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Recent advancement and assessment of green hydrogen production technologies

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A R T I C L E I N F O

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A B S T R A C T

Hydrogen energy has garnered substantial support from industry, government, and the public, positioning it as a pivotal future fuel source. However, its commercial realisation faces significant hurdles, including slow infrastructure growth and the high cost of producing clean hydrogen. This review uniquely emphasises the different colour codes of hydrogen, which have been rarely discussed in the literature to date. Hydrogen production methods are classified by colour codes, with green hydrogen, produced from renewable sources such as wind and solar, being the most desirable option. The demand for green hydrogen across various sectors is expected to surge. This review comprehensively evaluates the major hydrogen production methods based on cost, environmental impact, and technological maturity. Recent data confirm the increased efficiency, cost-competitiveness, and scalability of green hydrogen production technologies. The cost of green hydrogen has declined significantly, making it competitive with blue hydrogen (produced from fossil fuels with carbon capture). The review also scrutinises several recent hydrogen production technologies, highlighting their advantages, disadvantages, and technological readiness. Among these, the solid oxide electrolysis cell (SOEC) currently outperforms others, with anion exchange membrane (AEM) and electrified steam methane reforming (ESMR) also showing promise. This review also succinctly summarises global progress in hydrogen infrastructure and policies. By spotlighting the diverse colour codes of hydrogen and discussing the crucial takeaways and implications for the future, this review offers a comprehensive overview of the hydrogen energy landscape. This unique focus enriches the literature and enhances our understanding of hydrogen as a promising energy source.

1. Introduction

Global greenhouse gaseous (GHG) emission has surged to their highest level in history [1], presenting an existential threat to humankind as global warming continues to exacerbate. Among all human activities, burning fossil fuels for energy is the most significant contributor to GHG increase, particularly carbon dioxide. The heat from the sun was then trapped by the GHGs, raising the temperature. Therefore, the main goals of the 2015 Paris Agreement are to try to limit the temperature increase to 1.5 °C and to make a more vigorous global effort to address climate change by keeping the temperature increase this century below 2 °C above pre-industrial levels [2]. Hence, countries worldwide agreed that reducing carbon emissions is required to prevent the harmful effects of climate change, such as coral reef destructions, heatwaves, frequent wildfires and floods, droughts, and rising sea levels. Various solutions have been discussed, including transitioning to renewable energy for a sustainable future, as renewable energy is an abundant and continuously replenished natural resource.

Solar, hydro, wind, biomass, and biogas are sustainable energy sources that do not deplete and will not cause long-term harmful environmental effects. Sustainable energy requires energy conservation, efficiency, and renewable energy to reduce climate change and protect the environment. Hydrogen has great potential to be an essential part of a

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Nomenclatures

Air reactor AR
Anion exchange membrane AEM
Australian Renewable Energy Agency ARENA
Autothermal reforming ATR
Battery electric vehicle BEV
Bio-electrochemical systems BESs
Biological water gas shift reaction BWGS
Carbon capture and storage CCS
Carbon capture, storage, and use CCUS
Catalytic partial oxidation CPOX
Department of Energy DOE
Dry reforming DR
Electric vehicles EV
Electrified steam methane reforming ESMR
Electrochemical catalytic coal gasification ECG
Energy Information Administration EIA
Environmental, social, and governance ESG
European Union EU
Fuel cell electric vehicles FCEVs
Gas hourly space velocity GHSV
Greenhouse gas GHG
Gross domestic product GDP
High heating value HHV
Hydrogen energy technology HET
International Energy Agency IEA
International Renewable Energy Agency IRENA
Levelised cost of energy LCOE
Life cycle assessment LCA
Light intensity Lux
Methane pyrolysis MP
Microbial electrolysis cells MECs
Microbial fuel cells MFCs
Million metric tonnes per year MMTPA
Monodisperse iron oxide nanoparticles IONPs
Net Zero Emissions NZE
Partial oxidation POX
Partial oxidation of ethanol POE
Photovoltaic PV
Polymer electrolyte membrane electrolysis PEMEL
Proton exchange membrane PEM
Research and development R&D
SMR with CCS SMR-CCS
Solid oxide electrolysis cells SOEC
Steam methane reforming SMR
Technology Readiness Level TRL
Thermal decomposition TD
Thermochemical water-splitting cycle TWSC
Water-gas shift WGS

