

Green hydrogen in the renewable energy transition exploiting: A systematic review

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ABSTRACT

Green hydrogen, generated exploiting sustainable energy supplies, is materializing as a decisive component in the worldwide progression to eco-friendly energy systems. This review examines recent developments in green hydrogen production, focusing on key electrolysis technologies such as proton exchange membrane (PEM), basic and solid oxide methodologies, along with biological and thermochemistry strategies. Although the promise for clean hydrogen is substantial, several hurdles remain—particularly high production costs, significant energy demands, and difficulties related to storage and distribution. However, the sector is witnessing increased momentum, fuelled by international investments and supportive policy frameworks that are expected to reduce factory overheads to not more than \$2 per kilogram no later than 2030. Nations like India, Japan, Australia in addition Germany are piloting efforts with national strategies aimed at scaling up electrolyzer deployment and incorporating sustainable hydrogen in the direction of industries including transit, energy output and manufacturing. Technological innovations in electrolyzer efficiency, advanced materials, and seamless integration with renewable power sources are projected to augment the commercial proficiency and practicability of green hydrogen. This review underscores the importance of coordinated policy initiatives, ongoing research and development (R&D), and strategic investments to accelerate the adoption of green hydrogen as a pivotal solution for reducing carbon emissions and enhancing energy autonomy and supply reliability. By aligning technological innovation with supportive policy frameworks and financial mechanisms, stakeholders can overcome current barriers in infrastructure, production scalability, and cost competitiveness. Furthermore, fostering international collaboration, incentivizing public-private partnerships, and establishing standardized certification and regulatory pathways will be crucial for driving widespread deployment and ensuring the long-term sustainability of green hydrogen systems.

1. Introduction

Escalating climate change, ecosystems in decline, and dwindling fossil-fuel reserves have made sustainable energy an urgent priority [1].

As populations swell and economies grow, continued dependence on coal, oil, and natural gas pours vast amounts of greenhouse gases into the atmosphere and fouls the air, compounding the climate crisis [2–3]. Recognizing this, governments, industries, and communities are turning

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to low-carbon alternatives—green hydrogen, solar, wind, geothermal, and hydropower—that produce little or no emissions during generation [4–5]. Shifting to these renewables not only curbs climate impacts but also bolsters energy security, lessens vulnerability to finite fuel supplies, and opens new paths for economic expansion and technological progress [6]. Of the available options, hydrogen—the universe’s lightest and most plentiful element—has been recognized as particularly promising sustainable and green energy carrier for the decades ahead [7].

Hydrogen operates as a flexible energy supply with multiple production pathways, positioning it as the central figure in the evolution of the international energy domain [8]. Its application aligns with worldwide endeavours to curtail greenhouse gas emanations, reverse and tackle climate change. By incorporating hydrogen-based solutions, remarkable declines in carbon dioxide discharge can be realized, reinforcing the broader transformation to an environmentally conscious, low-carbon energy infrastructure [9]. The exhaustive statistics originating at International Energy Agency indicates a consistent rise in global hydrogen production, which grew from around 54.1 megatonnes in 2010 towards roughly 82 million metric tons in 2021 [10]. This upward trend is illustrated in Fig. 1 reflecting the growing global output of hydrogen over time.

In the evolving landscape of renewable energy, green hydrogen has gained prominence as a forward-looking solution. This clean energy carrier is stemmed from electrolysis—a method that cleaves water into hydrogen in addition to oxygen exploiting power originating from environmental sources such as sun energy, wind power, hydro, geothermal, or biomass [12]. Unlike conventional dihydrogen production processes, this technique generates hydrogen without emitting carbon dioxide or other pollutants, endorsing an eco-friendlier, sustainable, and green standby to fossil fuels [13]. Green hydrogen is rising in reputation as a key component in the universal push to reduce greenhouse gas emissions [14]. With growing momentum behind climate action, many countries view it as an essential tool for decarbonizing industries and achieving long-term sustainability targets. Since its production does not release CO₂, green hydrogen supports the transition toward carbon neutrality and aligns with climate policy objectives worldwide [15]. One of the notable advantages of renewable hydrogen is its capacity to support and stabilize alternative green energy systems. Solar and wind energy, while abundant, are inherently variable—affected by factors such as weather and time of day [16]. Green hydrogen provides a solution by allowing excess electricity to be stored in the manner of dihydrogen gas during periods of low demand. The stockpiled energy can subsequently be reconverted into power as needed, facilitating the balance between supply and demand in the competitive market and enhance network reliability. Furthermore,

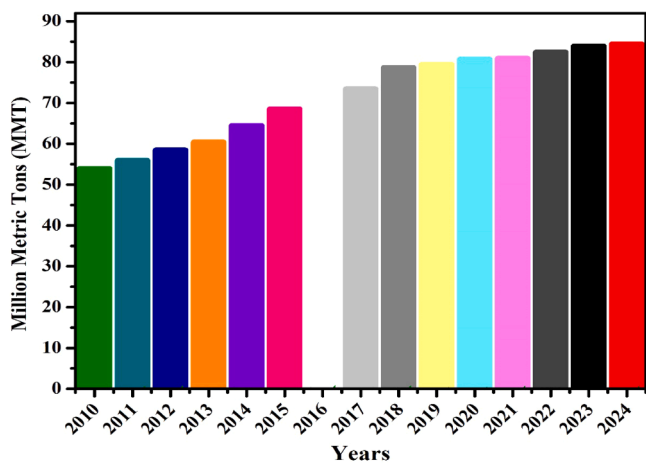


Fig. 1. Hydrogen on the world stage: Patterns of production and distribution [11].

recyclable hydrogen promotes greater energy safety by broadening the energy options and curtail dependence on shipped in fossil fuel resources [17]. The primary inputs—water and perpetual electricity—remain widely available in a number of parts of the world, making this technology scalable and adaptable across various regions. Fig. 2 exemplifies worldwide renewable clean hydrogen manufacturing trends, based on International Energy Agency records and figures in 2021.

Green hydrogen is emerging being a highly warranting renewable and sustainable energy remedy, particularly in light of growing worldwide energy needs and the critical goal of reducing carbon emissions [19]. It is produced by means of water electrolysis procedure powered by sustainable energy resources like wind power, sun energy, or hydroelectricity, which produces hydrogen besides oxygen without releasing harmful greenhouse gases [20]. This clean production technique positions clean hydrogen as a flexible as well as eco-friendly power source with wide-ranging uses across transportation, industry, electricity production, and heating systems. However, the advancement and widespread adoption of green hydrogen still encounter significant obstacles that demands a response [21,22]. The principal barrier is the expensive production costs, primarily driven by current expense of electrolyzers and the sporadic nature of natural energy sources, which affects continuous generation of hydrogen [23]. Moreover, the fundamental groundwork preferred for storing, transportation, and circulation of hydrogen is still underdeveloped, limiting its accessibility and use. Additionally, green hydrogen encompasses a lower energy density as opposed to conventional fossil fuels, which presents challenges for storage and transport, particularly for long distances or in mobile applications [24]. The market for green hydrogen remains nascent, with limited commercial-scale projects and low overall demand compared to traditional energy carriers. To enable its widespread adoption, strong policy frameworks and regulatory clarity are critical. Governments and stakeholders must create targeted financial incentives that encourage investment in research and development, build necessary infrastructure, and scale up production capacities [25]. Furthermore, international collaboration and standardization efforts are essential to establish safety standards, certification mechanisms, and market frameworks that support hydrogen’s integration into the global energy system. By addressing these economic, technical, and regulatory hurdles, green hydrogen can transition from an emerging technology to a cornerstone of a balanced, clean, low carbon energy prospect [26].

Green hydrogen attracts attention as versatile as well as guaranteeing energy carrier within the renewable sector, offering distinct advantages compared to other sources like solar, hydroelectric power, geothermal, wind energy and biomass [27]. While these renewable options primarily generate electricity by harnessing natural energy flows directly, clean hydrogen is generated differently—via electrolysis of water expending energy sourced from renewables for instance stellar

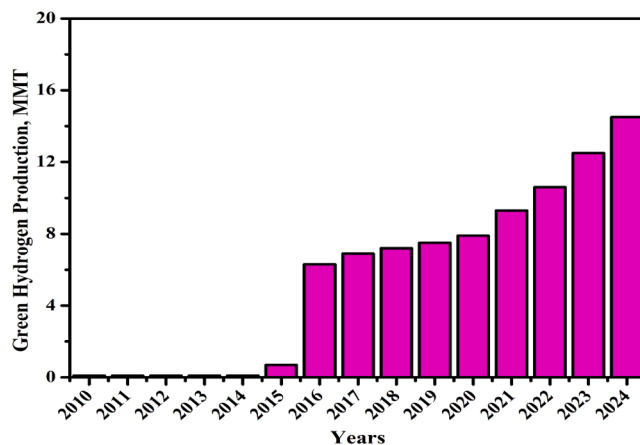


Fig. 2. The rise of green hydrogen: A global production outlook [18].

and wind. The approach enables surplus renewable energy, which might otherwise be wasted, to be effectively stored by converting it into hydrogen. The stored hydrogen can then be used as needed, enhancing energy system flexibility and resilience [28]. A major advantage of green hydrogen is the excellent capability for multi-generation energy storage, making it well-suited to support grid stability and manage energy supply over extended timeframes. Additionally, green hydrogen production can be expanded substantially to meet rising energy demands. While the electrolysis process does entail some energy losses that affect overall efficiency, green hydrogen remains vital for addressing the intermittent nature of renewable power and lessening carbon releases in critical segments like transport, manufacturing, and energy production [29–30]. With this growing momentum toward sustainable energy solutions, green hydrogen—when integrated with other renewable technologies—is expected to be a key component in building a hygienic, extra reliable, besides a robust power infrastructure. Table 1 demonstrates a detailed comparison between recyclable hydrogen and various sustainable energy sources, focusing on aspects such as efficiency, scalability, and energy storage potential.

The capacity to scale and store energy generated from renewable sources is heavily influenced by several key factors, including geographic location, advances in technology, and also the implementation of effective energy storage systems [42]. Every renewable energy basis whether solar, wind, hydro, or geothermal possesses unique strengths and inherent limitations. Solar power, for instance, depends on sunlight availability which varies by region and time, while wind energy is contingent on consistent wind patterns [43]. Technological innovations continue to augment the competence and profitable nature of capturing and storing this energy, yet challenges remain in integrating intermittent sources into the energy grid [44]. Consequently, achieving a reliable and sustainable energy supply requires a strategic combination of diverse renewable technologies alongside robust storage systems, such as batteries or pumped hydro storage, to balance supply and demand and address the variability of renewable generation [45]. This integrated approach is vital to endure the mounting global energy requirements while minimizing environmental impact [46].

Green hydrogen is gaining momentum worldwide, driven by a surge in investment and policy initiatives. In Europe, the European Economic Community has put an elaborate goal of installing 40 gigawatts of electrolyzer capacity by 2030—a crucial step toward scaling up green hydrogen output [47]. The EU's Hydrogen Policy outlines a foresight for hydrogen-powered economy not later than 2050, soliciting resilient

emphasis on environmental sustainability [48]. Key member states such as Germany, France, and the Netherlands are at the forefront of this push. In Asia, several countries are making significant strides. Japan plans to make 300,000 tons of green hydrogen per year sooner than 2030. South Korea has an even more aggressive target—5.8 million tons per year by 2040—while China aims to reach two million tons before 2025 [49]. Meanwhile, the Mideast is evolving as a strategic player, with oil-rich countries like Saudi Arabia and the UAE investing in hydrogen initiatives that capitalize on their abundant solar resources. North America is also advancing rapidly [50]. The United States, particularly California, has pledged to generate five million tons of hydrogen per annum before 2030. Nevertheless, Canada is focusing on affordability, aiming to bring the production cost of hydrogen down to CAD 1.52 per kilogram within the same timeframe. Collectively, these regional strategies are accelerating global progress in green hydrogen. As costs decrease and infrastructure matures, hydrogen is on the verge of becoming an essential component of the green energy transition, as illustrated in Fig. 3.

The review briefly acknowledges the significance of renewable resource availability in enabling green hydrogen production, but it does not sufficiently explore the regional variability of these resources—an essential factor for global scalability. The feasibility of technologies such as Proton Exchange Membrane (PEM) and Alkaline Water Electrolysis (AWE) is highly contingent upon regional parameters like electricity cost, solar/wind resource potential, and water availability. For instance, sun-rich regions like Australia, the Middle East, and North Africa are better positioned to produce low-cost green hydrogen compared to areas with less favorable climatic conditions. However, without a geospatial analysis—which incorporates variables such as solar irradiance, wind speeds, infrastructure access, and proximity to water sources—the paper misses an opportunity to identify region-specific opportunities and constraints. Recent studies have emphasized the utility of GIS-based multi-criteria decision analysis (MCDA) and spatial modeling in identifying optimal hydrogen production sites globally [52,53]. Incorporating such tools would enhance the strategic planning and policy relevance of the review by offering actionable insights for siting, investment, and infrastructure development based on regional techno-economic feasibility.

While clean hydrogen gaining prominence as a viable response intended for sustainable energy, several critical challenges still hinder its widespread adoption. Key areas requiring further research include scaling up production, improving economic viability, and ensuring

Table 1
Green hydrogen vs. Renewables: A comparative analysis of efficiency, storage, and scalability.

| S. No | Criteria | Green Hydrogen | Solar Power | Wind Power | Hydropower | Refs. |
|-------|------------------------------|--|-------------------------------------|--|--|-------|
| 1. | Primary Energy Source | Water + Renewable Electricity (e.g., solar/wind) | Sunlight | Wind | Flowing Water | [31] |
| 2. | Energy Conversion Method | Electrolysis | Photovoltaic (PV) cells | Wind turbines | Turbines driven by water flow | [32] |
| 3. | Carbon Emissions | Near zero (if powered by renewables) | Zero during operation | Zero during operation | Very low | [33] |
| 4. | Energy Storage Capability | High (can be stored and transported) | Limited (needs batteries) | Limited (needs batteries or other storage) | Moderate (can use pumped storage) | [34] |
| 5. | Efficiency (Well-to-End Use) | 25–35 % (electrolysis + conversion losses) | 15–20 % (PV to grid) | 35–45 % (turbine to grid) | 35–45 % | [35] |
| 6. | Maturity of Technology | Emerging/Developing | Mature | Mature | Mature | [36] |
| 7. | Infrastructure Availability | Limited | Widespread | Widespread | Site-specific (dams, rivers) | [37] |
| 8. | Capital Cost (2025 est.) | High (~\$4–6/kg H ₂ , decreasing) | Moderate, declining | Moderate, declining | High initial, low operating cost | [38] |
| 9. | Operation & Maintenance Cost | Moderate | Low | Low to Moderate | Low | [39] |
| 10. | Geographic Limitations | Needs water and renewable electricity supply | Best in sunny regions | Best in windy regions | Requires water bodies & elevation drop | [40] |
| 11. | Use Cases | Heavy transport, industry, energy storage | Residential, commercial electricity | Grid-scale power, remote areas | Grid-scale base load power | [41] |

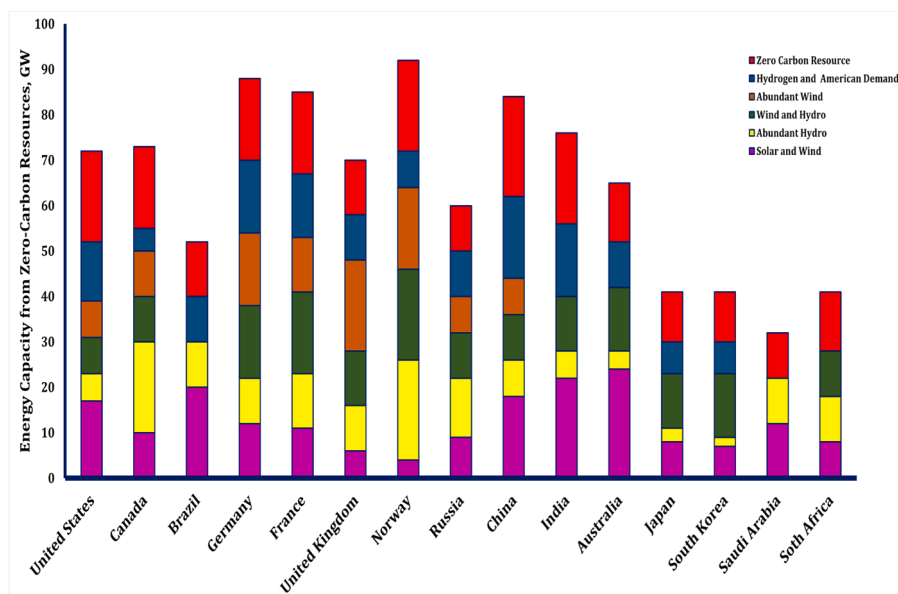


Fig. 3. High-capacity regions with abundant low-cost zero-carbon resources [51].

smooth integration into existing energy systems [54]. Although advancements have been made in production methods such as electrolysis, thermochemical conversion, and biological processes, challenges remain. Impediments persist in widespread adoption of green recyclable hydrogen, embracing the process's high energy requirements and relatively low efficiency. Moreover, production often relies on costly and scarce catalysts. Beyond technical issues, the absence of robust infrastructure for transporting and storing hydrogen presents a major hurdle. Compounding these difficulties are underdeveloped regulatory frameworks and limited financial incentives, both of which are crucial for supporting the large-scale rollout of green hydrogen technologies [55].

This study delivers an in-depth analysis of how green hydrogen contributes to the shift toward cleaner energy systems. It highlights recent technological advancements, ongoing challenges, and a wide spectrum of practical uses [56]. While multiple renewable energy sources support global sustainability goals, green hydrogen is particularly notable for its ability to cut emissions in critical areas such as transport, heavy industry, and power generation. To bridge current knowledge gaps, the research examines emerging preferences in hydrogen manufacture methods, technologies in storage capacity combined with applications [57]. It also identifies key cordons for instance elevated manufacture overheads, limited substructure besides insufficient strategy support. Drawing on these findings, the study outlines targeted strategies to help accelerate the employment of green and clean hydrogen being a core element in the move toward a carbon-negative opportunity [58–59].

A systematic review methodology was adopted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and reproducibility [60]. The literature search was conducted across major academic databases, including Scopus, Web of Science, and PubMed, using combinations of keywords such as “green hydrogen,” “electrolysis,” “PEM,” “AWE,” “SOEC,” “techno-economic analysis,” and “electrocatalysts.”

In total, 823 records were identified through database searches, with an additional 34 records obtained from reference lists and grey literature, summing to 857 records. After removing duplicates, 704 articles were screened based on their titles and abstracts. Of these, 516 were excluded due to irrelevance (e.g., focus on unrelated hydrogen production methods or lack of economic data).

The remaining 188 full-text articles were assessed for eligibility, with 91 excluded based on criteria such as the absence of techno-economic

focus (43 studies), exclusive coverage of fossil-based hydrogen production (25 studies), or lack of electrolyzer-specific analysis (23 studies). Ultimately, 97 studies were included in the qualitative synthesis.

The detailed inclusion and exclusion process is illustrated in the PRISMA flow diagram (Fig. 4), which outlines the selection pipeline for the studies incorporated in this review.

2. The hydrogen - physical and chemical characteristics

Dihydrogen can be generated through several different processes, each resulting in a distinct type of hydrogen. This article explores the various categories of hydrogen ascertained on the basis of production methods exercised [61].

2.1. Established hydrogen manufacture pathways

2.1.1. Grey hydrogen

This hydrogen is predominantly generated using steam methane reforming process (SMR), a method that consumes methane gas as its main raw material [62]. This approach is currently the most widely adopted technique for hydrogen production worldwide. However, it carries significant environmental drawbacks, as the process emits carbon dioxide (CO₂)—a major greenhouse gas—into the atmosphere [63]. The core chemical reaction underlying SMR, which illustrates how grey hydrogen is produced, is shown below.



