., Chakraborty, S., Roccotelli, M., & Sahu, U. K. (2022). Hydrogen fuel for future mobility: challenges and future aspects. *Sustainability*, *14*(14), 8285.

[12] Balasubramanian, R., Abishek, A., Gobinath, S., & Jaivignesh, K. (2022). Alternative fuel: hydrogen and its thermodynamic behaviour. Journal of Human, Earth, and Future, 3(2), 195-203.

[13] Farias, C. B. B., Barreiros, R. C. S., da Silva, M. F., Casazza, A. A., Converti, A., & Sarubbo, L. A. (2022). Use of hydrogen as fuel: a trend of the 21st century. *Energies*, *15*(1), 311.

[14] Chau, K., Djire, A., & Khan, F. (2022). Review and analysis of the hydrogen production technologies from a safety perspective. *International Journal of Hydrogen Energy*, *47*(29), 13990-14007.

[15] Zainal, B. S., Ker, P. J., Mohamed, H., Ong, H. C., Fattah, I. M. R., Rahman, S. A., ... & Mahlia, T. I. (2024). Recent advancement and assessment of green hydrogen production technologies. *Renewable and Sustainable Energy Reviews*, *189*, 113941.

[16] Nnabuife, S. G., Darko, C. K., Obiako, P. C., Kuang, B., Sun, X., & Jenkins, K. (2023). A comparative analysis of different hydrogen production methods and their environmental impact. *Clean Technologies*, *5*(4), 1344-1380.

[17] Hermesmann, M., & Müller, T. E. (2022). Green, Turquoise, Blue, or Grey? Environmentally friendly Hydrogen Production in Transforming Energy Systems. Progress in Energy and Combustion Science, 90, 100996.

[18] Jeje, S. O., Marazani, T., Obiko, J. O., & Shongwe, M. B. (2024). Advancing the hydrogen production economy: A comprehensive review of technologies, sustainability, and future prospects. International Journal of Hydrogen Energy, 78, 642-661.

[19] Al-Qahtani, A., Parkinson, B., Hellgardt, K., Shah, N., & Guillen-Gosalbez, G. (2021). Uncovering the true cost of hydrogen production routes using life cycle monetisation. *Applied Energy*, *281*, 115958.

[20] Lee, J., Hong, S., Cho, H., Lyu, B., Kim, M., Kim, J., & Moon, I. (2021). Machine learning-based energy optimization for on-site SMR hydrogen production. *Energy Conversion and Management*, *244*, 114438.

[21] Zhou, Y., Li, R., Lv, Z., Liu, J., Zhou, H., & Xu, C. (2022). Green hydrogen: A promising way to the carbon-free society. Chinese Journal of Chemical Engineering, 43, 2–13.

[22] Acar, C., & Dincer, I. (2019). Review and evaluation of hydrogen production options for better environment. Journal of Cleaner Production, 218, 835–849.

[23] Arsad, A. Z., Hannan, M. A., Al-Shetwi, A. Q., Mansur, M., Muttaqi, K. M., Dong, Z. Y., & Blaabjerg, F. (2022). Hydrogen energy storage integrated hybrid renewable energy systems: A review analysis for future research directions. International Journal of Hydrogen Energy.

[24] Gao, Y., Basem, A., Mohammad Sajadi, S., Jasim, D. J., Nasajpour-Esfahani, N., Salahshour, S., Esmaeili, S., & Baghaei, Sh. (2024). The effect of initial pressure on the thermal behavior of the silica aerogel/PCM/CuO nanostructure inside a cylindrical duct using molecular dynamics simulation. *Case Studies in Thermal Engineering*, *54*, 104064.

[25] M. Balat, Potential important of hydrogen as a future solution to environmental and transportation problems, Int. J. Hydrogen Energy 33 (2008) 4013–4029.

[26] Staffell, I., Scamman, D., Velazquez Abad, A., Balcombe, P., Dodds, P. E., Ekins, P., Shah, N., & Ward, K. R. (2019). The role of hydrogen and fuel cells in the global energy system. Energy & Environmental Science, 12(2), 463–491. https://doi.org/10.1039/c8ee01157e

[27] Ahmad Kamaroddin, M.F., Sabli, N., Tuan Abdullah, T.A., Siajam, S.I., Abdullah, L.C., Ab- dul Jalil, A., Ahmad, A., 2021. Membrane-based electrolysis for hydrogen production: A review. Membranes (Basel) 11. doi: 10.3390/membranes11110810

[28] Vidas, L., & Castro, R. (2021). Recent De-velopments on Hydrogen Production Technologies: State-of-the-Art Review with a Focus on Green-Electrolysis. Applied Sciences, 11(23), 11363.