Symbols/Molecular formulae/Units

Acetate CH_3COO^-
Acetic acid CH_3COOH
Atmospheric pressure atm
Australian dollar A$
Bicarbonate HCO_3^-
Butanoic acid $CH_3CH_2CH_2COOH$
Calcium oxide CaO
Canadian dollar CAD
Capacitive current density mA/cm^2
Carbon dioxide CO_2
Carbon monoxide CO
Cerium(IV) oxide CeO_2
Chromium Cr
Cobalt Co
Celenium Ce
Cubic meters m^3
Degree Celcius °C
Deuterium isotope ^2H
Dimethyl ether DME
Enthalpy change ΔH
Ethanol C_2H_5OH
Exajoule EJ
Gamma-alumina γ-Al_2O_3
Gibbs's energy ΔG
Gigawatt/gigatonnes GW/GT
Glucose $C_6H_{12}O_6$
Hybrid sulphur HyS
Hydrogen H_2
Hydrogen peroxide H_2O_2
Hydronium ion H^+
Hydroxide ions OH^-
Indian rupee crore INR Cr
Iron Fe
Iron (III) oxide Fe_3O_4
Kilojoules/mol kJ/mol
Megajoule MJ
Megajoule per cubic meter MJ/m^3
Megapascal MPa
Methane CH_4
Methanol CH_3OH
Metric tonne Mt
N–Methyl–2–pyrrolidone NMP
Nanoparticles of metal sulfides (zinc sulfide/cadmium sulfide) ZnS/CdS
Nickel Ni
Nickel (II) chloride hexahydrate $NiCl_2.6H_2O$
Oxygen O_2
Polycyclic aromatic hydrocarbons PAHs
Potassium carbonate K_2CO_3
Potassium hydroxide KOH
Propane C_3H_8
Protium isotope ^1H
Hydrogen proton H^+
Rhodium Rh
Sodium-borohydride $NaBH_4$
Standard enthalpy of formation $H°_{298}$
Terawatt hour TWh
Tetrahydrofuran THF
Tritium isotope ^3H
United States Dollar (USD) $
Vanadium-chlorine V–Cl
Water H_2O
Volt V

future energy system that is clean, secure, and cost-effective. Hydrogen is versatile and can enable renewables such as wind and solid photovoltaic (PV) to contribute more significantly. Hydrogen attempts have failed due to environmental factors caused by thermal processing. However, recent technological advancements include electric vehicles (EVs), wind, batteries, and solar PV. Policies have shown that they can create global clean energy industries. Clean hydrogen is gaining much attention and support, with increasing global projects and policies being developed. This is because hydrogen has the potential to address a range of energy challenges, such as reducing emissions, particularly in industries like iron and steel, chemicals, and long-distance transportation, and it has a variety of uses and applications, for example, in the production of fertilisers and the oil refining sector.

One of the crucial factors of incorporating hydrogen in energy strategy is that hydrogen can help decarbonise the energy sector by providing a clean and reliable energy storage and transportation source. This can help to reduce our reliance on fossil fuels and make our energy supply more resilient to climate change. Hydrogen is aligned with ESG principles, as it is environmentally friendly, socially beneficial, and economically viable. In addition, hydrogen can help to achieve several United Nations (UN) Sustainable Development Goals (SDG), such as SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 17 (Partnerships for the Goals).

However, the clean, widespread use of hydrogen in global energy transitions faces several challenges [3], including the slow development of hydrogen infrastructure, preventing widespread adoption. Moreover, producing hydrogen from low-carbon energy is prohibitively expensive, and hydrogen is almost entirely supplied by natural gas and coal. Currently, regulations are impeding the development of a clean hydrogen industry. Nonetheless, efforts have been made by several industries and companies to implement green hydrogen in their products. Green hydrogen is rising and will be the future's high-demand renewable energy. The awareness of the importance of green hydrogen has led to greener technology and acceptance worldwide. Moreover, hydrogen production from renewable power in a power-to-gas process may become more cost-effective due to the recent sharp decline in renewable energy costs [4].

Hydrogen technology showed remarkable resiliency during the COVID-19 pandemic, and its momentum will continue in 2020. With ten governments worldwide embracing hydrogen policies, it was a record year for low-carbon hydrogen generation and policy action. Fig. 1 shows the demand for the global hydrogen sector in 2020, with refining accounting for 37.18 Mt and the hydrogen industry accounting for 51.30 Mt. It is projected that by 2025–2030, there will be a rise in demand for grid injection (23.85–51.70 Mt), hydrogen for buildings (2.25–5.64 Mt), synfuels (1.10–7.28 Mt), transportation (2.12–8.55 Mt), and ammonia fuel (7.53–18.11 Mt), on top of the rise in hydrogen industry (63.22 Mt) but a downfall in refining (33.82 Mt) [5]. By 2030, it is also expected that there will be a demand for hydrogen in the power industry, which accounts for 18.50 Mt. This development, however, falls well short of what is required in the Net Zero Emissions (NZE) by 2050 Scenario [6]. Furthermore, the demand for innovative uses of low-carbon hydrogen remains confined to road transportation. As a result, extra efforts are required to create the need and reduce emissions related to producing hydrogen [5].

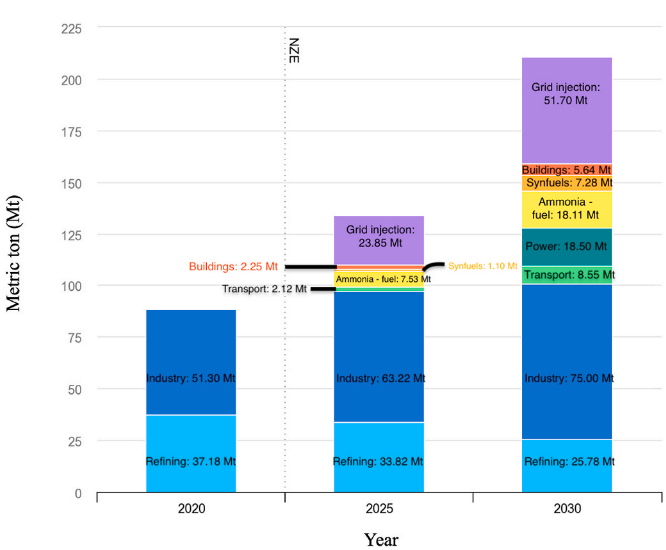


Fig. 1. Demand for global hydrogen by sector under the Net Zero Scenario, 2020–2030. NZE = Net Zero Emissions [5].