In this procedure, natural gas, primarily made up of methane, combines with steam under extreme heat in presence of a suitable catalyst, generating hydrogen as well as carbon monoxide [64]. Following this, carbon monoxide is combined with more steam in a separate reaction known as the water-gas shift, which creates extra hydrogen and releases carbon dioxide [65].



Steam Methane Reforming (SMR) typically functions at elevated temperatures ranging from 700 to 1000 °C, with the specific operating temperature influenced by the catalyst used and the desired reaction kinetics. Nickel-based catalysts are frequently employed in the production of grey hydrogen due to their durability and strong catalytic efficiency, especially under high-temperature conditions [66]. This method

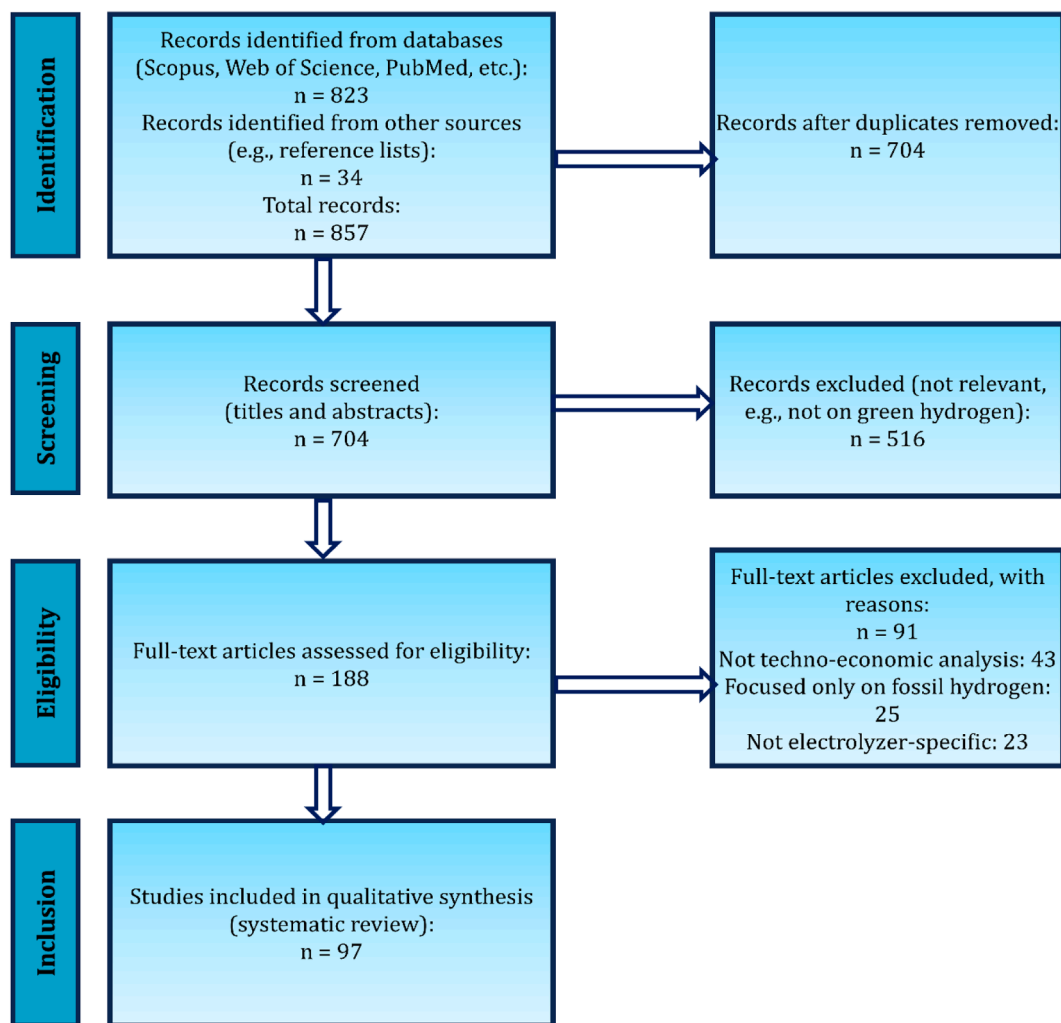


Fig. 4. PRISMA Flowchart: Inclusion and Exclusion Criteria for Green Hydrogen Electrolyzer Studies.

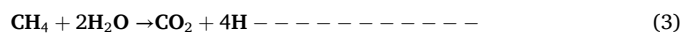
typically yields a hydrogen conversion rate of approximately 70 % to 80 %, effectively transforming a significant portion of the natural gas feed into hydrogen [67]. Nevertheless, the process also releases a substantial amount of carbon dioxide, as the carbon not converted into hydrogen is emitted as a by-product. This emission of greenhouse gases makes grey hydrogen less favorable from an environmental perspective, especially when compared to cleaner options like green or blue hydrogen [68].

While efforts are ongoing to reduce its carbon emissions, grey hydrogen is increasingly being supplanted by greener alternatives. Green hydrogen is manufactured through electrolysis energized by eco-friendly energy and the blue hydrogen combines hydrogen production together with carbon capture coupled with storage to lower emissions [69]. These alternatives perform a vital function in moving in the direction of a cleaner, trivial - carbon energy prospect.

2.1.2. Blue hydrogen: A sustainable energy solution

Blue hydrogen is generated using methods such as steam methane reforming route (SMR) otherwise via autothermal reforming measures (ATR), both of which utilize fossil gas as fundamental primary input, similar to grey hydrogen production [70]. What sets blue hydrogen apart is the integration of carbon reduction technologies, specifically carbon capture and storage or utilization (CCS) or (CCU). These know-hows capture the gaseous carbon dioxide produced during the hydrogen extraction process, either storing it in geological formations or repurposing it for industrial use. By preventing the release of CO₂ into the atmosphere, blue hydrogen significantly lowers greenhouse gas

emissions [71–72]. This added carbon control step positions blue hydrogen as a more environmentally responsible and sustainable alternative to conventional grey hydrogen. The crucial chemical reactions embroiled in the production of blue hydrogen via the SMR process are presented in Eq. (1) and the subsequent reaction [73].



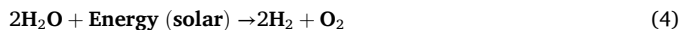
Steam methane reforming procedure for blue hydrogen creation is carried out at elevated temperatures, typically ranging from 700 to 1000 °C. This process commonly employs nickel-based catalysts due to their strong catalytic activity and ability to withstand such extreme thermal conditions. The efficiency of the process generally leads to the conversion of roughly speaking 70–80 % of dihydrogen material present in fossil centred natural gas into gaseous hydrogen suitable for use [74].

Blue hydrogen serves as an intermediate step in the journey toward a cleaner energy landscape, offering reduced carbon emissions relative to conventional hydrogen production techniques. Despite its lower environmental impact, blue hydrogen is not entirely emissions-free. For the energy sector to fully decarbonize, a complete transition to green hydrogen is essential. Green recyclable hydrogen is prepared distinctively all the way through the electrolytic cleavage of water exploiting electrical power engendered from clean energy sources, enabling hydrogen production without releasing any carbon dioxide [75].

2.2. Varieties of green hydrogen

2.2.1. The perception of yellow hydrogen

This type of hydrogen, also referred to as solar-thermochemical hydrogen, is generated by harnessing solar radiation to separate liquid water into its elemental components—hydrogen and oxygen gases. This technique endorses a cleaner substitute for conventional hydrogen production processes, which are typically dependent on fossil fuels. By capturing and converting sunlight directly into heat, the process drives the decomposition of water without emitting greenhouse gases [76]. The core reaction involves the absorption of solar heat to cleave the chemical bonding in water, resulting in release of gaseous mixture containing hydrogen and oxygen. This approach leverages renewable solar energy to create hydrogen sustainably, minimizing environmental impact [77].



Yellow hydrogen is produced using extremely high temperatures, generally ranging from 800 °C to about 1500 °C, contingent on the method employed. This process does not rely on catalysts but instead uses intense solar power to divide water as hydrogen and oxygen through direct thermal decomposition. The effectiveness of the given technique hinges on quite a few considerations, encompassing the design of solar concentrators, type of thermal system used, and to what degree the system minimizes heat loss. Although still in an emerging stage, this method holds competence for resourceful hydrogen generation when engineered as well as managed effectively [78].

2.2.2. Green hydrogen

It is produced by expending electrical power derived from renewable energy resources to separate water into gaseous hydrogen and oxygen gas via electrolysis. It is considered "green" because the energy used is entirely renewable, and no carbon dioxide is emitted during production [79]. The core chemical reaction involved describes the decomposition of water into its basic gaseous elements.



This type of hydrogen prepared using recyclable energy sources, universally known as green hydrogen, is often obtained through the electrolysis of water. This method typically operates at ambient or moderately elevated temperatures [80]. In this process, electricity is exhausted to split up water into its basic components to be precise hydrogen gas and gaseous oxygen. To improve the rate of these electrochemical reactions at the electrodes, specific substances known as catalysts are introduced [81]. While platinum is frequently utilized due to its superior catalytic properties, its high cost limits its widespread use. As a result, there is a growing focus on finding more affordable and readily available alternatives, such as various metal-based compounds [82]. The effectiveness of green hydrogen production is influenced by several elements, including the design and efficacy of electrolyzer, category of the catalyst employed, dependability of the replenishable power input, in addition to the way manner in which the system is configured. Technological developments in this field have led to notable efficiency gains, with some systems now capable of converting energy at rates of up to 70–80 % [83].

While noble metal catalysts such as platinum (Pt) and iridium (Ir) have demonstrated excellent catalytic activity for hydrogen evolution reaction (HER) and oxygen evolution reaction (OER), their high cost and scarcity limit large-scale adoption. As such, significant efforts have been directed toward developing non-precious, earth-abundant alternatives—such as transition metal phosphides, nitrides, oxides, and carbides—that offer comparable catalytic activity at lower cost. Although the review mentions these materials, it lacks in-depth analysis of their performance characteristics, including overpotential, Tafel slopes, electrochemical surface area, and durability under harsh electrolytic conditions (acidic/alkaline, high salinity, or elevated temperature).

Recent studies have reported promising advances in bifunctional electrocatalysts, capable of facilitating both HER and OER, thereby simplifying system design and reducing costs. This is particularly relevant in the context of unitized regenerative fuel cells and integrated electrolyzer systems. For instance, cobalt–nickel phosphides and iron-based layered double hydroxides (LDHs) have shown superior bifunctional activity with high current density and long-term operational stability. Their structural tunability and corrosion resistance make them attractive candidates for large-scale applications, including direct seawater electrolysis.

Emerging research, such as that by Zhang et al. (2022) [84], demonstrated engineered bifunctional electrocatalysts exhibiting low overpotentials (<300 mV) and robust corrosion resistance in simulated seawater. Similarly, Shang et al. (2020) [85] highlighted nickel–iron LDHs as highly stable and efficient catalysts under alkaline saline conditions. The inclusion of such examples would have greatly strengthened the review by providing empirical benchmarks and contextualizing the progress in catalyst design with respect to real-world deployment.

In 2020, global hydrogen production was approximately 76 million tonnes, with the vast majority derived from fossil fuels, a form commonly referred to as grey hydrogen. This type accounted for about 95 % of total production [86]. Blue hydrogen, which involves carbon capture and storage, represented around 4 %, while green hydrogen—produced using renewable electricity—made up only about 1 %. Another variant, yellow hydrogen, typically produced from coal, was even less prevalent and mainly limited to regions where coal remains a key energy source [87]. Despite the dominance of grey hydrogen, the global energy landscape is poised for significant change. Growing efforts to reduce carbon footprint emissions coupled with expanding clean energy resources are driving investment in low-carbon hydrogen alternatives [88]. As stated by International Energy Agency (IEA), clean and green hydrogen could constitute to the extent of 30 % of comprehensive hydrogen production world-wide by 2050. Regional conditions will influence this shift; for example, areas with abundant solar and wind resources are more likely to adopt green hydrogen due to its environmental and long-term economic benefits [89]. As nations and industries increase their commitment to sustainability, the transition toward cleaner hydrogen production is expected to accelerate. Fig. 5 presents the international distribution of hydrogen generation in accordance with type for the 2021 calendar year.

3. Approaches to generation of green hydrogen

The renewable hydrogen production is a developing field, continuously evolving through ongoing advancements and innovations. This article investigates the different methods employed to produce cleaner

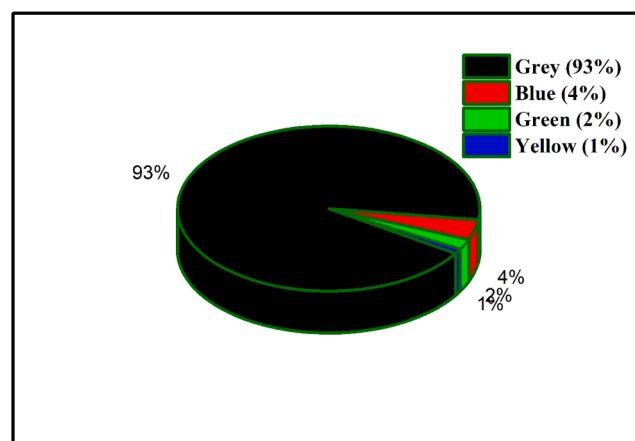


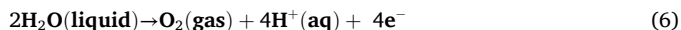
Fig. 5. Dissecting the hydrogen mix: Global production shares by source in 2024 [90].

green hydrogen in addition evaluates their prevailing stages of progress.

3.1. Hydrogen production via electrolysis

Electrolysis of water uses electrical energy to break down molecules of water to gaseous hydrogen and oxygen gas. When powered by way of renewable sources like wind or solar power, this technique offers an eco-friendly way to produce hydrogen. This section explores the core principles behind electrolysis, reviews current advancements in equipment in addition expertise and considers its possibilities for pervasive acceptance as a green hydrogen production methodology. The portion given below summarizes the chemical transformations involved in the process [91].

At the anode (the positively charged electrode):



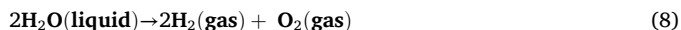
The given procedure produces gaseous oxygen and releases positive charged hydrogen ions (protons) into the neighbouring electrolyte [92].

At the negatively charged cathode:



This approach uses hydrogen ions and furthermore electrons formed at the positive anode to produce dihydrogen gas.

Overall reaction:



Water electrolysis needs an outside energy input—commonly electricity—to power the chemical reactions at the electrodes. This electricity can come from different sources, including renewable options like sun and wind power, in addition to traditional resources such as non-renewable fuel sources along with atomic power, which is illustrated in Fig. 6.

3.1.1. Present technological landscape

Notable advancements are underway to optimize productivity, expand scalability along with minimizing financial outlay. Currently, multiple electrolysis cell technologies are utilized, each presenting distinct advantages and encountering particular obstacles [93].

- Alkaline Water Electrolyzers (AWE): Alkaline water electrolyzers are among the earliest and most established technologies for hydrogen

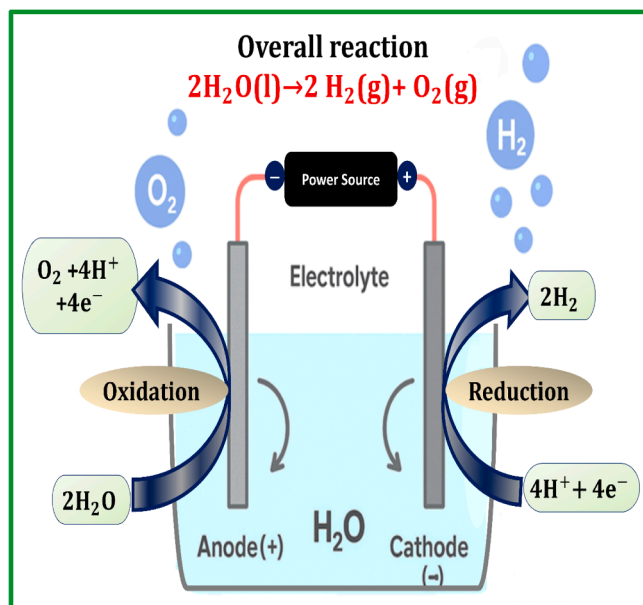


Fig. 6. Electrochemical splitting of water.

production through water electrolysis. These systems use a liquid alkaline electrolyte typically potassium hydroxide which can manage at intense heat and high pressure. Their relatively low initial investment costs make them well-suited for small to medium-scale or decentralized hydrogen generation. This adaptability is ideal for applications such as in-plant hydrogen generation in manufacturing environment or local fuel filling stations. Thanks to their affordability and reliable performance, alkaline electrolyzers remain a practical solution for supplying hydrogen at a regional level [94].

- Proton Electrolyte Membrane (PEM) Electrolyzers: These type of electrolyzers utilize a solid polymer membrane as ionic medium, which separates hydrogen and oxygen during the electrolysis process. These systems generally run at lower temperatures and pressures compared to alkaline electrolyzers and often provide higher energy efficiency. Their modular and scalable design enables deployment across a range of sizes, from compact units to large-scale hydrogen plants. The combination of sleek design and fast response times has made PEM electrolyzers increasingly popular in commercial hydrogen projects where stable output and operational flexibility are critical [95].
- Solid Oxide Electrolyzers (SOEC): This category operates at rising temperatures as well as employing an inorganic solid ceramic electrolyte to break up water as a gaseous mixture of hydrogen and oxygen. The high operating temperatures improve electrical efficiency and allow integration with industrial waste heat sources. Despite these advantages, SOECs face challenges such as material degradation, complex system requirements, and limited commercial maturity. However, ongoing research and technological improvements aim to address these issues, positioning SOECs as a cutting-edge technology for decarbonized hydrogen production in the future predominantly in scenarios where high-temperature heat is readily available [96].

Novelties in materials research and engineering have greatly enhanced both efficacy and the lifespan of electrocatalysts used in water electrolysis. These improved catalysts play a crucial role in speeding up electrochemical reactions and minimizing energy consumption during hydrogen generation [97]. Noticeably, alloys of nickel/iron, and nickel/molybdenum besides iridium oxide have emerged as leading candidates with significant promise for practical deployment. Additionally, progress in control technologies and automation has increased the operational effectiveness and dependability of electrolysis systems [98]. These smart control solutions enable continuous monitoring and optimization of the process, helping to prevent mechanical failures and boost overall system performance. A comprehensive comparison outlining the advantages and drawbacks of different electrolysis techniques is presented in Table 2.