[29] Yassin, K., & Dekel, D. R. (2025). Grand challenges in anion exchange membrane energy applications. *Frontiers in Membrane Science and Technology*, *4*, 1691096.

[30] Neelima, J., & Singh, R. K. (2025). Recent advances in anion-exchange membranes for electrolyzers, fuel cells and redox-flow batteries. *Journal of Materials Chemistry A*, *13*(43), 36853-36880.

[31] Emam, A. S., Hamdan, M. O., Abu-Nabah, B. A., & Elnajjar, E. (2024). A review on recent trends, challenges, and innovations in alkaline water electrolysis. *International Journal of Hydrogen Energy*, *64*, 599-625.

[32] Zhang, Q., Hao, Y., Chen, H., Li, J., Zeng, Y., Xiong, J., ... & Li, F. (2026). Toward Energy-Efficient Alkaline Water Electrolysis: Advances in Mass Transport Optimization and Electrolyzer Design. *Advanced Energy Materials*, *16*(1), e04039.

[33] Zhang, L., Qi, F., Ren, R., Gu, Y., Gao, J., Liang, Y., ... & Wu, L. (2025). Recent advances in green hydrogen production by electrolyzing water with anion-exchange membrane. *Research*, *8*, 0677.

[34] Tello, A., Cataño, F. A., Arunachalam, A., Oyarzún, D., Henriquez, R., Valdivia, P., ... & Gómez, H. (2025). Green hydrogen production by photovoltaic-assisted alkaline water electrolysis: a review on the conceptualization and advancements. *International Journal of Hydrogen Energy*, *107*, 378-395.

[35] Jimena Incer-Valverde, Korayem, A., Tsatsa-ronis, G., & Morosuk, T. (2023). "Colors" of hy-drogen: Definitions and carbon intensity. Energy Conversion and Management, 291, 117294–117294. 36- Igwe, C. I., [36] Achebe, C. H., & Chinweze, A. E. (2022). Design of an alkaline water electrolyzer for hydrogen production. *American Journal of Mechanical and Industrial Engineering*, *7*(6), 89-98.

[37] Sebbahi, S., Assila, A., Belghiti, A. A., Laasri, S., Kaya, S., Hlil, E. K., ... & Hajjaji, A. (2024). A comprehensive review of recent advances in alkaline water electrolysis for hydrogen production. *International Journal of Hydrogen Energy*, *82*, 583-599.

[38] Brauns, J., & Turek, T. (2020). Alkaline water electrolysis powered by renewable energy: A review. *Processes*, *8*(2), 248.

[39] Barco-Burgos, J., Eicker, U., Saldaña-Robles, N., Saldaña-Robles, A. L., & Alcántar-Camarena, V. (2020). Thermal characterization of an alkaline electrolysis cell for hydrogen production at atmospheric pressure. Fuel, 276, 117910.

[40] Yang, L., Dong, S., Yang, T., Liu, J., Liu, S., Wang, K., ... & Hou, X. (2025). Membrane Electrode Assembly Design for High-Efficiency Anion Exchange Membrane Water Electrolysis. *Research*, *8*, 0907.

[41] Yang, N., Li, H., Lin, X., Georgiadou, S., Hong, L., Wang, Z., ... & Lin, W. F. (2025). Catalytic electrode comprising a gas diffusion layer and bubble-involved mass transfer in anion exchange membrane water electrolysis: a critical review and perspectives. *Journal of Energy Chemistry*, *105*, 669-701.

[42] Mohsen, A. M., & Basem, A. (2024). Enhancing Heat Removal and H2o Retention in Passive Air-Cooled Pem Fuel Cell by Altering the Flow-Field Geometry. *SSRN Electronic Journal*.

[43] Wang, Y., Pang, Y., Xu, H., Martinez, A., & Chen, K. S. (2022). PEM Fuel cell and electrolysis cell technologies and hydrogen infrastructure development–a review. *Energy & Environmental Science*, *15*(6), 2288-2328.

[44] Wang, C. R., Stansberry, J. M., Mukundan, R., Chang, H. M. J., Kulkarni, D., Park, A. M., ... & Zenyuk, I. V. (2025). Proton exchange membrane (PEM) water electrolysis: cell-level considerations for gigawatt-scale deployment. *Chemical Reviews*, *125*(3), 1257-1302.