In parallel with other advancements, electrolytic splitting of water has emerged as the dominant methodology aimed at hydrogen generation. For example, the research group led by Zhang [99] explored a high-temperature proton exchange membrane (PEM) electrolyzer, demonstrating superior hydrogen output compared to traditional low-temperature PEM models. Meanwhile, Ni et al. evaluated solid oxide electrolysis cells (SOECs) utilizing nickel-oxide-based electrodes, achieving a current density value of about 1.5 A/cm² furthermore producing hydrogen to the extent of 1.47 mL per minute at around 850 °C [100]. In another investigation, Barco-Burgos examined an alkaline water electrolyzer (AWE) incorporating a iridium oxide overlaid titanium mesh, which operated at 80 °C with a current intensity estimate of roughly 550 mA/cm² moreover generated dihydrogen with a flow rate of 2.26 mL per minute [101]. Marshall and his team improved PEM electrolyzer performance by incorporating a porous titanium electrode, resulting in a hydrogen flow of 3.1 mL/min at 100 mA/cm². Additionally, Shetty et al. reported promising results with nickel-foam-supported electrodes in SOEC setups, obtaining a current density of 0.8 A/cm² and a hydrogen generation volume flow rate of nearly 0.56 mL/min

Table 2
Electrolysis in focus: pros, cons, and potential.

| S. No | Category | Pros | Details | Cons | Details |
|-------|----------------------|---|---|--|--|
| 1. | Technical | High Purity Hydrogen | Produces 99.999 % pure hydrogen (suitable for fuel cells). | Low Efficiency (Traditional Alkaline) | Alkaline electrolysis efficiency ~60–70 %; PEM ~70–80 %; SOEC still experimental. |
| 2. | | Modular & Scalable | Can be scaled from small units (kW) to large (MW) for different applications. | Intermittent Operation Limitations | Frequent start-stops reduce stack life and performance, especially in PEM systems. |
| 3. | | Fast Start-Up (PEM) | PEM electrolyzers can ramp up/down quickly, ideal for grid-balancing with renewables. | Limited Lifetime | Electrolyser stacks degrade over time; PEM: ~40,000–60,000 hrs; Alkaline: ~60,000–90,000 hrs. |
| 4. | Economic | Declining Capital Costs | Electrolyser CAPEX has fallen ~50 % in the past decade and continues to decrease. | High Initial Cost | As of 2024, typical cost: \$800–\$1500/kW (PEM); \$500–\$1200/kW (Alkaline). |
| 5. | | Uses Off-Peak Electricity | Can utilize cheap or surplus renewable energy during off-peak hours. | High OPEX with Grid Power | Using grid electricity can make hydrogen cost >\$5–7/kg, not competitive with fossil H ₂ (~\$1.5/kg). |
| 6. | Environmental | Potential for Revenue via Grid Services | Can earn from demand response programs and ancillary services in smart grids. | Limited Infrastructure | Lack of widespread hydrogen pipelines, storage, and fueling infrastructure limits uptake. |
| 7. | | Zero Carbon (with Green Power) | Produces no CO ₂ if powered by renewable electricity (wind, solar, hydro). | Water Consumption | Requires ~9 liters of pure water per kg H ₂ ; purification adds cost and resource use. |
| 8. | | Decentralized Production | Enables distributed hydrogen production, reducing transmission emissions. | Energy Intensive | Electrolysis consumes ~50–55 kWh of electricity per kg H ₂ – high compared to alternatives. |
| 9. | Safety & Regulation | Clean & Safe Working Fluids | Alkaline uses KOH/NaOH; PEM uses solid polymer membrane no toxic by-products. | H ₂ Storage & Handling Challenges | Hydrogen is flammable, requires high-pressure tanks or cryogenic storage, raising safety risks. |
| 10. | | Mature Technology (Alkaline) | Over 100 years of history in industrial applications (chlor-alkali industry). | Regulatory Gaps | Hydrogen production, storage, and transport regulations still evolving in many regions. |
| 11. | Innovation Potential | Emerging Technologies (SOEC, AEM) | Solid Oxide Electrolyzers and Anion Exchange Membranes promise higher efficiency & lower costs. | Early-Stage R&D Challenges | SOECs operate at 600–800 °C and face material degradation; AEMs not yet fully commercial. |

observed at 850 °C. An in-depth examination and analysis of these international studies on electrolysis technologies is compiled in [Table 3](#).

3.1.2. Challenges in electrolysis technology

Water electrolysis is an attractive approach for generating green hydrogen, yet several major obstacles prevent its broad adoption. One key challenge is the relatively low practical energy efficiency. Although the process shows high theoretical efficiency, real systems experience significant energy losses caused by factors such as over potentials, internal resistance, and limitations in mass transport, all of which reduce the overall effectiveness. Another important issue is the longevity of electrolyzer components. Operating conditions often involve high temperatures and corrosive environments, which can accelerate the wear and degradation of electrodes and other parts, negatively impacting performance and increasing maintenance demands due to frequent replacements [117].

Additionally, the reliance on renewable electricity presents complications. For hydrogen to be genuinely sustainable, the electricity driving electrolysis must originate from sustainable resources. However, spasmodic nature of sun and wind energies leads to erratic supply of electricity, making continuous hydrogen production challenging [118]. Scaling up electrolysis to industrial levels also introduces both technical and financial hurdles. While the technology works efficiently at smaller scales, expanding it without sacrificing cost-effectiveness or performance remains difficult. The lack of a comprehensive infrastructure for hydrogen storage and transportation further constrains widespread deployment [119].

Cost factors remain a significant limitation as well. Electrolysis systems require substantial initial capital investment, and the electricity consumption contributes heavily to operational expenses. Consequently, hydrogen generated by electrolysis is still more expensive compared to fossil fuel-based methods. Achieving cost reductions in both equipment and renewable energy sources is crucial for electrolysis to become economically viable. Overall, although water electrolysis offers significant promise for clean hydrogen production, advancements in efficiency, durability, renewable energy integration, scalability, and cost reduction are essential to unlock its full potential on a large scale [120].

3.1.3. Innovations to improve hydrogen production through electrolysis

Upgrading hydrogen manufacture by way of electrolytic split-up of water requires a multifaceted approach aimed at boosting efficiency, cutting expenses, and supporting large-scale adoption. A primary emphasis is the evolution of cutting-edge catalysts, which accelerate the electrochemical reactions and reduce the energy input needed. Exploring novel supplies, such as oxides of transition metals, allows scientists to create catalysts that offer enhanced performance and longer lifespan, thereby increasing hydrogen output efficiency. Fine-tuning the operating conditions of electrolysis cells is equally important. Influences like electrolyte composition, pressure, and temperature impact the system's effectiveness. For example, elevating temperature can decrease energy demand and expedite hydrogen generation [121].

Linking electrolysis units with replenishable and sustainable energy resources like wind and solar power may help in producing hydrogen in an environmentally friendly and cost-effective manner by eliminating carbon emissions. To meet growing hydrogen demand, it is essential to develop scalable designs, including modular, stackable cells or multi-stage reactors, that can expand production capacity without losing efficiency. Moreover, recycling elements like electrodes and membranes contributes to cost reduction and environmental sustainability. Integrating water electrolysis along with carbon capture - utilization and storage (CCUS) technologies can elevate its ecological advantages, potentially enabling hydrogen production with a net-zero or negative carbon footprint. These advancements highlight the vital potential of water electrolysis in establishing dihydrogen as a keystone alternative fuel for the worldwide shift toward sustainable energy [122].

3.2. Heat-driven water splitting technologies

Thermochemical water splitting involves using intense heat to break down molecules of water molecules to hydrogen gas and gaseous oxygen. Hydrogen produced via this method can then be gotten and warehoused for specific purpose as a non-conventional environmentally friendly fuel. This technique is regarded as a highly promising approach for generating green hydrogen because it relies on sustainable heat sources like concentrated solar energy or nuclear power, eliminating the need for electrical energy in the process [123].

Table 3
Recent progress in electrolysis technology for enhanced hydrogen production.

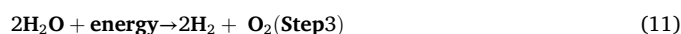
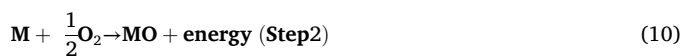
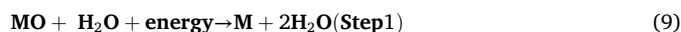
| S. No | Country | Technology | Electrolysis Projects & Developments | Strategic Goals & Investments | Refs. |
|-------|----------------|------------|--|---|-------|
| 1. | China | AWE | Significant projects like the 150 MW Ningxia Solar Hydrogen Project. | Scaling up large-scale green hydrogen projects. - Expanding electrolyser manufacturing, including in Europe. | [102] |
| 2. | India | PEM | Major investments by companies like Reliance and Adani. | \$2.3 billion approved to support green hydrogen initiatives. - Targeting 125 GW of renewable energy capacity addition. | [103] |
| 3. | Germany | AWE | Hydrogen Lab Leuna's 1 MW high-temperature electrolyser integrated into chemical industry pipelines. | €9 billion investment to construct 5 GW of electrolyser capacity by 2030. | [104] |
| 4. | United Kingdom | AWE | Labour's plan to double green hydrogen production target to 10 GW by 2030. | Emphasis on renewable electricity for electrolysis. - Addressing challenges in scaling up production. | [105] |
| 5. | Singapore | PEM | Development of the world's largest ocean carbon dioxide removal facility using the Equatic Process, which involves electrolysis. | \$20 million collaboration with UCLA aiming for net-zero emissions by 2050. | [106] |
| 6. | United States | PEM | Boston Metal's development of molten oxide electrolysis (MOE) technology for steelmaking. | Advancing electrolysis technologies to reduce costs and emissions in industrial processes. | [107] |
| 7. | Canada | AWE | Installation of a 20 MW PEM electrolyser by Air Liquide in Quebec, producing up to 8.2 tons of hydrogen per day. | Leveraging renewable energy for large-scale hydrogen production. | [108] |
| 8. | Japan | PEM | Kyoto University's development of ruthenium-iridium nanosized coral (RuIr-NC) electrodes for efficient water electrolysis. | Enhancing performance and durability of electrolysis electrodes. | [109] |

Table 3 (continued)

| S. No | Country | Technology | Electrolysis Projects & Developments | Strategic Goals & Investments | Refs. |
|-------|-------------|------------|---|---|-------|
| 9. | Australia | AWE | Frontier Energy's selection of alkaline water electrolysis (AWE) for the Bristol Springs Solar Project. | Integrating electrolysis with renewable energy sources to produce green hydrogen. | [110] |
| 10. | Egypt | PEM | Signing of seven memoranda of understanding for green hydrogen and renewable technology investments. | Targeting \$40 billion investment in green hydrogen projects, with an initial \$12 billion in pilot phases. | [111] |
| 11. | Switzerland | AWE | Energy's selection of alkaline water electrolysis (AWE) for the Bristol Springs Solar Project | Targeting \$50 billion investment in green hydrogen projects, with an initial \$22 billion in pilot phases | [112] |
| 12. | Italy | AWE | alkaline water electrolysis (AWE) for the Bristol Springs Solar Project | - | [113] |
| 13. | Korea | AWE | Energy's selection of alkaline water electrolysis (AWE) for the Bristol Springs Solar Project | Enhancing performance and durability of electrolysis electrodes. | [114] |
| 14. | Malaysia | PEM | Integration of PEM with solar power and heat storage showed efficient hydrogen | \$32 billion investment in green hydrogen projects, with an initial \$12 billion in pilot phases | [115] |
| 15. | Turkey | PEM | Graphene-based PEM showed improved performance and stability | \$45 billion investment in green hydrogen projects, with an initial \$15 billion in pilot phases | [116] |

3.2.1. Overview of current technologies

The production of green hydrogen using solar thermochemical methods is still in the research and development phase. While many laboratory studies have demonstrated the potential of this technique, substantial technological and financial hurdles must be overcome prior to being implemented on a commercial scale. The thermochemical process of splitting water encompasses quite a few phases, including the heat-driven steam induced reduction of a metal oxide, followed by the oxidation process involving the reduced metal oxide in presence of air, which generates heat [124]. This entire process might be explained as a sequence of chemical transformations.



The power needed for the reaction may be supplied from various resources such as concentrated solar thermal power, thermonuclear energy, or industrial residual heat. Typically, the reaction requires high temperatures ranging between 800 upto 1200 °C, contingent on the exact category of metal oxide included. In this process, the metal oxide serves as catalyst, triggering the reaction to take place and staying unspent. As an opening move, the chosen metal oxide undergoes electron gain to form a lower oxidation state, followed by re-oxidation in the second step. This periodic behaviour sanctions the metal oxide to facilitate the reaction repeatedly without depletion. Fig. 7 illustrates the conceptual design of a solar thermochemical system using metal oxides for hydrogen production [125].

Several types of metal oxides serve as catalysts in thermochemical water splitting. These include cerium oxide (CeO_2), ferrites with the formula MFe_2O_4 —where M can be metals such as cobalt, nickel, or copper—and perovskite materials represented by ABO_3 , wherein A and B are metal ions chosen. The choice of a particular metal oxide affects not only the resourcefulness and affordability of the procedure but also the operational requirements [126]. Solar energy driven thermochemical systems propose an effective way to make cleaner green hydrogen by directly usage of sun energy as fundamental input. Recently, research has intensified to improve these processes for sustainable hydrogen production. For example, Wang and co-researchers developed a ceria-based redox cycle for solar thermochemical hydrogen generation that showed promising efficacy and permanence, presenting it as a robust and amenable choice for large-scale deployment [127]. Likewise, research work by Tong exemplified a solar-powered two-step water splitting method that uses a hybrid cycle combining ceria and zinc oxide, achieving a notable solar-to-hydrogen efficiency of 20.6 % in lab experiments [128].

These investigations highlight the stellar thermochemical methodologies can accomplish robust productivity and durability, and their integration with additional renewable power resources such as earth heat can further boost dihydrogen output. Wang et al. proposed an innovative system combining solar and geothermal energy to enhance green hydrogen production, illustrating how geothermal heat can upsurge the overall throughput of the given thermochemical procedure

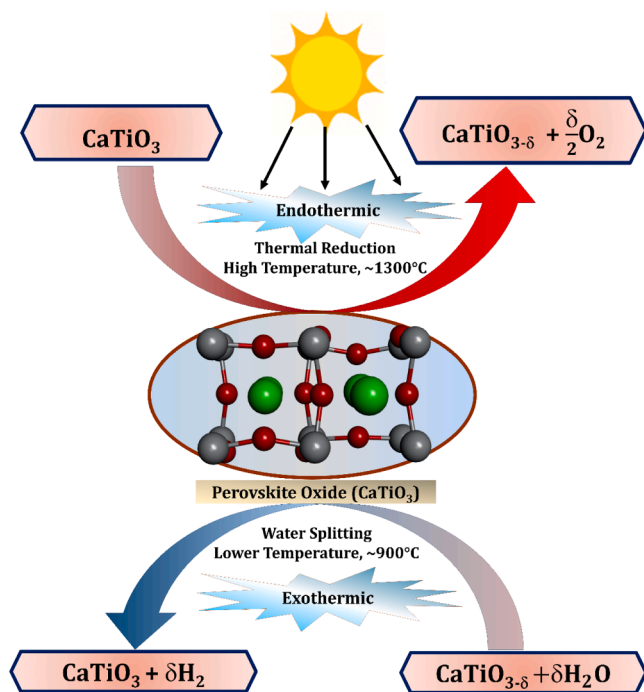


Fig. 7. Process diagram of MO-driven solar thermochemical hydrogen generation.

[129]. Another study by De Luca and collaborators explored a different integration scheme where geothermal energy supplies the heat necessary for heat-absorbing reduction phase, while solar power drives the exothermic oxidation step [130]. Continued inquiry is essential to refine the blueprint and functioning of solar-driven thermochemical conversion reactors to enable their deployment at industrial scales for sustainable hydrogen production [131].

Pan and colleagues developed a sun-powered hybrid oxidation–reduction cycle that combines ceria with iron oxide to generate hydrogen, achieving a solar energy to hydrogen productiveness of about 15.7 % in research facility tests. In an alternative investigation, Li and co-researchers inspected the utility of a fluidized bed reactor in the process of solar driven thermochemical generation of dihydrogen, emphasizing its superior heat transfer properties and scalability potential [132]. Thanda and collaborators introduced an innovative solar thermochemical process employing a hybrid cyclic process involving nickel oxide and ceria, reporting an efficiency of 11.8 % in their experimental setup [133]. Additionally, Nailwal et al. examined a multi-tube solar reactor design aimed at green hydrogen generation, demonstrating improvements in heat transfer and reactant separation, which supports its suitability for industrial applications [134]. Table 4 provides a summary of these important studies focused on thermochemical methodology of splitting of water to prepare hydrogen.

Although solar thermochemical methods for green hydrogen are still emerging, the recent advances offer a strong footing for ongoing inquiries and bringing the technology to the market in the future.

3.2.2. Obstacles in solar thermochemical green hydrogen production

Solar thermochemical techniques offer great potential for generating recyclable green hydrogen, but numerous problems call for resolution ahead of this technology to be universally deployed.

- **Efficiency:** Solar power thermochemical water split-up procedure relies on directing high-temperature concentrated solar power to disintegrate water molecules to oxygen and hydrogen gases. Achieving and sustaining the exceedingly blistering heat mandatory and not exceeding 1500 °C displays significant challenges. The overall efficiency depends heavily on the performance of solar concentrators, which focus sunlight onto the reactor. Currently, these concentrators have relatively low efficiency, and advancements are necessary to enhance the process's overall effectiveness [142].
- **Reactor Design:** The reactor plays a vital role in determining both the efficiency and the potential for scaling up this technology. It must endure extreme heat and frequent temperature fluctuations without deterioration. Additionally, it should enable effective heat transfer starting from concentrated solar power system to the reaction vessel while minimizing thermal losses. Optimizing reactor design is essential to maximize hydrogen output and maintain operational durability [143].
- **Material Selection:** Materials used in this process must resist degradation at high temperatures and in harsh chemical conditions. Many of the currently available materials are costly and not easily sourced in large amounts, which could hinder widespread adoption. Developing more affordable, durable materials is critical for the future expansion of this technology [144].
- **Cost:** Presently, solar thermochemical water splitting remains more expensive than traditional hydrogen production techniques. High expenses stem primarily from the cost of solar concentrators, specialized materials, and the energy input required for operation. Reducing these costs is crucial for making the technology financially competitive [145].
- **Scalability:** Scaling solar thermochemical water splitting from laboratory experiments to industrial applications presents challenges. It is still uncertain how the process will perform on a larger scale, and adjustments to reactor designs and materials may be necessary to facilitate mass production and commercial viability.

Table 4
Innovations in thermochemical water-splitting techniques for efficient hydrogen production.

| S. No | Material/System | Reduction Temp (°C) | O2 released average (μmol/g) | Re-oxidation Temp (°C) | H ₂ Produced (μmol/g) | Refs. |
|-------|---|----------------------|------------------------------|-------------------------|--|-------|
| 1. | La _{0.3} Sr _{0.7} Co _{0.7} Fe _{0.3} O ₃ (LSCF3773) | 900 | 30 | 500 / 700 / 900 | 261 / 1760 / 1815 | [135] |
| 2. | Sr ₂ CoNb _{0.3} Ti _{0.7} O _{6-δ} (Perovskite) | 1000 | 100.8 | 800 | 410 | [136] |
| 3. | Gd _{0.5} La _{0.5} Co _{0.5} Fe _{0.5} O ₃ (Perovskite) | 1350 | 79.1 | 850 / 1000 | 101 / 141 | [137] |
| 4. | SrTi _{0.5} Mn _{0.5} O _{3-δ} (STM55) | 1350 | 69.2 | 1100 | 7.4 mL/g | [138] |
| 5. | CeO ₂ (Cerium) | 2300 | 263.4 | 750–950 | Not specified | [139] |
| 6. | CeO ₂ (Photo-thermochemical cycle) | Not specified | 49.55 | 547.2 | 8.85 μmol/g/h | [140] |
| 7. | Sm ₂ O ₃ (Samarium Oxide) | 2280–3000 | 96.4 | <6800 K | Up to 3 mol H ₂ /mol Sm ₂ O ₃ | [141] |

Solar thermochemical water splitting offers a promising route to generate green hydrogen, yet several obstacles need to be tackled before it can achieve commercial success. Enhancing the performance of solar concentrators, refining reactor configurations, creating materials that balance durability with affordability, and lowering overall costs are critical areas requiring attention. Despite these hurdles, the advantages of green hydrogen production through solar thermochemical methods highlight its significant potential and justify continued research and development [146].

- Enhance solar concentrator design: Optimizing solar concentrators to achieve higher solar energy concentration can lower the energy input required for producing green hydrogen.
- Innovate advanced materials: Creating new materials that offer greater durability, cost-efficiency, and widespread availability will help decrease overall technology costs and improve scalability.
- Boost hydrogen output: Refining reactor designs and utilizing superior materials can accelerate hydrogen production rates, enhancing the economic feasibility of the process.
- Combine with energy storage solutions: Integrating solar-driven water splitting with storage systems like batteries or hydrogen tanks can ensure a stable and dependable supply of green hydrogen, supporting applications such as backup power for intermittent renewables like solar and wind.
- Create hybrid renewable: Systems by combining solar-powered thermochemical mode of splitting of water with alternative clean energy sources like Eolic energy and earth's heat. This integrated approach can boost overall efficiency and scalability, leveraging the unique capabilities of different energy sources to ensure a more reliable hydrogen production.
- Expand production capacity: Collaborating with industry participants besides government bodies to initiate gigantic pilot projects will expedite the path toward commercial adoption of this technology.

Enhancing the performance of solar concentrators, advancing material technologies, boosting hydrogen generation rates, combining with energy storage solutions, creating hybrid systems, in addition boosting output are key avenues for advancing renewable green hydrogen generation mediated through solar driven thermochemical methods. Tackling all of these obstacles could enable solar thermochemical water splitting to emerge as a cost-effective and sustainable approach for generating green hydrogen from renewable energy [147].

3.3. Hydrogen generation through biological processes

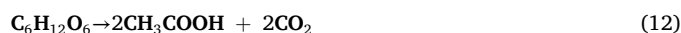
Biological hydrogen production represents an innovative and sustainable approach for generating renewable hydrogen gas. This field encompasses several techniques such as fermentation processes, bi-photolysis, and bio-electrochemical systems. These methods harness natural biological pathways to convert organic waste materials and solar energy into hydrogen, offering an ecologically sound replacement to customary methods of hydrogen generation [148]. Utilizing waste

substrates and sunlight, biological hydrogen production holds significant promise for fostering a green hydrogen economy. The technologies involved in this process are illustrated in Fig. 8.

3.3.1. Biological fermenting techniques

Biological hydrogen production is an eco-friendly, green, renewable, and carbon-neutral approach that exploits microbes like algae or bacteria to manufacture dihydrogen gas. The two primary biological processes employed in hydrogen generation are light-independent fermentation and photofermentation. The process of fermentation engaged in producing hydrogen is shown in Fig. 9.

Dark fermentation takes place without the presence of light, during which microorganisms decompose organic materials to release hydrogen gas. The process follows these stages.



During this stage, one molecule of glucose undergoes biochemical breakdown, resulting in the formation of two molecules of acetic acid along with the release of two molecules of carbon dioxide.

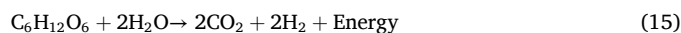


At this stage, acetic acid undergoes a biochemical conversion process that produces four molecules of hydrogen gas alongside two molecules of carbon dioxide as by-products. The overall chemical reaction representing this transformation can be summarized as follows:



A single molecule of glucose participates in a biochemical reaction that results in the formation of four hydrogen molecules other than two molecules of carbon dioxide gas. The clean hydrogen generated through this process acts as a sustainable and environmentally friendly energy carrier, offering a clean alternative to fossil fuels. Meanwhile, gaseous carbon dioxide produced can be recycled and repurposed in certain industrial uses or agricultural purposes, contributing to a more circular and resource-efficient system [151].

The light dependant photo fermentation is a biological process in which certain microorganisms harness radiant energy to transform organic compounds to gaseous hydrogen by means of a particular chemical reaction [152].



In this process, microorganisms create carbon dioxide and hydrogen gases starting from glucose and water, exploiting the energy-releasing to drive hydrogen manufacture. Commonly dark and photo fermentation strategies show tremendous potential as biological methods for generating hydrogen. The effectiveness of these techniques is impacted by a variety of factors, encompassing the specific microorganisms involved, substrates used, and the environmental conditions during operation. Scientists are actively investigating strategies to enhance these processes, aiming to improve their efficiency and reduce costs for practical application [153].

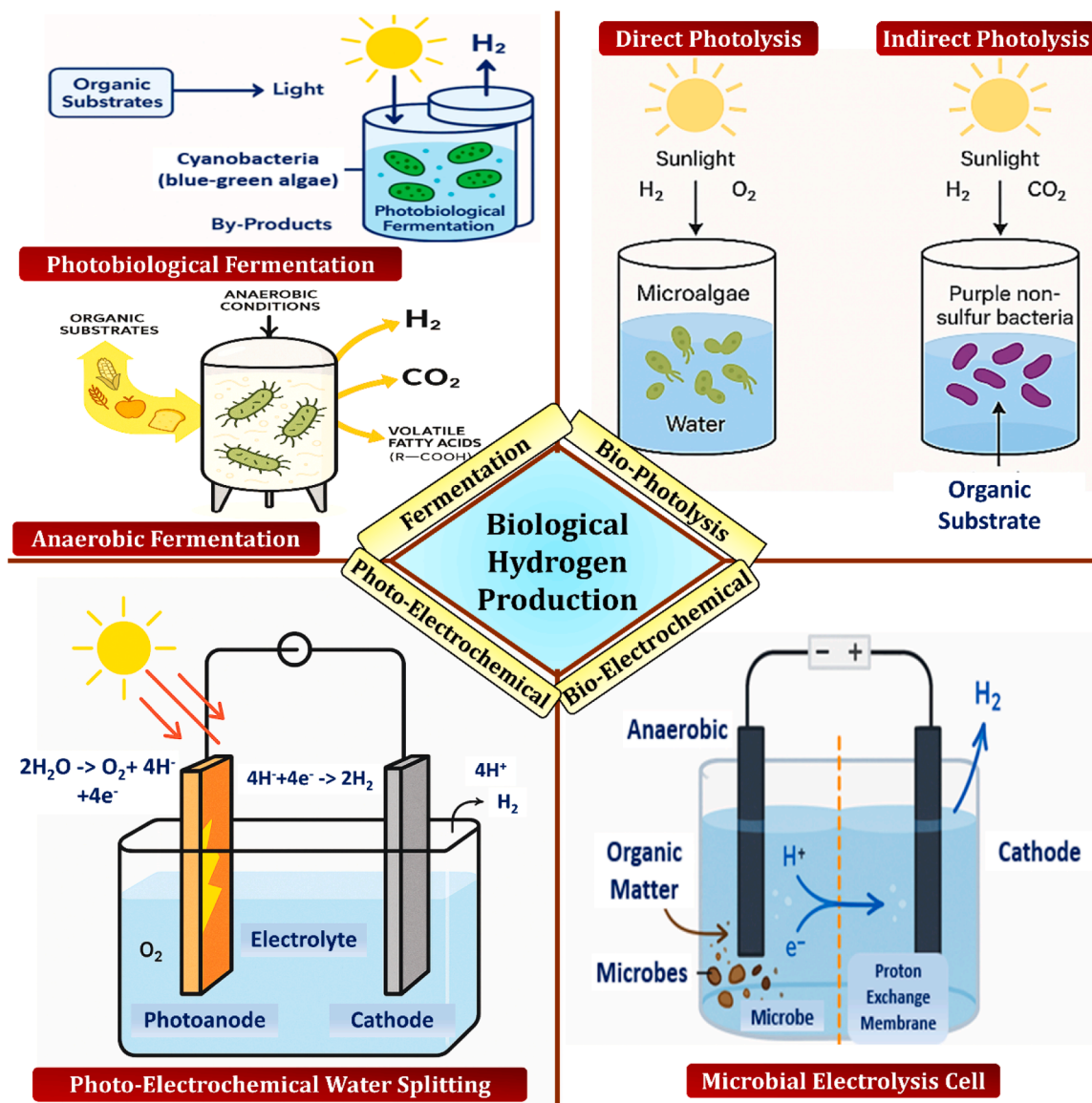


Fig. 8. Biological pathways for hydrogen generation [149].

3.3.2. Biological photolytic procedures

Biological production of dihydrogen via bio-photolytic route involves photosynthetic microorganisms like algae and cyanobacteria that utilize sunlight to divide molecules of water, releasing gaseous hydrogen and oxygen. This activity converts energy of the sun into chemical energy, enabling various organisms to carry out the water-splitting reaction compulsory for green hydrogen generation [154]. Bio-photolysis method is generally divided into two categories: direct bio-photolysis, where light energy is used by the organisms themselves to split water inside their cells, and roundabout convoluted bio-photolysis, which is a process where light first helps produce organic compounds that are later fermented by microbes to produce hydrogen [155].

Direct Biological Photolysis

This methodology employs photosynthetic microorganisms, for instance cyanobacteria or green algae to prepare gaseous hydrogen by harnessing water along with sunlight. Fig. 10 illustrates the mechanistic aspects of dihydrogen generation through this process. The underlying chemical reaction involved is as follows.

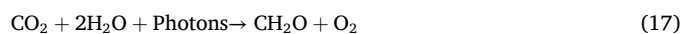


In this process, light energy drives the split in water molecules to

generate hydrogen and oxygen as products. An enzyme known as hydrogenase facilitates the conversion of protons (H^+) into molecular hydrogen (H_2). Meanwhile, oxygen is released as a by-product into the air. Although direct bio photolysis shows potential for generating hydrogen biologically, its effectiveness is limited by factors like low hydrogen output and the need for intense light to sustain manufacture [157].

Indirect Bio photolysis

In this method photosynthetic microorganisms are utilised to generate organic substances, which are subsequently converted into hydrogen gas. As illustrated in Fig. 11, this hydrogen production pathway follows a sequence of chemical reactions detailed below.



Indirect biophotolysis involves two main stages. First, photosynthetic microorganisms convert the mixture of carbon dioxide and water to organic molecules, like sacchaarides, while discharging oxygen gas, using light irradiated as an efficient energy resource. In the subsequent stage, these carbon-based molecules undergo further biological or

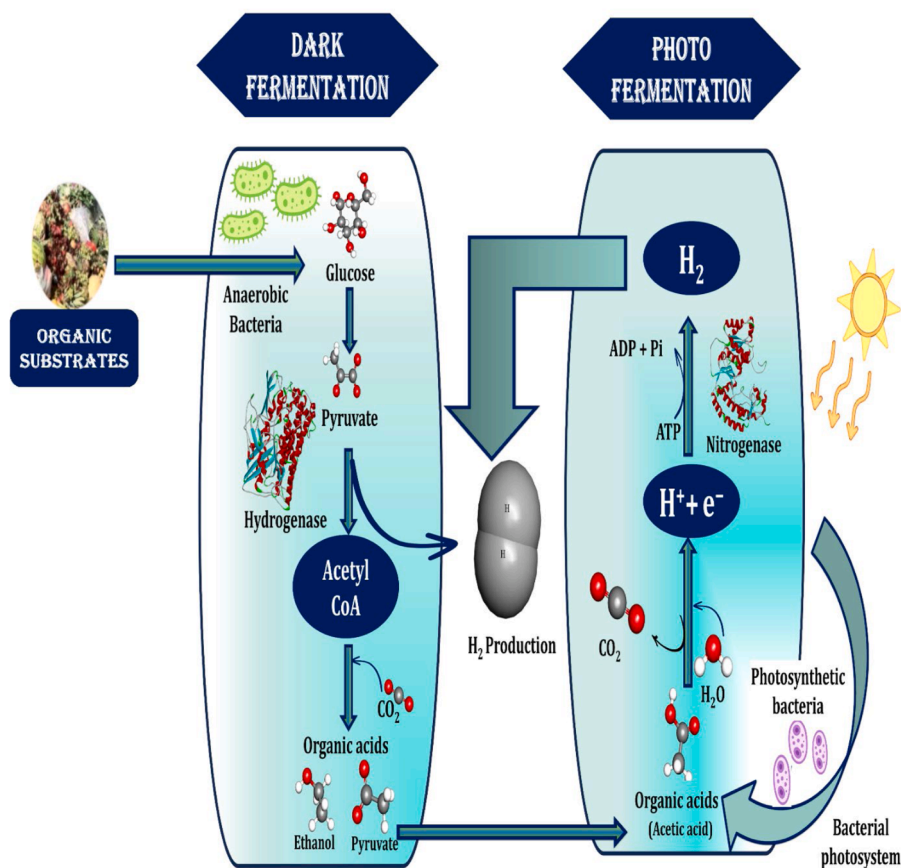


Fig. 9. Biohydrogen production through anaerobic fermentation [150].

biochemical processing to generate hydrogen gas together with carbon dioxide as some spin-off [158].

Compared to direct biophotolysis, this method offers benefits such as increased hydrogen production and the ability to function under lower light intensities. However, it also introduces additional complexity due to the need for extra sequence of steps involving treatment to take out hydrogen from intermediate organic compounds formed [159]. Biophotolysis, overall, represents a promising approach to sustainable hydrogen production. Its efficiency is influenced by various factors, including the species of microorganisms used, light availability, and operational parameters. Ongoing research aims to enhance process performance and reduce costs, thereby improving the commercial potential of this renewable energy technology [160].

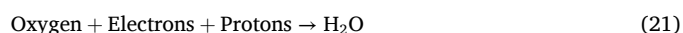
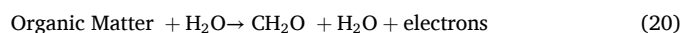
3.3.3. Bio electrochemical

Bio hydrogen manufacture using bio electrochemical approaches relies on systems like microbial electrochemical fuel cells (MFCs) in the company of biocatalyzed microbial electrolysis cells (MECs). These proficiencies harness microbial metabolic processes either to generate electrical current or to use external electrical input for hydrogen generation. In MECs, the overall process of hydrogen production can be described by a representative chemical reaction [161].



Hydrogen gas can be generated via the catalytic action as a result of hydrogenase enzymes derived from specific microbes. In the microbial fuel cells, these microscopic organisms break down organic matter in the anode chamber, leading to the release of protons along with electrons. These electrons travel via an external power circuit to the corresponding electrode and at the same time, protons migrate internally. The electrons, protons, and oxygen interact to engender water at the cathode.

This process can be summarized by a simplified overall chemical reaction [162].



Electrons generated in the system can facilitate the production of hydrogen gas when a catalyst like platinum is applied at the cathode. The complete process of hydrogen generation in microbial fuel cells might be summarized subsequently by the overall equation of the reaction.



Functioning of bioelectrochemical routines in hydrogen production is influenced by factors such as the selection of microbial communities, electrode materials, and system operating conditions. Among the different types of BES, microbial electrolysis cells (MECs) demonstrate higher efficiency for hydrogen generation compared to microbial fuel cells (MFCs), as they operate by consuming a small external voltage rather than generating electricity. These systems present an innovative route for sustainable hydrogen production, capable of processing a wide variety of organic feedstocks and converting them into hydrogen gas or electrical energy [163].

Bio based hydrogen generation represents a green and recyclable substitute to conventional methodologies, offering advantages of inexhaustible inputs coupled with the potential for carbon-neutral operation. Since the pioneering work by Klass in 1974, which utilized mixed microbial cultures for hydrogen generation, the field has witnessed significant advancements [164]. Researchers have since examined a broad spectrum of microbial species, feedstock options, and reactor designs aimed at enhancing process efficiency and scalability. More

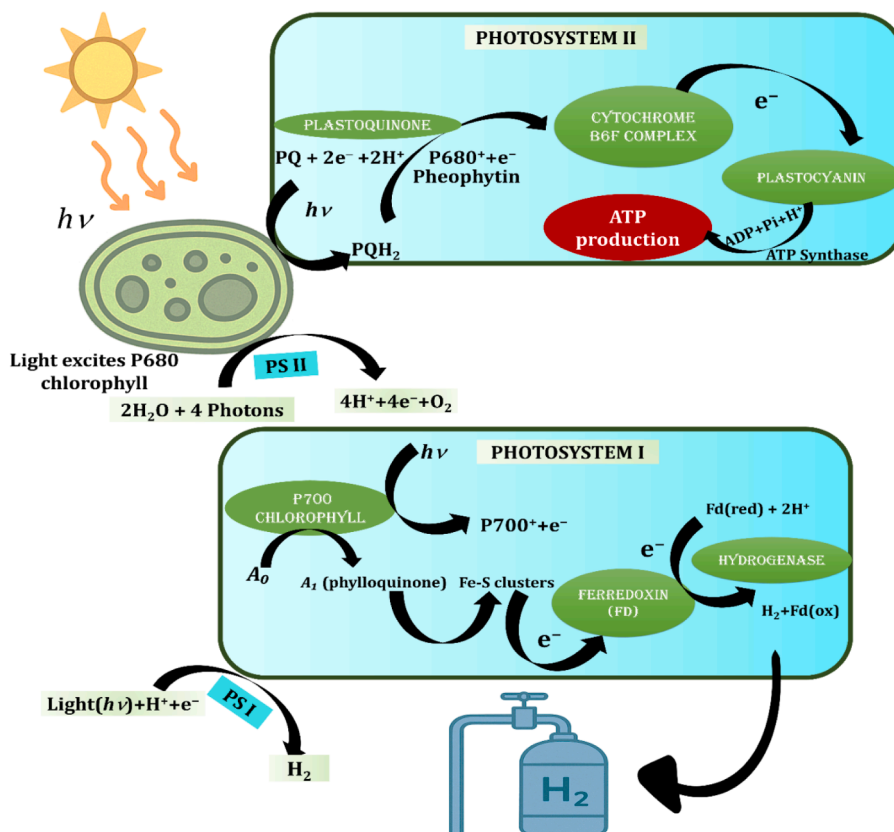


Fig. 10. Hydrogen production via direct biophotolysis: Process overview [156].

recent efforts have focused on utilizing organic refuse and debris like sugarcane pulp, spent cooking oil besides waste water solids as cost-effective and abundant substrates. The continuous evolution of this field underscores a commitment to improving the technological, economic, and environmental aspects related to biological creation of hydrogen [165].

2015 developments in biological generation of hydrogen:

In 2015, biological hydrogen production experienced a pivotal advancement, with research intensifying around improving hydrogen yields using various microbial systems. A key focus was the investigation of co-cultivation strategies, particularly involving *Clostridium* species and *Methanosarcina barkeri*. Scientists explored how the metabolic interactions between these microorganisms could lead to increased hydrogen output [166]. Concurrently, there was a surge of interest in leveraging genetic engineering to enhance microbial efficiency. Researchers such as Chandrasekhar et al. and Sekoai and Daramola turned their attention to genetically modified cyanobacteria, aiming to refine their photosynthetic mechanisms for more effective hydrogen generation [167]. These developments illustrated a significant step toward integrating modern biotechnology with conventional microbial processes, paving the way for more sustainable hydrogen production solutions.

In 2016 developments:

In 2016, extensive studies surveyed the distinctive potential of diverse microbial variants to facilitate hydrogen generation. Researchers scrutinized marine bacteria to assess their ability to produce hydrogen. Another prominent topic was the influence of bio-char on hydrogen output by *Clostridium* species. Moreover, considerable attention was given to evaluating the performance of different reactor designs in biological hydrogen production, with significant contributions from studies conducted by several research groups for instance Hallenbeck and Liu, Lu et al. and Yin and Wang [168].

In 2017 shift in focus:

In 2017, significant progress was made in developing environmentally eco-friendly and economical practices for hydrogen production. Various investigators examined the conversion of agricultural residues like by-products of sugar production into dihydrogen fuel, utilizing *Clostridium* bacteria known for their fermentative capabilities [169]. Parallel studies focused on harnessing sunlight to enhance hydrogen generation in the photosynthetic bacterium *Rhodobacter capsulatus*, tapping into its natural light-driven metabolic pathways. Furthermore, Nikolaidis and Poullikkas reviewed advancements in bioelectrochemical technologies designed to increase hydrogen yields, underscoring their potential to contribute to greener energy solutions [170].