[45] Ayers, K., Danilovic, N., Harrison, K., & Xu, H. (2021). PEM electrolysis, a forerunner for clean hydrogen. *The Electrochemical Society Interface*, *30*(4), 67.

[46] Groenemans, H., Saur, G., Mittelsteadt, C., Lattimer, J., & Xu, H. (2022). Techno-economic analysis of offshore wind PEM water electrolysis for H2 production. *Current Opinion in Chemical Engineering*, *37*, 100828.

[47] Buttler, A., Spliethoff, H., 2018. Current sta-tus of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. Renew. Sustain. En-ergy Rev. 82, 2440–2454. doi: 10.1016/j.rser.2017.09.003

[48] Elkholy, M., Boureima, A., Kim, J., & Aziz, M. (2025). Data-driven modeling and prediction of PEM fuel cell voltage response to load transients for energy applications. Energy, 138047.

[49] El Idi, M. M., Ankouni, M., Slama, R. B. H., Nobrega, P. A., Hajjar, A., & Atli, A. (2026). Critical review of the latest advances in thermal management techniques for PEM fuel cells. *Renewable and Sustainable Energy Reviews*, *226*, 116199.

[50] Ren, G., Qu, Z., Niu, Z., & Wang, Y. (2025). Advancing porous electrode design for PEM fuel cells: from physics to artificial intelligence. Electrochemical Energy Reviews, 8(1), 6.

[51] Pandiyan, A., Uthayakumar, A., Subrayan, R., Cha, S. W., & Krishna Moorthy, S. B. (2019). Review of solid oxide electrolysis cells: a clean energy strategy for hydrogen generation. Nanomaterials and Energy, 8(1), 2–22.

[52] Liang, J., & Han, M. (2022). Different performance and mechanisms of CO2 electrolysis with CO and H2 as protective gases in solid oxide electrolysis cell. *International Journal of Hydrogen Energy*, *47*(43), 18606-18618.

[53] Teng, Z., Xiao, Z., Yang, G., Guo, L., Yang, X., Ran, R., ... & Shao, Z. (2020). Efficient water splitting through solid oxide electrolysis cells with a new hydrogen electrode derived from A-site cation-deficient La0. 4Sr0. 55Co0. 2Fe0. 6Nb0. 2O3-δ perovskite. *Materials Today Energy*, *17*, 100458.

[54] Kannah, R. Y., Kavitha, S., Karthikeyan, O. P., Kumar, G., Dai-Viet, N. V., & Banu, J. R. (2021). Techno-economic assessment of various hydrogen production methods–A review. *Bioresource technology*, *319*, 124175.

[55] Minutillo, M., Perna, A., Forcina, A., Di Micco, S., & Jannelli, E. (2021). Analyzing the levelized cost of hydrogen in refueling stations with on-site hydrogen production via water electrolysis in the Italian scenario. *International Journal of Hydrogen Energy*, *46*(26), 13667-13677.

[56] Ahmed, S. F., Mofijur, M., Nuzhat, S., Rafa, N., Musharrat, A., Lam, S. S., & Boretti, A. (2022). Sustainable hydrogen production: Technological advancements and economic analysis. *International Journal of Hydrogen Energy*, *47*(88), 37227-37255.

[57] Li, J., Cai, Q., & Horri, B. A. (2025). Highly conductive and stable electrolytes for solid oxide electrolysis and fuel cells: fabrication, characterisation, recent progress and challenges. *Materials Advances*, *6*(1), 39-83.

[58] Han, F. Z., Wang, Z. X., Zhang, S. L., Li, C. X., & Barnett, S. A. (2025). Highly efficient perovskite-based fuel electrodes for solid oxide electrochemical cells via in-situ nanoparticle exsolution and electron conduction enhancement. *Applied Catalysis B: Environment and Energy*, *361*, 124676.

[59] Shang, D., Zhang, B., Zhang, L., Li, J., Zhao, Y., Huang, Y., ... & Xia, C. (2025). Improving electrocatalytic activity through multi-element doping to A-site of Fe-based perovskite cathode for solid oxide fuel cells. Chemical Engineering Journal, 506, 160067.

[60] Ayub, H. M. U., Alnouri, S. Y., Stijepovic, M., Stijepovic, V., & Hussein, I. A. (2024). A cost comparison study for hydrogen production between conventional and renewable methods. *Process Safety and Environmental Protection*, *186*, 921-932.

[61] Terlouw, T., Bauer, C., McKenna, R., & Mazzotti, M. (2022). Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment. *Energy & Environmental Science*, *15*(9), 3583-3602.