In 2018 Continued investigations:

In 2018, research efforts focused on exploring various microbial strains to supplement both efficacy and environmental sustainability of bio based hydrogen generation. Investigations revealed that employing mixed bacterial communities could significantly enhance hydrogen output compared to single-strain cultures. Alongside this, waste cooking oil was examined as an alternative and cost-effective feedstock for hydrogen-generating microbes, presenting a way to vaporize waste materials. Moreover, microbial electrolytic cells transpired as a propitious technology, leveraging bioelectrochemical processes to produce hydrogen more sustainably. These advances were notably discussed in studies conducted by Yang and Wang, as well as Sekoai and colleagues [171].

Advances in Microbial Strains and Feedstocks in 2019

In 2019, research advanced in exploring diverse microbial strains and substrates to optimize hydrogen production. Particular attention was given to *Clostridium* species, which were studied for their ability to convert cheese whey into hydrogen, offering a way to valorize this dairy industry by-product. Additionally, the use of dark fermentation involving mixed microbial consortia gained prominence, often combined with microbial electrolysis cells to achieve dual benefits of wastewater treatment and hydrogen generation. These integrated

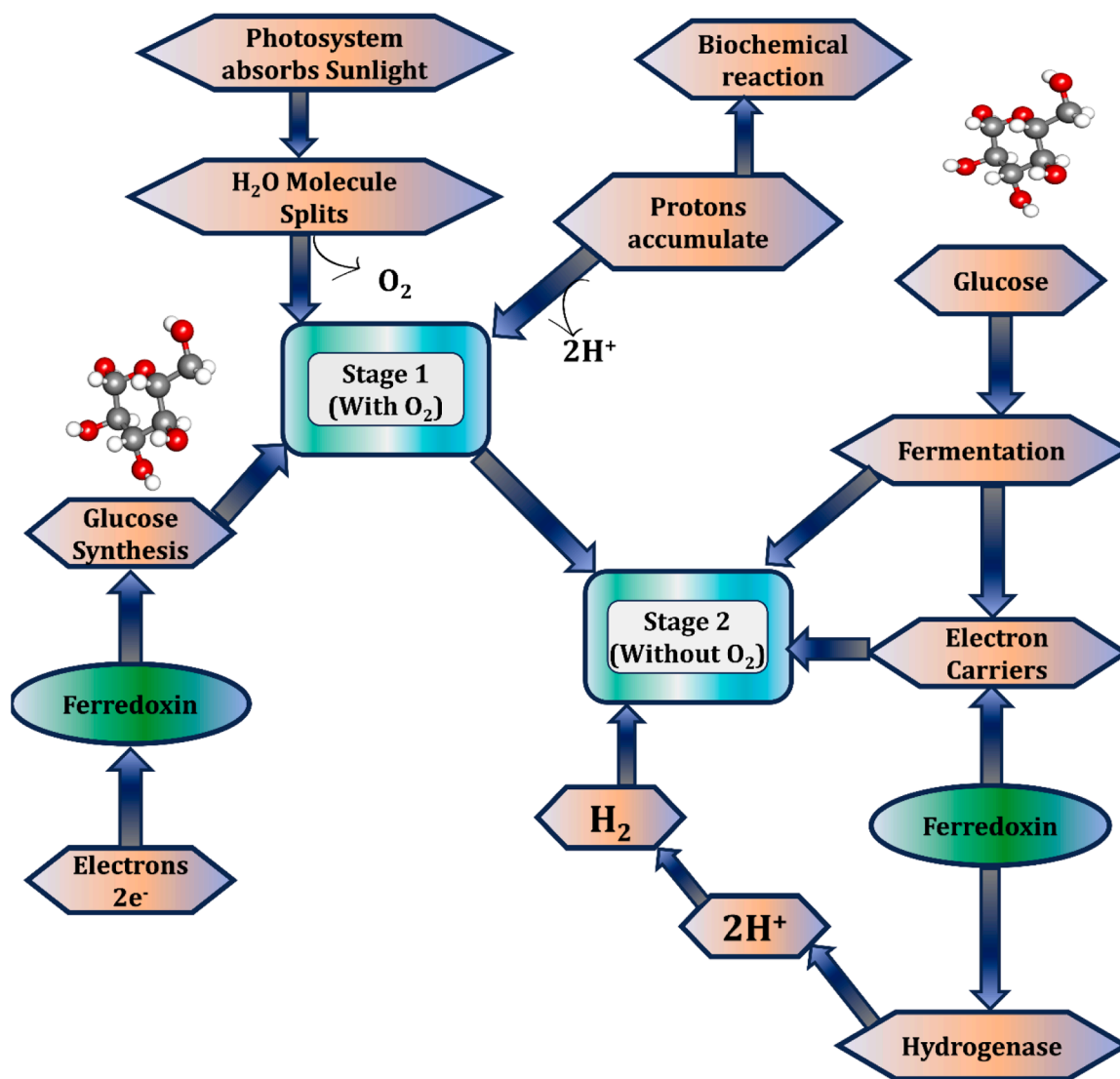


Fig. 11. Hydrogen production via Indirect biophotolysis: Mechanistic overview.

approaches, as detailed in studies by Bolatkhan and colleagues as well as Fakhimi and co-researchers, demonstrated promising potential for sustainable and efficient biohydrogen production [172].

2020 Trends in Novel Methods and Strategic Solutions

In 2020, researchers investigated innovative approaches for hydrogen production, such as utilizing inexpensive carbon sources like agricultural residues through *Clostridium* species and employing sewage sludge as a feedstock. Additionally, significant attention was given to

Table 5

Advances in biological hydrogen production technologies: A review of recent studies.

| S. No | Technology | Substrate(s) / Feedstock | Operating Conditions | Hydrogen Yield / Efficiency | Estimated Cost (\$/kg H ₂) | Refs. |
|-------|------------------------------|---|--|---|--|-------|
| 1. | Dark Fermentation | Organic waste, black liquor, wastewater | Anaerobic; 25–80 °C; pH 5.5–6.5 | 4–44 g H ₂ /kg feedstock; up to 0.63 mol H ₂ /mol glucose | 1.68–2.57 | [174] |
| 2. | Photofermentation | Organic acids, cheese whey, beer grains | Anaerobic; 30–35 °C; light intensity 6–6000 lx | 9–49 g H ₂ /kg feedstock; up to 0.63 mol H ₂ /mol glucose | 2.57–2.83 | [175] |
| 3. | Biophotolysis (Direct) | Water, glucose | Light-dependent; ambient temperature; anaerobic | 10–15 % energy efficiency; low H ₂ yield | 1.42–2.13 | [176] |
| 4. | Biophotolysis (Indirect) | Biomass-derived carbohydrates | Two-stage: photosynthesis followed by fermentation | Improved H ₂ yield over direct biophotolysis; efficiency varies | 1.20 | [177] |
| 5. | Microbial Electrolysis Cells | Organic wastewater, glycerol, ethanol | Anaerobic; external voltage >0.11 V; ambient temperature | Up to 68 % energy efficiency; 100 % faradaic efficiency | Not specified | [178] |
| 6. | Pyrolysis | Agricultural residues (e.g., wheat straw) | 400–800 °C; absence of oxygen | 25–65 g H ₂ /kg feedstock; gas yield up to 58.7 % | 1.59–2.20 | [179] |
| 7. | Gasification | Biomass (e.g., forest residues) | 700–1000 °C; presence of oxidizing agents | 40–190 g H ₂ /kg feedstock; H ₂ concentration up to 93.58 vol % | 1.77–2.05 | [180] |
| 8. | Hydrothermal Liquefaction | Wet biomass (e.g., algae) | 250–374 °C; high pressure; no drying required | 0.3–2 g H ₂ /kg feedstock; energy efficiency 85–90 % | 0.54–1.26 | [181] |

how reactor configurations influence the effectiveness of biological hydrogen generation, with notable studies accomplished by Akhlaghi and Najafpour-Darzi [173].

2021 Developments in Scaling and Commercialization

In 2021, research primarily targeted enhancing the adaptability and economic practicality of biological production of dihydrogen. One key focus was on utilizing surplus glycerol as a feedstock for generating hydrogen through synthetic microbial cocktail. Another important area involved the development of membrane-based systems aimed at boosting process efficiency, with significant advancements contributed by Zhang and colleagues. Furthermore, Table 5 presents a summary of the results achieved by varied bio based hydrogen manufacturing technologies. Biological generation of hydrogen holds promise as an environment friendly hydrogen source moving forward. Although each approach presents unique benefits and challenges, ongoing innovation and refinement will be essential to increase their overall efficiency and scalability.

3.3.4. Light-induced water splitting in photoelectrochemical systems

Photoelectrochemical splitting of water is a state-of-the-art and environmentally friendly technique for producing green hydrogen by utilizing solar energy. In this process, sunlight is transformed into electric power, which induces the formation of gaseous hydrogen and oxygen due to breakdown of molecules of water. This reaction, illustrated in the Eq. (16), stands out as a sustainable method since it generates no carbon emissions or harmful by products. Central to the system is a photoelectrodes that absorbs solar radiation, creating electron-hole pairs. The electrons drive the reduction reaction that forms hydrogen gas, while the holes promote the oxidation reaction that produces oxygen gas [182]. The combined reaction can be summarized as follows:



Photoelectrochemical water splitting presents an innovative method for generating green hydrogen by harnessing renewable energy. During this process, positive charged hydrogen ions (H^+) and negative electrons (e^-) unify to create dihydrogen gas (H_2), however oxygen gas (O_2) gets released as a result of water oxidation. Continued advancements and research in this technology could make it a vital component in moving towards a cleaner, renewable carbon neutral energy system.

3.3.5. Barriers to photoelectrochemical hydrogen generation

Although photoelectrochemical process involving split-up of water holds great potential for sustainable hydrogen generation, various obstacles must be overcome to achieve commercial feasibility.

- **Efficiency:** Enhancing the efficiency of photoelectrochemical water splitting remains a significant hurdle. Presently, the process suffers from energy losses due to factors like inefficient charge transference, surface reunification, as well as limited light absorption. To address this, scholars are investigating various supplies and innovative system designs aimed at boosting overall performance.
- **Durability:** Photoelectrodes often experience degradation when exposed to challenging environments for instance erosion, intense heat and ultraviolet emissions. This decomposition curtails the operational lifespan of electrodes furthermore negatively impacts process adeptness. Consequently, development of more robust and long-lasting photoelectrode materials is a critical focus area.
- **Cost:** The expense associated with the materials and fabrication techniques for photoelectrochemical water splitting systems poses a barrier to widespread adoption. Efforts are underway to identify cost-effective alternatives in both materials and manufacturing to enhance economic feasibility.
- **Scaling Up:** While currently confined to laboratory experiments, scaling photoelectrochemical water splitting technology to industrial levels presents considerable challenges. Creating large-scale systems

that maintain high efficiency, durability, and affordability is essential for transitioning to commercial applications.

- **System Integration:** Seamlessly incorporating photoelectrochemical means of splitting water into prevailing energy infrastructures, including the power grid and hydrogen infrastructure remains complex. Developing strategies that enable smooth, efficacious, and price-conscious integration is vital for the successful market deployment of the technology.

Photoelectrochemical water splitting holds great potential for generating green hydrogen; however, multiple obstacles must be resolved before it can become a practical and market-ready solution. Continued research and innovation are essential to tackle these issues and advance the technology toward commercial application.

3.3.6. PEC water splitting: improvement opportunities

Several strategies exist to improve green hydrogen generation via photoelectrochemical water splitting. Key focus areas for advancement include:

- **Advancement in materials:** Enhancing the efficiency and longevity of photoelectrodes is crucial for optimizing photoelectrochemical water splitting. Scientists are investigating innovative materials like metal-organic frameworks (MOFs) and perovskites, which show great potential in boosting both the performance and durability of photoelectrodes.
- **Optimizing device architecture:** Refining the design of photoelectrochemical water splitting devices can significantly improve process efficiency. Various configurations, including tandem cells and nanowire arrays, are being studied for their ability to enhance the overall energy conversion rate.
- **Combining with renewable energy sources:** Combining photoelectrochemical water splitting with replenishable energy resources for example solar and wind potential has the competence to substantially amplify the overall efficiency and performance of the power scheme. By amalgamating these innovations, surplus electricity realized as a result of intermittent renewables might be effectively utilized to drive hydrogen production, creating a more balanced and reliable energy supply while maximizing the use of clean energy inputs. This synergy allows surplus energy from these sources to be directed toward driving the water splitting reaction, thereby improving overall efficiency.
- **Mimicking natural photosynthesis:** Efforts are underway to replicate the mechanism of natural photosynthesis through artificial photosynthesis, aiming to increase the throughput besides selectivity in creation of hydrogen and oxygen via photoelectrochemical systems.
- **Scaling for commercialization:** To make this technology market-ready, development of massive-scale photoelectrochemical water split up routines is indispensable for advancing sustainable hydrogen production. To achieve this, researchers are actively investigating diverse fabrication methods and scale-up strategies aimed at lowering production costs and improving the economic viability of these technologies. Efforts focus on optimizing materials, reactor designs, and manufacturing processes to enable efficient and affordable deployment on an industrial scale.

Photoelectrochemical (PEC) water splitting holds great potential for boosting green hydrogen production. Ongoing innovation and advancing research are imperative in overcoming current challenges, making this technology economically feasible, and press forward the shift in the direction of a recyclable decarbonized energy scheme [183]. Voluminous investigations have probed new materials, including graphene-based compounds, layered double hydroxides (LDHs), and metal oxide semiconductors, to improve the efficiency and stability of PEC systems. These developments have significantly enhanced water-splitting performance, making PEC a more practical option for

large-scale hydrogen generation. Current research highlights PEC water splitting as an eco-friendly, zero-discharge process for producing green hydrogen. Progress in electrode equipment's, catalysts, coupled with tool design has fostered improved efficiency plus durability. However, challenges such as strengthening and boosting the technology and minimizing spending still need to be addressed. Moving forward, efforts have to target maximizing the efficiency of the materials in the process, advancing equipment architectures combined with developing ground-breaking methods to fortify performance, extend operational life, and facilitate broader implementation of the PEC water-separation technologies [184].

3.4. Advances in integrated hydrogen production pathways

Hybrid hydrogen production systems are gaining traction as innovative solutions to overcome the limitations of standalone methods. Configurations such as solar-thermochemical integrated with geothermal energy and electrolysis combined with carbon capture, utilization, and storage (CCUS) are emerging as viable approaches to improve operational efficiency and reduce emissions. For instance, integrating geothermal heat with solar-driven thermochemical cycles offers consistent thermal input, enhancing reactor stability and allowing continuous operation even during off-sunlight hours [185] (Grandcolas et al., 2025). Similarly, electrolysis + CCUS pathways can utilize renewable electricity while offsetting the carbon footprint of blue hydrogen routes (Li et al., 2024) [186]. Despite this promise, many reviews still lack comprehensive techno-economic evaluations and TRL-based comparisons of such hybrid models (IRENA & WTO, 2024) [187]. Therefore, future research should focus on modeling hybrid system synergies, improving integration strategies, and establishing supportive policy frameworks.

3.5. Comparative treatment of hydrogen production methods

The article presents analytically rich evaluation of green hydrogen production pathways, integrating technological breadth with empirical depth. Among the three primary routes—electrolysis, thermochemical, and biological—the discussion on electrolysis technologies is particularly robust. It includes Proton Exchange Membrane (PEM), Alkaline Water Electrolysis (AWE), and Solid Oxide Electrolysis Cells (SOECs), offering detailed comparisons in terms of energy efficiency (ranging from 60 to 85 %), operating temperature and pressure regimes, material considerations, and Levelized Cost of Hydrogen (LCOH). For instance, PEM electrolysis exhibits an efficiency of 65–82 % and LCOH ranging from \$4–6/kg H₂, while AWE offers \$2.5–4/kg H₂ with slightly lower efficiencies [52,188,189]. This level of quantitative assessment enhances the manuscript's technical rigor and relevance to both industry stakeholders and policy frameworks.

Thermochemical methods such as biomass gasification are addressed with moderate technical granularity, emphasizing their operational flexibility across diverse feedstocks and varying hydrogen yields, typically between 50 and 150 g H₂ per kg of biomass, depending on process conditions and gasification efficiency. The manuscript appropriately highlights the potential for integration with carbon capture and utilization (CCU) systems, thereby positioning thermochemical pathways as viable options for decentralized hydrogen production, particularly in biomass-rich regions.

Biological pathways, including photofermentation and dark fermentation, are succinctly but effectively covered. These processes are described in terms of their underlying bio-catalytic mechanisms, product selectivity, and yield ranges—such as 1.2–3.0 mol H₂/mol substrate for photofermentation [190]. Though these technologies currently exhibit lower Technology Readiness Levels (TRLs) and face scale-up challenges, their inclusion reflects the broader landscape of innovation in sustainable hydrogen production.

Overall, the manuscript aligns the level of technical detail with the

maturity and deployment potential of each pathway, maintaining clarity without oversimplification. This comparative framework, supported by empirical benchmarks such as efficiency (%), yield (g H₂/kg or mol/mol), energy consumption (kWh/kg H₂), LCOH, and TRLs, enables comprehensive techno-economic evaluations. It also facilitates informed decision-making for future R&D, infrastructure development, and policy implementation. Such a balanced and data-driven approach fosters a holistic understanding of green hydrogen technologies and supports strategic prioritization in global decarbonization efforts.

3.6. Environmental sustainability and life cycle considerations of hydrogen production pathways

While this review outlines the technical potential and economic aspects of diverse green hydrogen production methods, a deeper assessment of their environmental sustainability is necessary for a holistic evaluation. Life Cycle Assessment (LCA), which captures cradle-to-grave environmental impacts, remains underutilized in comparative analyses, despite being a vital tool for understanding the full implications of these technologies.

Electrolysis-based methods, such as Proton Exchange Membrane (PEM) and Alkaline Water Electrolysis (AWE), are widely acknowledged for their synergy with renewable electricity sources. However, key LCA indicators—such as Global Warming Potential (GWP), Energy Return on Energy Invested (EROEI), water footprint, and material intensity—are seldom systematically reported. This limits the ability to compare these technologies on a robust environmental basis, especially when scaling to industrial levels.

The lack of lifecycle consideration is even more pronounced in the context of emerging biological hydrogen production pathways, including dark fermentation and microbial electrolysis cells (MECs). These technologies present a dual advantage of hydrogen generation and organic waste valorization. However, they may simultaneously introduce environmental burdens such as methane leakage, nitrate-rich effluent streams, and dependence on feedstocks that carry high upstream emissions. These trade-offs are rarely quantified in current literature, which often emphasizes yield and conversion metrics without equivalent environmental scrutiny.

Photoelectrochemical (PEC) routes, though promising in terms of solar-to-hydrogen conversion efficiency, pose additional sustainability concerns. Materials such as cadmium selenide (CdSe) and gallium arsenide (GaAs), commonly used in PEC cells, are associated with high toxicity, resource criticality, and end-of-life disposal challenges. Without LCA data that account for these material flows and long-term ecological implications, the perceived advantages of PEC technologies risk being overstated.

A recent study by Weidner et al. (2023) underscores the importance of prospective LCAs in evaluating the environmental sustainability of large-scale hydrogen production [191]. Their work highlights how incorporating metrics such as emissions per kg H₂ produced, land use intensity, human and ecological toxicity potential, and material circularity can reveal critical trade-offs and inform more balanced technology comparisons. Such insights are essential for guiding policy development, funding allocation, and technology adoption strategies.

Incorporating rigorous LCA data into future techno-economic assessments will help bridge the gap between theoretical potential and practical sustainability. It will also strengthen the credibility of emerging hydrogen technologies in climate policy dialogues, ensure responsible scaling, and support global decarbonization goals.

4. Cutting-edge recyclable green hydrogen technologies

4.1. Advances in electrolytic process for hydrogen production

Electrolysis technology is rapidly evolving, with Solid Oxide Electrolysis (SOE) along with Proton Exchange Membrane (PEM) emerging

as leading methods. While these advanced technologies typically incur higher costs than conventional alkaline electrolysis, they provide greater efficiency. PEM electrolyzers operate at higher current densities, allowing for more compact designs without sacrificing hydrogen output, making them well-suited for commercial and industrial applications. Industry leaders for instance, Air Liquide besides Siemens Energy are at the foreground of PEM system development. For instance, Siemens' Silyzer series achieves efficiencies ranging from 60 % to 70 %, with continuous improvements underway. 'A' Series electrolyzers which are atmospheric alkaline electrolyzers from Nel Hydrogen address far-reaching manufacturing requirements, producing dihydrogen with 999.9 fineness besides reaching efficiencies virtually 90 % under optimal conditions [192].

High-temperature electrolysis, especially Solid Oxide Electrolysis (SOE), offers significant advantages by utilizing heat to lessen the volume of electrical power necessitated to split water molecules, thus augmenting the overall throughput of the routine. SOE procedures achieve efficiencies nearing 90 %. For instance, Sunfire GmbH, a German conglomerate, has employed SOEC (Solid Oxide Electrolyzer Cell) technology at Salzgitter Flachstahl to generate cleaner green hydrogen intended for steel making. Moreover, amalgamating electrolytic process with recyclable power resources (solar and wind energy) is increasingly favoured as a strategy to minimize both carbon emissions and production costs of green hydrogen. ITM Power has successfully combined electrolyzers with renewable energy installations to improve hydrogen output, while Danish company Ørsted employs offshore wind power to operate their electrolysis plants, further reducing environmental impacts [193].

4.2. Enhancing efficiency and lowering costs

Increasing production capacity is indispensable for boosting the cost-effectiveness and marketability of renewable hydrogen in the market, as wide-ranging global-scale projects characteristically benefit from cost savings by realizing cost savings from scale. For specimen, joint effort amongst Ørsted and ITM Power to develop 100 MW cleaner green hydrogen plant in the British Isles aims to drive down manufacture expenses thanks to its considerable scale. Likewise, Nel Hydrogen is expanding its production capabilities by constructing a novel water electrolysis plant on Norwegian soil with an annual capacity of approximately 360 MW. Its modular construction enables easy future scaling, further boosting cost-effectiveness through flexible manufacturing. These efforts highlight the industry's dedication to reducing the cost of green hydrogen and promoting its role as a practical energy solution [194].

Advances in electrolyzer technology play a key role in reducing costs and improving efficiency. The ALISE project—a collaboration between Siemens Energy, Iberdrola, and Vestas—is working on an advanced alkaline electrolyzer designed to achieve energy efficiency greater than 72 % and a lifespan surpassing 90,000 h. These enhancements are crucial for boosting the affordability and durability of green hydrogen production equipment. Another major cost driver is the use of expensive metals like platinum and iridium in electrolyzers. To combat this, researchers and industry players are investigating more affordable alternatives. For instance, a group at University of Arkansas ensured the creation of an innovative catalyst for usage in PEM water electrolyzers which diminishes quantity of platinum, proffering promising cost savings. Proton Energy Systems is also developing electrolyzers that incorporate less costly materials, further aiding efforts to cut expenses. These innovations underscore the ongoing obligation of transforming renewable green hydrogen more economically feasible as well as widely accessible as a clean energy remedy [195].

4.3. Growth in manufacture capacity in addition economic practicality

The economic feasibility of recyclable green hydrogen as a fuel

hinges on producing it on a large scale at affordable costs. Consequently, numerous significant initiatives have emerged to expand green hydrogen production capacity.

Scaling Up Electrolyzer Projects: To lower hydrogen production costs by leveraging economies of scale, leading energy firms are making significant investments in large-scale electrolyzer projects. For example, Ørsted accompanied by ITM Power are working together at a 100MW level electrolyzer plant in the UK, which stands as one of the largest efforts aimed at producing cost-effective green hydrogen. Additionally, BP and Ørsted are partnering on a 50MW green and clean hydrogen initiative in the region of Lingen in Germany, intended to replace conventional grey hydrogen used in refinery operations, highlighting a growing transition toward cleaner hydrogen solutions [196].

Strategic Infrastructure Expansion for Green Hydrogen: National governments and regional authorities are rolling out ambitious plans to establish the infrastructure required for widespread green hydrogen production, a crucial step to ensure its commercial viability. Launched in mid-2020, the European Union's Green Hydrogen Strategy aims to deploy a minimum of 6000 megawatts of replenishable hydrogen electrolyzers throughout its member states and generate as good as a million metric tons of sustainable hydrogen before the year 2024. Concurrently, the Asian Renewable Energy Hub of Australia intends to create a massive ammonia in addition to cleaner green hydrogen creating complex, utilizing as far as 26 GW of wind and solar power, with a major share of the output designated for export [197].

Hydrogen's inherently low volumetric energy density necessitates energy-intensive transport options such as compression (350–700 bar), liquefaction (−253 °C), or chemical conversion (e.g., ammonia, LOHCs), each adding cost and energy penalties [52] (IEA, 2022). Hydrogen embrittlement—a process where hydrogen weakens pipeline metals—raises safety and durability issues, yet most reviews give minimal attention to underlying materials science, integrity testing, or long-term maintenance strategies. Although repurposing natural gas pipelines is often proposed as a cost-effective option, few assessments thoroughly evaluate material compatibility (e.g., steel grade performance), pressure-dependent leakage risks, or the economics of retrofitting versus new builds.

Similarly, hydrogen storage—critical for grid balancing and seasonal energy buffering—is generally addressed in broad terms. There is a lack of comparative analysis across geological storage options such as salt caverns, aquifers, and depleted hydrocarbon fields, especially with respect to geological suitability, permitting, and cost variations by region [198]. On the regulatory side, while hydrogen certification and guarantees of origin are frequently mentioned, few reviews explore challenges in lifecycle emissions accounting, the harmonization of certification standards, or regulatory frameworks such as the EU's RED II, which influence green hydrogen eligibility and subsidy access.

To strengthen future assessments, reviews should incorporate techno-economic models of hydrogen logistics, durability testing data for transport materials, and geospatial analysis of storage infrastructure potential. In parallel, policy discussions must delve deeper into evolving certification systems, cross-border regulatory challenges, and infrastructure investment needs to ensure green hydrogen can scale sustainably and globally.

Rising Investments in renewable Green Hydrogen Technologies: The progress in making of green hydrogen is impelled by increased funding directed towards companies focused on this sector. For instance, Nel Hydrogen has recently expanded its manufacturing capabilities by inaugurating an innovative facility within Norway. These budgetary obligations are decisive for cultivating modernism, boosting production efficiency besides lowering costs in the advancement of green hydrogen technologies [199].

5. Hydrogen manufacture cost

Hydrogen can be generated through several different techniques,

each carrying distinct cost implications. Over time, the expenses linked to producing hydrogen have steadily decreased, driven by improvements in technology, larger-scale operations, and a growing focus on greener production methods. As hydrogen becomes more widely recognized as a sustainable energy alternative, ongoing reductions in production costs are expected, enhancing its appeal for various uses such as transportation, manufacturing, and storing energy.

5.1. Present costs of hydrogen production

The expenditure for producing clean hydrogen is a crucial element swaying its broad implementation. Production expenses differ considerably depending on the method used, with each technique having distinct financial implications. According to the IEA report from 2022, Table 6 details the cost ranges for various hydrogen production methods from 2010 to 2021. In 2010, the cost of Grey hydrogen generated from methane gas using the steam methane reforming (SMR) procedure without employing carbon capture and utilization (CCU) was estimated between \$1.5 and \$2.5 per kilogram [200]. Blue hydrogen, generated through SMR process but with CCU to lower discharges, required prices fluctuating between \$1.5 to \$3.0 per kilogram. Yellow hydrogen, made by partially oxidizing natural gas along with CCU, was pricier, and prices are sandwiched between \$6.0 and \$11.0 per kilogram. Green hydrogen, manufactured by means of electrolysis of water driven by recyclable energy resources like solar energy and wind, initially have an expenditure between \$5.00 and \$10.00 per kilogram [201]. Over the next ten years, improvements in technology, growing demand for clean energy, and expanded production capacity contributed to substantial price drops. By 2021, the cost of various hydrogen types had decreased: Grey hydrogen ranged from \$0.60 to \$1.20 per kilogram, Blue hydrogen between \$0.60 and \$1.30 per kilogram, Yellow hydrogen from \$1.50 to \$4.50 per kilogram, and Green hydrogen fell to a range of \$1.50 to \$4.00 per kilogram [202]. These cutbacks were driven principally by better manufacturing methods, cost advantage besides increased integration of inexhaustible energy in the domain of green hydrogen manufacturing. It is imperative to recognize that the costs can vary depending on local energy markets, technological progress, and policy frameworks. As the energy sector shifts toward lower emissions, hydrogen's role is expected to grow, with further cost reductions likely as production technologies continue to advance and scale up.

5.2. Future trends in costs of green hydrogen production

The price tag of producing clean recyclable hydrogen is expected to drop substantially over the next few decades, empowered by improvements in technology, increased production capacity, and expanded

Table 6
Hydrogen production cost year wise (\$/kg).

| S. No | Year | Grey Hydrogen | Blue Hydrogen | Yellow Hydrogen | Green Hydrogen |
|-------|-------------|---------------|---------------|-----------------|----------------|
| 1. | 2010 | 1.00–2.00 | N/A | N/A | 10.00–15.00 |
| 2. | 2011 | 1.00–2.00 | N/A | N/A | 9.50–14.00 |
| 3. | 2012 | 1.00–2.00 | N/A | N/A | 9.00–13.00 |
| 4. | 2013 | 1.00–2.00 | N/A | N/A | 8.50–12.00 |
| 5. | 2014 | 1.00–2.00 | N/A | N/A | 8.00–11.00 |
| 6. | 2015 | 1.00–2.00 | N/A | N/A | 7.50–10.00 |
| 7. | 2016 | 1.00–2.00 | N/A | N/A | 7.00–9.00 |
| 8. | 2017 | 1.00–2.00 | N/A | N/A | 6.50–8.00 |
| 9. | 2018 | 1.00–2.00 | N/A | N/A | 6.00–7.00 |
| 10. | 2019 | 1.00–2.00 | N/A | N/A | 5.50–6.50 |
| 11. | 2020 | 1.0 – 2.0 | 1.5 – 2.5 | 2.0 – 3.5 | 3.5 – 6.0 |
| 12. | 2022 | 1.2 – 2.2 | 1.5 – 2.8 | 1.8 – 3.2 | 3.0 – 5.5 |
| 13. | 2023 | 1.3 – 2.3 | 1.6 – 2.6 | 1.7 – 3.0 | 2.5 – 5.0 |
| 14. | 2024 | 1.3 – 2.4 | 1.6 – 2.5 | 1.6 – 2.8 | 2.0 – 4.5 |
| 15. | 2025 (Est.) | 1.3 – 2.5 | 1.5 – 2.4 | 1.5 – 2.6 | 1.8 – 4.0 |

access to low-cost renewable energy sources. Projections for 2030 indicate that the price could fall below \$2 per kilogram, with some estimates suggesting it may even reach \$1 per kilogram. Various factors will affect these cost developments, such as the accessibility and cost of recyclable power, enhancements in electrolyzer technology, and policy amendments that could accelerate or hamper the embracing of green hydrogen. Continuous innovation in electrolyzer efficiency and reductions in the cost of renewable energy generation will be crucial in lowering production costs. As renewable energy becomes more economical and efficient, the cost of this essential input will play a crucial role in lowering production expenses for green hydrogen. Additionally, scaling up electrolyzer manufacturing and technology maturation is expected to reduce capital costs, further driving down prices [203].

Nevertheless, these cost estimates involve uncertainties, including potential unexpected technological advances or setbacks, variations in the cost of renewable energy and electrolyzers, shifts in government policies, and changing hydrogen market demand. Researchers, energy experts, and policymakers continuously evaluate these variables to update projections and support informed decisions regarding hydrogen adoption. At the 2050 milestone, the price of renewable hydrogen produced via inexhaustible - steered electrolytic process is projected to drop significantly—feasibly by up to 85 %—and could fall below \$1 per kilogram globally. Various organizations have issued forecasts consistent with this expectation. For instance, International Renewable Energy Agency (IRENA) projects the recyclable hydrogen costs to range between \$1.5 and \$5 per kilogram by 2030. Hydrogen Council forecasts a cost diminished by fifty percent by the year 2030, propelled mainly by lower sustainable energy prices in addition to scaled-up manufacture. Likewise, hydrogen strategy put forward by European Commission envisions green hydrogen becoming competitive with fossil fuel-based alternatives within the next ten years, although competitiveness will differ across regions and uses. Supporting these developments, companies such as ITM Power, Nel Hydrogen, and Siemens Energy are investing in improving electrolyzer efficiency and reducing production expenses. Meanwhile, government initiatives and regional programs are financing large-scale infrastructure projects to augment the cost-effectiveness and growth of cleaner green hydrogen production [204].

5.3. Levelized cost of hydrogen (LCOH) and economic competitiveness

The robustness of techno-economic comparisons for hydrogen production hinges on the use of accurate, recent, and region-specific Levelized Cost of Hydrogen (LCOH) data. Reports from authoritative agencies such as the International Renewable Energy Agency (IRENA), the International Energy Agency (IEA), and the Hydrogen Council offer credible benchmarks. IRENA's 2024 assessment projects that the LCOH for green hydrogen could fall to \$0.8–\$1.6/kg in regions with abundant solar and wind resources by 2030 [188]. The IEA's 2023 Global Hydrogen Review supports this outlook, estimating LCOH values between \$1.5 and \$4.0/kg under current conditions and forecasting costs below \$2/kg by 2030, assuming technological improvements and policy incentives [205]. Similarly, the Hydrogen Council, in collaboration with McKinsey, estimates green hydrogen LCOH values of \$1.0–\$2.0/kg by 2030, particularly under large-scale and policy-driven deployment scenarios [206]. These up-to-date figures are critical in benchmarking green hydrogen against blue hydrogen (natural gas with carbon capture, ~\$1.2–\$2.6/kg) and grey hydrogen (without capture, typically cheaper but non-sustainable). Reviews that rely on outdated data or ignore regional electricity price variation and electrolyzer capacity utilization risk making misleading feasibility claims. Inclusion of sensitivity analysis and regionally disaggregated LCOH figures enhances decision-making for technology choice and policy formulation (Table 7).

Table 7
Comparative LCOH Estimates by Source and Technology (2023–2024).

| Source | Technology | Estimated LCOH (USD/kg H ₂) | Time Frame | Key Notes | Refs. |
|------------------------------------|--------------------------|---|-----------------------------|--|-------|
| IRENA (2024) | Green (Electrolysis) | 0.8 – 1.6 | 2030 | Based on low-cost renewable electricity in Chile, Morocco, Australia | [188] |
| IEA (2023) | Green (Electrolysis) | 1.5 – 4.0 | Present 2030 (target) | Varies by electricity price and electrolyzer efficiency With CAPEX/OPEX reductions and high utilization | [205] |
| IEA (2023) | Green (Electrolysis) | <2.0 | | | [205] |
| Hydrogen Council + McKinsey (2023) | Green (Electrolysis) | 1.0 – 2.0 | 2030 | Assumes scale-up, policy incentives, infrastructure support | [206] |
| IEA (2023) | Blue (Natural Gas + CCS) | 1.2 – 2.6 | Present | Cost sensitive to gas price and CO ₂ storage economics | [205] |

6. Countries pioneering large-scale green hydrogen operation

With the emergent global prominence on eco-friendly energy, many nations are launching ambitious programs to scale up clean and green hydrogen production. For instance, Australia which is capitalizing on its abundant recyclable energy sources, is striving to become a leading international producer of hydrogen owing to its exclusive National Hydrogen Strategy. A key focus of this strategy is the “H₂ under \$2” initiative, which aims to render dihydrogen economically affordable along with traditional power resources [207]. China, which is the largest emitter of greenhouse gases, is incorporating clean hydrogen into its power grid by way of system by building large electrolytic process facilities besides promoting the utilisation of hydrogen fuel cell automobiles. In the intervening time, Germany has apportioned €9 billion toward its National Hydrogen Strategy, with plans to significantly boost the electrolysis capability within the next 15 years and develop world-wide collaborations to safeguard reliable hydrogen supply network [208].

In the Hydrogen Program of United States Department of Energy, focus is on improving hydrogen production efficiency and expanding infrastructure. States such as California are at the forefront, working to increase the availability of hydrogen refuelling stations and enhance public access. Meanwhile, Japan with South Korea happen to be key participants in the shift toward clean hydrogen. For the moment, Japan’s Basic Hydrogen Strategy envisions creating a “Hydrogen Society” by means of expanding hydrogen driven applications along with encouraging the use of vehicles involving fuel cells. South Korea has visualized its Hydrogen Economy Roadmap targeted to boost fuel cell vehicle manufacturing and production, with the goal of significantly cutting fossil fuel imports and establishing the nation as a hydrogen technology leader by 2040 [209]. Together, these national plans demonstrate a worldwide obligation in the direction of fusing green hydrogen with economies and power systems as a foundation stone of a reusable and renewable, low-carbon prospect. Table 8 provides an overview of the policies these countries have implemented to promote green hydrogen growth [210].

Fig. 12 presents the anticipated expansion of green hydrogen production capacity across six leading countries: Japan, China, South Korea, Australia, United States and Germany. The projections reveal a substantial rise in capacity over the coming decades, underscoring a worldwide transition to cleaner energy sources and significant investments in green hydrogen technologies. By 2050, Australia aims to reach 25 million metric tons (MMT), while China targets 90 gigawatts (GW). Germany plans to achieve 75 GW, the United States is aiming for 110 gigawatts, Japan and South Korea strategize and set their sight on 80 and 50 GW respectively. These goals highlight each country’s dedication to embedding green hydrogen in their energy mix, motivated by growing obligation aimed at sustainable energy, advancements in inexhaustible innovation, enabling policies coupled with commitments to accomplish their objectives [212].

National policies are increasingly aimed at growing green hydrogen infrastructure and production capacity. Germany is focusing on boosting

investments in electrolysis plants, whereas Australia is working to establish itself as a leading hydrogen producer globally. Likewise, South Korea, China, United States and Japan have initiated programs to develop and reinforce their domestic hydrogen industries. On an international level, collaboration is key, with organizations for instance Hydrogen Council, Clean Energy Ministerial Hydrogen Proposal, and the renewable hydrogen policy of the European Commission promoting joint efforts. Despite these advances, challenges remain, including regulatory fragmentation, infrastructure readiness, market acceptance, inconsistencies in reusable power resource and cost issues—each requiring ongoing innovation and supportive policies [213].

The guidelines, protocols, and enticements of the Government perform a crucial role in developing green hydrogen sector. These measures include financial aid programs, carbon pricing mechanisms, regulatory frameworks, public procurement strategies, infrastructure investments, funding for research, workforce development, and international cooperation. For instance, the united states runs dedicated hydrogen research initiatives, while the european union operates an emissions trading system that impacts hydrogen markets [214]. As technologies related to green hydrogen advance, flexible and responsive policies will be vital to support sustainable expansion, delivering both environmental and economic advantages. Partnership amongst state and private sectors is also important for risk management, infrastructure financing, and market growth. Notable examples of collaboration in the green hydrogen sector include the important projects of common European interest (IPCEI) commenced by the European Commission for clean hydrogen, the US H₂@Scale proposal, combined with Hydrogen Energy Supply Chain project by Australia. These partnerships consolidate expertise, share costs and also speed up innovation. By encouraging cooperation among governments, industry players, and research organizations, they significantly contribute to the global advancement and wider adoption of green hydrogen technologies [215].

7. Challenges facing implementation

7.1. Economic barriers and production expenses

The production of green hydrogen faces significant obstacles, primarily due to its high costs, which currently make it less economically viable compared to traditional “grey” hydrogen derived from fossil fuels. One of the main cost drivers is the expensive electrolyzers necessitated to detach water into hydrogen along with oxygen. Although their prices are expected to decrease as manufacturing scales up, these devices remain a substantial barrier to widespread adoption. Furthermore, the price of recyclable hydrogen is heavily influenced by electrical energy costs, which in many regions surpass the price of natural gas, especially where fossil fuel supplies are plentiful and inexpensive [216].

Achieving economic competitiveness is another major challenge. For green hydrogen to gain market traction, it must compete financially with both other energy sources and hydrogen produced through conventional means [217]. Estimates indicate that price parity with grey hydrogen could be reached around 2030, contingent on advances in

Table 8
Policy frameworks supporting green hydrogen energy.

| S. No | Country | Policy Name & Year | Key Targets & Initiatives | Definition of Green Hydrogen |
|-------|----------------|---|--|---|
| 1. | China | Medium and Long-Term Hydrogen Industry Plan (2021–2035) | Produce 100,000–200,000 tons of renewable-based hydrogen annually by 2025 - Deploy 50,000 hydrogen fuel vehicles by 2025 - Focus on renewable energy-based hydrogen production and limit fossil fuel-based hydrogen | Not explicitly defined; emphasis on clean, low-carbon, and low-cost hydrogen production systems |
| 2. | India | National Green Hydrogen Mission (2022) | Produce 5 million metric tons (MMT) of green hydrogen annually by 2030 - Add 125 GW of renewable energy capacity - Implement mandates for green hydrogen use in refineries, fertilizers, and city gas systems - Allocate \$2.4 billion for initial funding | Emissions-based standard: <2 kg CO ₂ per kg of hydrogen produced |
| 3. | Japan | Basic Hydrogen Strategy (2017, updated 2023) | Increase hydrogen supply to 3 MMT by 2030 and 20 MMT by 2050 - Attract over \$97 billion in investments by 2038 - Expand domestic electrolyzer capacity to 15 GW by 2030 - Target 800,000 fuel cell vehicles (FCVs) and 900 hydrogen refueling stations by 2030 | Clean hydrogen defined as having well-to-gate emissions of 3.4 kg CO ₂ per kg of hydrogen produced |
| 4. | South Korea | Hydrogen Economy Roadmap (2019) | Produce 6.2 million FCVs and establish 1200 refueling stations by 2040 - Deploy 15 GW of hydrogen fuel cells for power generation by 2040 - Implement clean hydrogen certification with a threshold of 4 kg CO ₂ per kg of hydrogen | Clean hydrogen certification threshold set at 4 kg CO ₂ per kg of hydrogen produced |
| 5. | European Union | EU Hydrogen Strategy (2020) | Install 40 GW of renewable hydrogen electrolyzer capacity by 2030 - Produce up to 10 MMT of renewable hydrogen by 2030 - Launch the European Clean Hydrogen Alliance to support investment and deployment | Focus on emissions-free green hydrogen; specific definitions may vary by member state |
| 6. | Germany | National Hydrogen Strategy (2020) | Invest €9 billion to construct 5 GW of electrolyzer capacity by 2030 | Aligns with EU definitions; emphasis on green hydrogen |

Table 8 (continued)

| S. No | Country | Policy Name & Year | Key Targets & Initiatives | Definition of Green Hydrogen |
|-------|----------------------|---|--|---|
| 7. | United States | Hydrogen Earth shot Initiative (2021) | Reduce cost of clean hydrogen to \$1 per 1 kg in 1 decade ("1–1" goal) - Allocate \$9.5 billion for clean hydrogen development under the Infrastructure Investment and Jobs Act | produced from renewable energy sources Emphasis on clean hydrogen; specific definitions may vary by project and funding source |
| 8. | United Arab Emirates | National Hydrogen Strategy (2023) | Produce 1.4 MMT of hydrogen annually by 2031 and 15 MMT by 2050 - Establish hydrogen research and development centers and fueling stations by 2030 | Focus on low-carbon hydrogen; specific definitions to be established |
| 9. | Oman | Hydrogen Oman (Hydrom) Agreements (2023) | Develop green hydrogen projects worth over \$20 billion - Target annual production of 0.5 MMT with 12 GW of renewable energy capacity | Emphasis on green hydrogen produced from renewable energy sources |
| 10. | Egypt | Green Hydrogen MOUs (2024) | Attract \$40 billion in investments for green hydrogen and renewable technology - Develop projects in the Suez Canal Economic Zone | Emphasis on green hydrogen; specific definitions to be established |
| 11. | Scotland (UK) | Hydrogen Policy Statement (2020) | Generate 5 GW of clean and low-carbon hydrogen by 2030 - Pledge £100 million for the hydrogen industry during 2021–2026 | Focus on clean and low-carbon hydrogen; specific definitions may vary |
| 12. | South Africa | Green Transport Strategy (2018) | Establish a Platinum Valley and develop an integrated hydrogen ecosystem - Promote the use of fuel cell vehicles | Emphasis on green hydrogen; specific definitions to be established |
| 13. | Turkey | National Hydrogen Strategy and Roadmap (2023) | Reduce green hydrogen cost to \$2.40/kg by 2035 and below \$1.20/kg by 2053 - Achieve 70 GW of installed electrolyzer capacity by 2053 | Focus on green hydrogen; specific definitions to be established |

technology, economies of scale, and fluctuations in energy prices. Furthermore, without robust greenhouse gas pricing mechanisms, the ecological advantages of clean hydrogen are not monetarily recognized, hindering its ability to contend with hydrocarbon-based options. Progress in scientific innovation aimed at reduced production costs, combined with policies that appropriately account for environmental benefits, will be critical to overcoming these barriers. While significant strides have been made, there remain considerable challenges in front of green hydrogen which can be generated affordably and at large-scale [218].

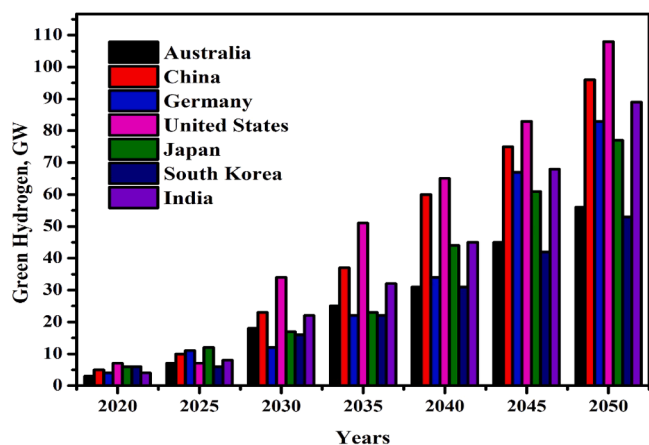


Fig. 12. Future pathways for green hydrogen generation: Trends and projections [211].

7.2. Obligations for infrastructure and assimilation in green hydrogen production

Adapting the current natural gas infrastructure for green hydrogen use presents significant obstacles. One major issue is hydrogen embrittlement, which weakens the metal components of existing pipelines, compromising their structural integrity. Additionally, hydrogen's extremely small molecular size enables it to escape through seals that effectively contain larger gases like methane. Another concern is low volumetric energy density of dihydrogen contrasted with natural gas, meaning it occupies more space to store the same energy. To address this, hydrogen must be stored either under high pressure, at cryogenic temperatures, or chemically bonded within substances for instance metal hydrides. Every single storage technique, however, poses quite a few challenges related to cost, efficiency, and safety. Transportation also requires specialized solutions: because of hydrogen's low energy density and its high flammability risk, dedicated pipelines and transport vehicles must be designed, requiring considerable investment [219].

Integrating clean and green hydrogen into current power and industrialized systems involves numerous as well as convoluted hurdles. Electrolytic hydrogen production can support electrical grid stability by operating flexibly—producing hydrogen when there is surplus renewable electricity and pausing during shortages. Achieving this, however, depends on sophisticated control systems capable of balancing supply and demand while optimizing electrolyzer performance [220]. On the demand side, widespread adoption is complicated because most existing equipment and processes are optimized for conventional fuels. Industries such as steel manufacturing hold promise for green hydrogen use but require technological advancements and retrofitting of existing infrastructure. Moreover, regulatory frameworks remain underdeveloped, as comprehensive safety standards, certification processes, and codes specifically tailored to hydrogen applications are largely absent. Overcoming these technical, economic, and regulatory challenges is essential to unlocking green hydrogen's full potential in decarbonizing various sectors, necessitating substantial investments, innovation, and policy support [221].

7.3. Enhancing electrolysis: energy efficiency and optimization strategies

Green hydrogen production via electrolysis presents a transformative pathway toward decarbonizing various sectors; however, it is currently constrained by two primary challenges: improving energy efficiency and optimizing process control. Energy losses are not limited to the electrolysis stage but extend to downstream processes, such as hydrogen compression, storage, transportation, and reconversion to electricity. As a result, in certain applications, direct electrification—such as battery

storage—can offer higher round-trip efficiencies than hydrogen-based systems. Moreover, the energy demand for hydrogen logistics adds further complexity to achieving high overall system efficiency.

From a process optimization standpoint, the performance and cost of electrolyzers remain critical concerns. For instance, Proton Exchange Membrane (PEM) electrolyzers, while capable of dynamic operation and high hydrogen purity, are hindered by the high cost of catalyst materials (e.g., platinum-group metals) and limited membrane lifespan. Additionally, the intermittency of renewable energy sources challenges the stability of large-scale electrolyzer operations, requiring advancements in system integration and load-following capabilities. Innovations in catalyst engineering, membrane durability, and balance-of-plant design are essential to improve long-term performance, extend operational life, and reduce capital expenditures [222].

This article provides three major water electrolysis technologies used in green hydrogen production: Proton Exchange Membrane (PEM), Alkaline Water Electrolysis (AWE), and Solid Oxide Electrolysis Cells (SOECs). PEM electrolyzers operate at moderate temperatures (60–80 °C) and are valued for producing high-purity hydrogen with system efficiencies ranging from 65 % to 75 % based on the Higher Heating Value (HHV). Despite these advantages, their widespread adoption is currently limited by relatively high capital and operational costs, yielding a Levelized Cost of Hydrogen (LCOH) in the range of \$4–6/kg H₂.

Alkaline Water Electrolysis (AWE), one of the most mature electrolysis technologies, uses a liquid alkaline electrolyte and has been deployed commercially for several decades. It is characterized by robust system design, lower material costs, and cost-effective operation, with system efficiencies typically ranging from 60 % to 70 % and an LCOH of \$2.5–4/kg H₂. Although AWE systems generally operate at lower current densities and longer startup times compared to PEM, their technological maturity and proven scalability make them suitable for centralized hydrogen production.

Solid Oxide Electrolysis Cells (SOECs) operate at elevated temperatures (~700–850 °C), allowing for high theoretical efficiencies of up to 85 % by leveraging both electrical and thermal energy inputs. This thermally-assisted process enables higher conversion efficiency and offers integration potential with industrial heat sources or concentrated solar power systems. While SOEC technology holds significant promise for efficiency gains and sector coupling, further development is needed to address material stability, thermal cycling tolerance, and system cost.

A structured and standardized comparison across these technologies—using metrics such as LCOH, energy consumption (kWh/kg H₂), system efficiency, and Technology Readiness Levels (TRLs)—is crucial for rigorous techno-economic analysis. Recent assessments by authoritative bodies, including the International Energy Agency [52] and the International Renewable Energy Agency [188], provide valuable benchmarks. For instance, LCOH values are estimated at \$4–6/kg for PEM systems and \$2.5–4/kg for AWE systems, with SOECs demonstrating potential for further cost reduction upon scale-up. Such comparative frameworks enhance clarity for policy-makers, investors, and industrial stakeholders, enabling strategic planning and effective deployment of green hydrogen technologies at scale.

7.4. Comparative assessment based on efficiency, cost, and technology readiness

A consistent comparative framework based on key performance indicators—namely energy efficiency, Levelized Cost of Hydrogen (LCOH), and Technology Readiness Level (TRL)—is crucial for evaluating green hydrogen production technologies. Commercial options such as Proton Exchange Membrane (PEM) and Alkaline Water Electrolysis (AWE) differ substantially: PEM electrolyzers offer higher efficiency (65–75 %) and dynamic response but have a higher LCOH (\$4–6/kg H₂) due to reliance on expensive noble metals like platinum and iridium [52,223]. In contrast, AWE systems are more cost-effective (\$2.5–4/kg H₂) with slightly lower efficiency (60–70 %) and rely on

mature, less expensive materials, making them attractive for widespread deployment [188].

Solid Oxide Electrolysis Cells (SOECs) deliver superior thermodynamic efficiency (up to 85–90 %) under high-temperature operation but remain at pilot scale (TRL 6–7), facing durability and material stability challenges [224]. Meanwhile, emerging technologies such as photocatalytic water splitting, thermochemical cycles, and biological hydrogen from algae show promise but are still at low TRLs, indicating limited scalability in the near term.

Structuring each hydrogen production pathway into two evaluation domains—technical readiness (efficiency, innovation, durability) and economic viability (LCOH, CAPEX, grid compatibility)—enhances review clarity. Including TRL assessments (Table 9), comparative matrices, and region-specific case studies—such as Sweden’s H2 Green Steel project, which leverages abundant hydropower to balance technical and economic parameters—offers nuanced, actionable insights [229]. Without such refinements, reviews risk overemphasizing high-tech but economically constrained solutions while overlooking lower-cost, scalable options.

8. Future pathways for green hydrogen use

As the world intensifies efforts to reduce carbon emissions and address climate crisis, renewable hydrogen materializes as a resourceful and promising power solution. Within 2030, it is anticipated to become a key player among various industries such as transportation, heating, electricity generation, and manufacturing, driving meaningful progress in the global shift toward a low-carbon future. As illustrated in Fig. 13, the projected distribution of hydrogen use highlights its widespread adoption.

8.1. Transportation sector: the leading consumer of hydrogen

The transportation sector is expected to be the largest hydrogen consumer, accounting for about 46.9 % of total demand. This includes various modes of transport incorporating hydrogen at different rates: aviation (9.4 %), motorbuses (4.1 %), passenger automobiles (6.12 %), maritime shipping (3.2 %) and rail transport (9.4 %). The assimilation of hydrogen fuel cell technology in these means of transportation will greatly diminish the reliance on nonrenewable fuel sources, thereby lowering Kyoto gas emanations. For instance, hydrogen-fueled aeroplanes could dramatically cut aviation’s carbon footprint, while hydrogen-fueled buses, cars, and trains offer cleaner alternatives for urban transit. Similarly, hydrogen in shipping presents a significant opportunity to reduce emissions in an industry traditionally associated with high pollution levels. Heating represents another important area for hydrogen use, projected to consume around 12.5 % of the total hydrogen supply. Within this sector, building heating accounts for roughly 6 %, while industrial heating makes up about 5.6 %. Green

Table 9
TRL comparison across hydrogen production pathways.

| Production Pathway | Technology | TRL (2024) | Status | Key Refs. |
|----------------------------------|---------------------------|------------|------------------------|------------|
| Water Electrolysis (PEM) | Proton Exchange Membrane | 8–9 | Commercial, scaling up | [188, 225] |
| Alkaline Electrolysis | Alkaline Electrolyzer | 9 | Commercial | [52] |
| Solid Oxide Electrolysis (SOEC) | High-temp ceramic cells | 6–7 | Pilot scale | [188] |
| Photocatalytic Water Splitting | Semiconductor materials | 3–4 | Lab scale | [185] |
| Thermochemical Splitting (Cu-Cl) | Multi-step thermal cycles | 4–5 | Bench scale | [226] |
| Biohydrogen from Algae | Dark/Photo fermentation | 3–5 | Early development | [227, 228] |

hydrogen can replace fossil fuels in heating residential and commercial buildings, advancing cleaner energy use. Industrial heating, known for its heavy carbon emissions, also stands to benefit from hydrogen’s cleaner profile, helping to drive significant emission reductions.

8.2. Electricity and grid integration

In the electric power industry, the green hydrogen is anticipated headed for representing about 18.3 % of over-all consumption [231]. This includes its use in energy preservation (3.9 %) along with aiding the intermingling of renewable energy sources (7 %), with an additional 2 % contributing to improving grid stability. Attributable to its propensity to be stockpiled and distributed, hydrogen helps overcome the variability of alternatives to fossil fuels like wind and solar energies, enhancing both the flexibility and reliability of given energy system. The industrial sector is expected to consume roughly 9.3 % of hydrogen, while green ammonia production will account for around 3.2 %. Ammonia, commonly used in fertilizers and explosives, is typically produced through processes that emit significant carbon. Replacing these with green hydrogen-based methods can significantly lower emissions in this important industrial field. Altogether, green hydrogen offers ground-breaking assurance across various industries for example transportation, heating, power sector and manufacturing - supporting a cleaner energy transition and performing a crucial part in global climate emergency mitigation efforts, as shown in Fig. 13.

8.3. Knowledge and data gaps in hydrogen production pathways

Despite significant advancements in hydrogen production technologies, several critical knowledge and data gaps persist across various production pathways. In the case of electrolytic hydrogen (green hydrogen from renewable electricity), a major challenge lies in the incomplete understanding of long-term electrolyzer degradation and performance under variable renewable energy (VRE) inputs. Additionally, empirical data on system integration, especially in decentralized or off-grid applications, remains limited. Future research must emphasize real-world pilot demonstrations involving electrolyzer-VRE coupling, focusing on dynamic operating profiles, load-following behavior, and power intermittency adaptation.

Thermochemical water-splitting routes—including photo-electrochemical (PEC) and solar thermochemical cycles—are constrained by low technology readiness levels (TRLs), insufficient evidence of material durability, and limited data on solar-to-hydrogen conversion efficiencies under real-world sunlight conditions. Addressing these issues through AI-assisted material discovery and extended outdoor testing is a promising path forward.

For biological hydrogen production routes such as dark fermentation and algal biohydrogen, challenges include low hydrogen yields, oxygen sensitivity, and the complexity of metabolic pathways. To improve commercial viability, research should prioritize genetic modification of microbial strains, synthetic biology-enabled metabolic control, and scenario-specific techno-economic modeling, particularly for waste-to-hydrogen conversion systems.

Furthermore, inconsistencies in life cycle assessment (LCA) methodologies across the literature hinder transparent and meaningful comparisons of environmental impact. The adoption of standardized LCA frameworks, coupled with open-access techno-economic and process simulation tools, would facilitate cross-technology comparisons and benchmarking.

Bridging these gaps through interdisciplinary collaboration, standardized evaluation tools, and pilot-scale validation will be essential to reduce investment risk and accelerate the transition toward a resilient and economically viable hydrogen economy [227].

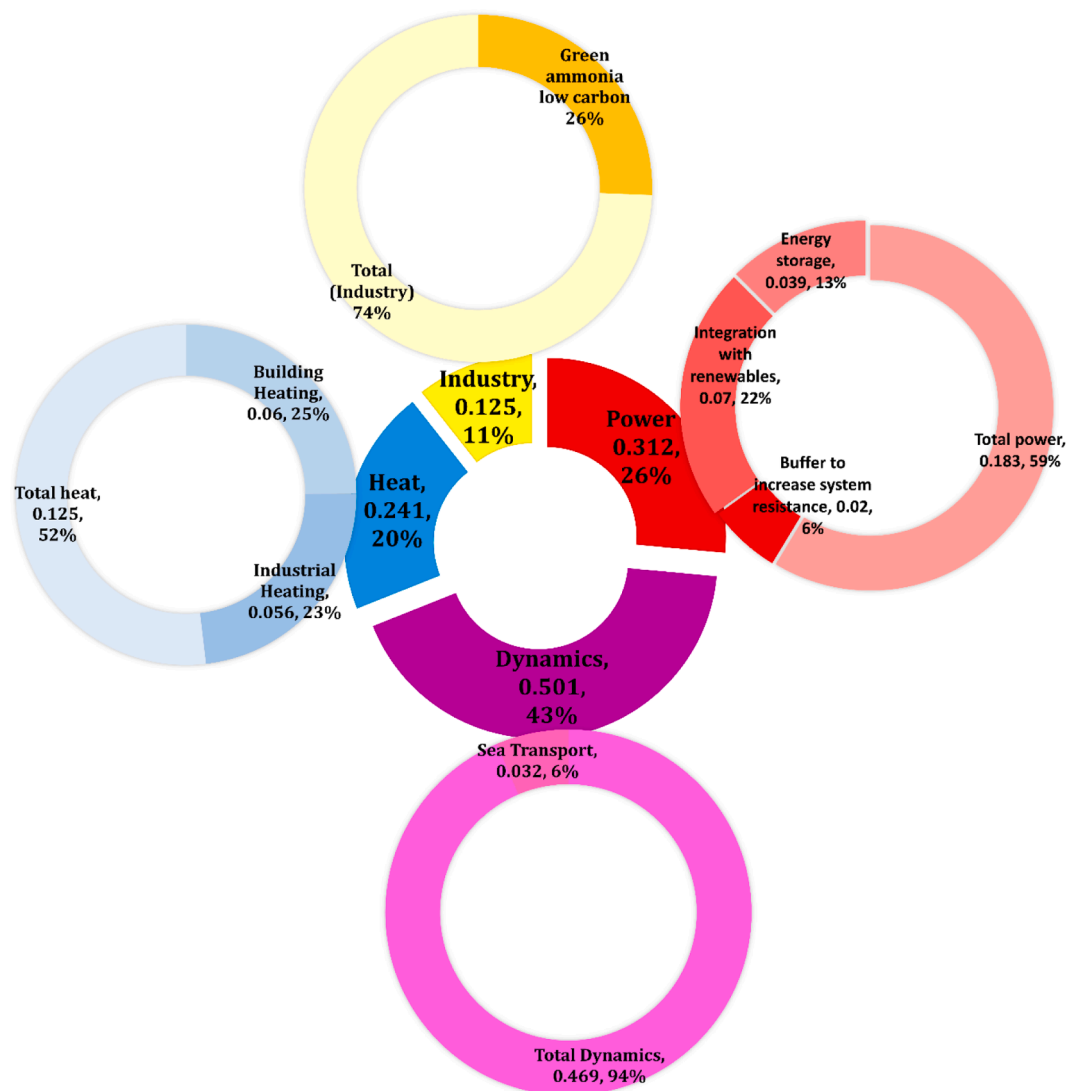


Fig. 13. Estimated hydrogen demand by sector in 2030 [230].

8.4. Economic feasibility: reassessing the \$2/kg green hydrogen target

The widely cited target of achieving green hydrogen production costs below \$2/kg by 2030 demands a critical evaluation of CAPEX, OPEX, renewable electricity pricing, and electrolyzer efficiency. Currently, the levelized cost of hydrogen (LCOH) from electrolysis ranges from \$3.5–6/kg, largely driven by electricity costs—which can comprise up to 70 % of LCOH. While solar and wind prices have fallen to \$0.02/kWh in some regions, global averages still range from \$0.04–0.06/kWh [188].

Electrolyzer CAPEX, currently \$1000–1500/kW, is projected to drop to \$380/kW by 2030 and \$130/kW by 2050, though this depends on scale-up, innovation, and raw material availability [232,233]. Operating costs—such as maintenance and water—along with suboptimal system efficiency (60–70 %) and low capacity factors (<35 %) further constrain economic viability. Hybrid systems and storage can improve utilization but add complexity and cost [205,234].

Policy incentives, including the U.S. IRA's \$3/kg credit and EU's Hydrogen Bank, are helping early deployment, but their long-term durability is uncertain [235]. Overall, achieving <\$2/kg is possible under ideal conditions, but widespread realization hinges on technology improvements, robust policy frameworks, and regional infrastructure support. Thus, projections must be interpreted cautiously and include transparent assumptions and sensitivity analyses.

8.5. Strategic research roadmap and future directions (2025–2040)

Future research directions in green hydrogen production are increasingly centered on region-specific technology development, enhanced electrolyzer efficiency, and the integration of complementary systems such as carbon capture, utilization, and storage (CCUS) and hybrid renewable platforms. As depicted in Fig. 14, the projected roadmap from 2025 to 2040 outlines a phased progression—from early-stage R&D and pilot demonstrations to full-scale commercialization and global deployment. Key short-term priorities include reducing electrolyzer capital costs, improving efficiency, and ensuring stable renewable power supply. Mid-term strategies emphasize hybrid systems (e.g., solar-thermochemical–geothermal or electrolysis–CCUS integration) to enhance energy yields and system flexibility. Long-term goals involve scaling infrastructure, developing hydrogen transport networks, and aligning global policies [52,188,225]. These strategic stages underscore the multifaceted innovation required to make green hydrogen economically viable and globally scalable.

8.6. Roadmap for green hydrogen scale-up: technological, economic, and policy synergies

This figure illustrates the coordinated advancement of technological, economic, infrastructure, and policy domains required to achieve

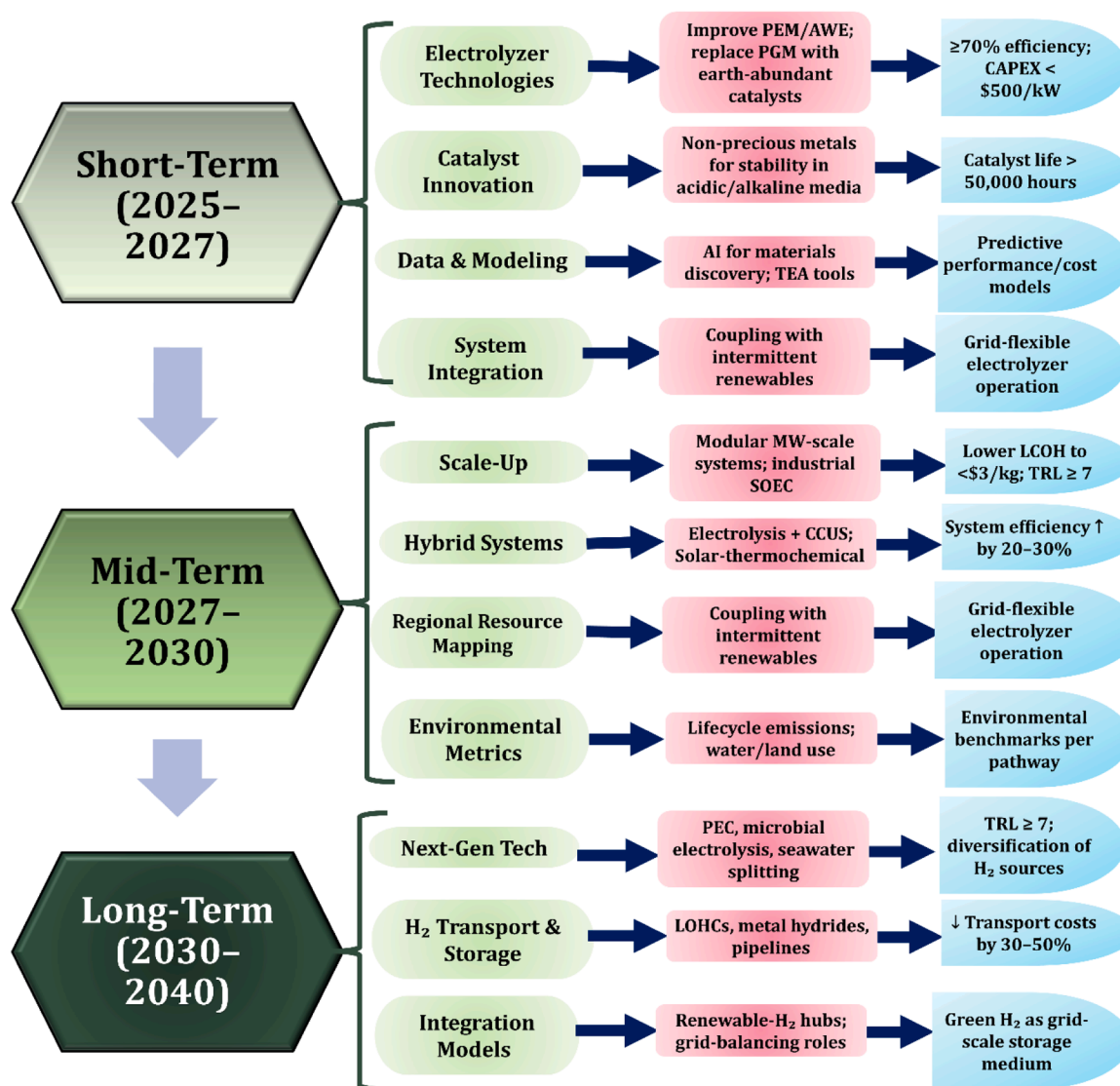


Fig. 14. Green Hydrogen Pathways: R&D Priorities and Outcomes (2025–2040).

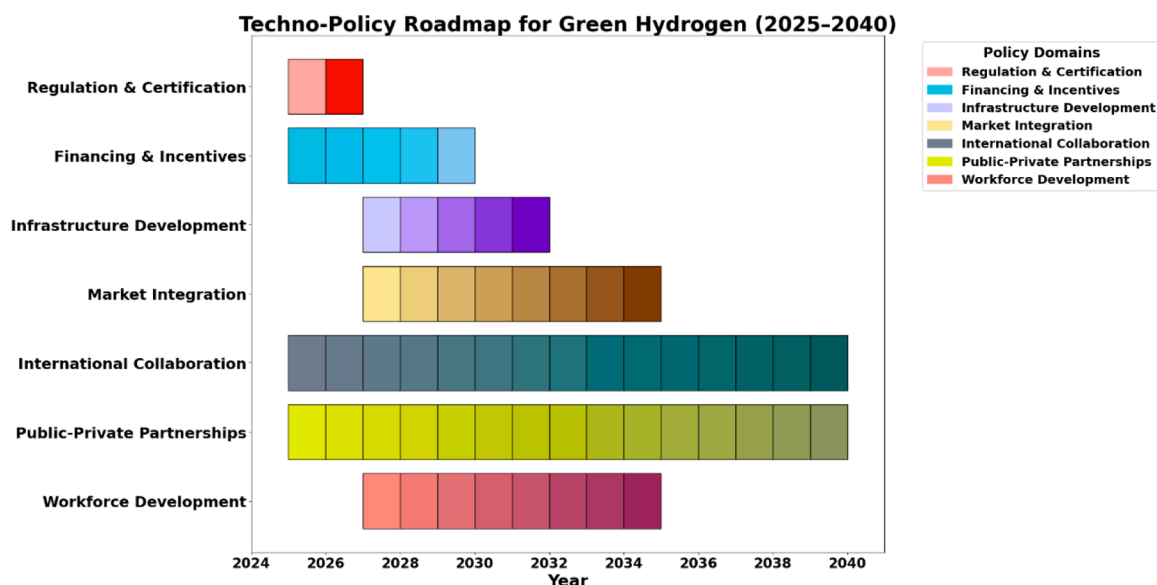


Fig. 15. Techno-Policy Roadmap for Green Hydrogen (2025–2040), with gradient color bars indicating timeline and strategy progression for each domain.

widespread adoption of green hydrogen (Fig. 15). The timeline spans from 2025 to 2040, with gradient bars representing the transition from R&D phases to commercialization and scalability. Key technological priorities include lowering electrolyzer costs, improving efficiency, and developing integrated hybrid systems. Parallel policy frameworks—such as subsidies, carbon pricing, and certification standards—are essential to enable market pull. The roadmap also highlights the importance of international collaboration, infrastructure readiness (e.g., pipelines, storage), and workforce development. This structured visualization aligns with recent recommendations from IRENA and IEA reports, emphasizing the interdependence of these domains to achieve the target of <\$2/kg hydrogen production by 2030 [188,205].

9. Extensive green hydrogen manufacturing projects

Despite its potential as a clean energy alternative, green hydrogen currently accounts for only a minor share of global hydrogen output. For it to significantly contribute to the decarbonization of energy systems and heavy industries, its production must expand substantially in the coming decades. This growth is critical if green hydrogen is to become a foundational element in a low-carbon, circular economy.

9.1. NEOM

Saudi Arabia's NEOM Green Hydrogen Company (NGHC) is nearing 80 % completion of its green hydrogen facility, wind garden, solar farm, and transmission grid at Oxagon. The world's largest green hydrogen plant remains on track, aiming to generate 4 GW of solar and wind power by mid-2026 and begin ammonia production in 2027. NGHC is developing a skilled Saudi workforce and partnering with educational institutions for talent development. A joint venture between ACWA Power, Air Products, and NEOM, the facility will produce up to 600 tonnes of carbon-free hydrogen daily as green ammonia. NGHC has secured a 30-year off-take agreement with Air Products and achieved an \$8.4 billion financial close with major lender support. This project supports Saudi Arabia's Vision 2030 for economic diversification and clean energy leadership [205]. This is a part of a whole futuristic commercial zone envisioned as part of a \$600 billion initiative to develop a city powered entirely by renewable energy. NEOM takes advantage of the region's natural conditions, plentiful sunlight, and steady winds, to generate affordable renewable electricity. The facility is expected to have a power capacity of 4 gigawatts, which will support the daily production of about 700 t of clean hydrogen, totalling roughly 0.24 megatons each year [210].

9.2. Asia sustainable energy hub

The Asian Renewable Energy Hub (AREH), envisioned for Pilbara region in West Australia, is an ambitious effort to create one out of earth's massive eco-friendly energy developments. First proposed in 2014, the initiative is being led by a confederation of international enterprises with the goal of generating up to 26 gigawatts of power through a mix of wind and solar energy. Spanning around 668,100 hectares, the project area could support approximately 1743 wind energy conversion systems, individually reaching up to around 300 m in height, alongside approximately 1500 hectares allocated to about 18 large-scale solar farms expected to produce a total of 600 megawatts. Given the strong political influence of the fossil fuel industry in Australia, there are considerable obstacles to expanding renewable infrastructure on a national scale [236,237]. Consequently, the hub is primarily oriented toward producing energy for export rather than feeding into the domestic grid. The project aims to convert the electricity it generates into green hydrogen or related fuels for shipment to countries in the Asia-Pacific region. Despite its promise, the venture must navigate a complex web of regulatory requirements, needing approvals at both state and federal levels. The approval process alone could span

about two years, reflecting the administrative challenges that slow progress on clean energy projects and green hydrogen production in Australia [238].

9.3. Fukushima renewable hydrogen development site

The Fukushima Hydrogen Energy Research Field hosts the world's largest facility for producing hydrogen using renewable energy. To support this effort, a 12 MW solar power plant was built nearby starting in 2018. The facility can generate up to one and a half cubic kilolitres of hydrogen hourly. However, the mission faces several challenges. The electrolyser system is relatively modest in size compared to other innovative green hydrogen projects, coupled with the elevated cost of renewable electricity within Japan impacts the venture's overall viability. The infrastructure for electrolysis is estimated to cost about \$850 per kilowatt of capacity, which translates to a base hydrogen production cost of around \$1 per kilogram just from capital expenses. Additionally, most hydrogen projects remain much smaller than traditional energy and chemical plants, which commonly operate at the gigawatt scale [239].

10. Conclusion

As the international transformation in the direction of sustainable power accelerates, clean hydrogen is progressively seen as an indispensable remedy for cutting emissions in essential sectors like transportation, heavy industry, and power generation. This report reviews recent advancements in making of green hydrogen, focusing on know-hows such as electrolytic decomposition, thermo-chemical conversion, and biological approaches. In particular, electrolytic approaches especially solid oxide electrolyzer systems and proton exchange membrane have patterned notable progress in efficiency and scalability. Nonetheless, challenges persist chief among them are the high energy demands, reliance on rare and costly catalyst materials like platinum and iridium, and a lack of infrastructure to support widespread deployment. Encouragingly, research into cost-effective alternatives using non-precious metals is showing promise in reducing these barriers.

A significant takeaway from this review is the budding international sponsoring in novel hydrogen technologies. Republics such as South Korea, Germany, Japan and Australia are allocating substantial resources to build hydrogen economies. For instance, Germany has pledged €9 billion under its National Hydrogen Strategy to foster domestic production and infrastructure development. Similarly, Japan has set an ambitious goal of generating reaching 300,000 tons of green hydrogen production each year by 2030. These endeavours are indicative of a global movement to target hydrogen as a core constituent of future energy and power systems, supported by favourable policy frameworks and public funding that aim to drive down costs through innovation and scale.

Despite its promise, green hydrogen remains more expensive to produce than hydrogen sourced from fossil fuels. However, analysis suggests that with continued technological improvements, enhanced integration with renewable energy sources, and expanded production capacities, the cost could decline to below \$2 per kilogram by the end of this decade. Reaching this target will require not only advances in electrolyzer technology but also expanded renewable generation, supportive government measures, and sustained capital allocation in research and innovation.

Addressing the confronts of storage of hydrogen and transportation remains a critical focus. Several methods are being explored to overcome these hurdles, including high-pressure gas compression, cryogenic liquefaction to maintain dihydrogen in liquefied form at exceptionally freezing temperatures, and the usage of chemical transporters such as ammonia and fluid organic hydrogen carriers. Each approach presents unique advantages and technical complexities that must be managed to enable efficient and safe handling of hydrogen throughout the supply

chain. While liquefied hydrogen allows for denser energy storage, it requires extremely low temperatures, which drives up both costs and energy consumption. Alternatives like ammonia and LOHCs involve lower energy penalties but require conversion steps that reduce overall system efficiency. Progress in this area will be critical to establishing trustworthy and inexpensive global logistics networks.

Over and above its role as a clean fuel, green hydrogen offers strategic value in managing electricity supply variability. It can store surplus power engendered from intermittent perpetual resources like solar energy and wind power, thereby enhancing grid reliability. Nations for instance Netherlands and Denmark are already amalgamating hydrogen in their energy systems towards providing greater amenability and resilience. Environmental factors also merit close attention. The water demand of electrolysis is significant and could pose sustainability issues in regions with limited freshwater resources, prompting interest in technologies that integrate seawater desalination. Furthermore, the development of large-scale hydrogen facilities must consider land use and potential ecological impacts. An all-inclusive methodology that poises environmentally friendly stewardship with socioeconomic goals is essential for the sustainable expansion of this sector.

This review underscores the importance of coordinated policy initiatives, ongoing research and development (R&D), and strategic investments to accelerate the adoption of green hydrogen as a pivotal solution for reducing carbon emissions and enhancing energy autonomy and supply reliability. By aligning technological innovation with supportive policy frameworks and financial mechanisms, stakeholders can overcome current barriers in infrastructure, production scalability, and cost competitiveness. Furthermore, fostering international collaboration, incentivizing public-private partnerships, and establishing standardized certification and regulatory pathways will be crucial for driving widespread deployment and ensuring the long-term sustainability of green hydrogen systems.

In summary, green hydrogen is poised to play a central role in the transition to a low-carbon future. However, realizing its full potential will require coordinated action across government, industry, and academia. Breakthroughs in production, storage, and distribution technologies—coupled with the development of international markets—are essential to accelerate adoption and deliver the environmental and economic benefits of a green hydrogen economy.

CRedit authorship contribution statement

Abdulrahman M. Abdulaal: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Abraham Altho-nayan:** Conceptualization, Writing – review & editing. **Nadavala Siva Kumar:** Data curation, Resources, Writing – review & editing. **Ahmed A. Ibrahim:** Resources, Supervision, Writing – review & editing. **S. Padmanabhan:** Supervision, Validation. **S. Ganesan:** Supervision. **S. Mahalingam:** Supervision. **T.Vinod Kumar:** Supervision. **P. Sar-avanan:** Supervision. **L. Gunganathan:** Supervision. **P. Tamizhdurai:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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