In the following sections, this study will delve into the various facets of hydrogen, its significance in the transition to sustainable energy, and the critical factors that shape its adoption and development. Section 2 also generally introduces hydrogen as a versatile and sustainable energy carrier. This section explores the hydrogen colour codes, production capacity, market status, and various applications. Subsequently, Section 3 discusses hydrogen production, categorising the technologies into fossil fuel-based (blue), renewable sources-based (green), and recent green hydrogen production methods. These technologies are pivotal in determining hydrogen's environmental impact and feasibility as an energy source. Following that, Section 4 explores the global landscape of green hydrogen strategies adopted by different countries and delves into the investments that underpin the growth of the hydrogen economy. Understanding these policies and economic drivers is crucial to grasping the potential future of green and clean hydrogen. Finally, Sections 5 and 6 critically assess the potentials and challenges of green hydrogen production methods. The former section offers insights into the factors that can either accelerate or hinder the widespread adoption of hydrogen as a clean energy source, while the latter discusses areas where further research, development and innovation are needed to enhance the efficiency, sustainability, and cost-effectiveness of hydrogen production and utilisation.

The literature review in this area has covered the techno-economic analysis of different hydrogen colour codes [7], the environmental impact [8] and the complementary and competitive aspects of blue and green hydrogen production methods based on sensitivity analysis and its coverage in Europe [9]. However, there is a lack of reviews that compile current green hydrogen production technologies, government initiatives and policies worldwide, and commercially available green hydrogen technologies and startups. This study uniquely contributes to the literature by providing an in-depth analysis of hydrogen colour codes. It explores the thirteen colour codes of hydrogen, including their production methods, environmental impacts, advantages, and drawbacks. This extensive analysis offers a unique perspective on producing and utilising hydrogen. Additionally, by reviewing recent hydrogen production technologies, market status, global strategies and policies, and the economic drivers behind the hydrogen economy, this study provides readers with a comprehensive overview of hydrogen's role in the transition to sustainable energy. Furthermore, the research aims to differentiate the resources and technologies used and the advantages and disadvantages of each hydrogen colour code. It also highlights the key takeaways and implications for the future of hydrogen as a renewable energy resource.

2. Methodology

A comprehensive search within the Scopus database and Google Scholar was initiated with keywords including 'green, hydrogen production, technologies, biomass' in the search features like 'title, abstract, and keywords'. The primary goal was to assess the recent advancements and technologies in this field. Next, the search continued by filtering the research fields, *viz.* 'Energy', 'Engineering', 'Environmental Sciences', and 'Chemical Engineering'. Further filtrations to document type include the most highly cited articles and review papers to see the hydrogen trends for the past five years. A broader set of keywords used or incorporating additional relevant terminologies could mitigate this limitation. Meanwhile, data were mainly extracted from the International Energy Agency (IEA) website for hydrogen policy and economy, as it has recently updated the hydrogen economy and policy for all countries. The reports were also extracted from government websites, such as the Australian Renewable Energy Agency (ARENA). Other countries' policies, such as Indonesia's, were gathered from research articles. News and press conferences were also cited to get hydrogen experts' latest opinions and perceptions. Finally, we summarise this review by gathering all the information from scholars and experts in the private and government sectors. The scope of this literature review is limited to the relatively established state-of-the-art of green hydrogen production technologies rather than every available technology. In addition, another limitation of this review stems from data scarcity, particularly in assessing the availability and sustainability of required resources such as renewable energy sources (e.g., solar, wind) and water for green hydrogen production in specific regions and obtaining comprehensive environmental impact data for all stages of the hydrogen production life cycle, including emissions, water use, and land use. The selected methodology, i.e. the use of specific keywords, may inadvertently exclude relevant research not captured by those keywords. In addition, the scope of the literature review, focusing on established state-of-the-art technologies, may exclude emerging and potentially significant technologies that are not yet recognised as state-of-the-art. The policy implications of this selected methodology would be to focus on emerging and potentially significant technologies, enhanced research and data collection, cross-regional collaboration, global policy coordination, standardised assessment methodologies, and long-term planning for resource sustainability.

3. The colour spectrum of hydrogen

Hydrogen is a colourless gas, but it can be identified by thirteen different colour codes, which refer to the method or source used to produce it. These codes include green, blue, grey, brown or black, turquoise, purple, pink, red and white [5]. Green, blue, brown, yellow, turquoise, and pink hydrogen are the nicknames or colour codes used in the energy industry to distinguish hydrogen. Distinct manufacturing methods could give hydrogen different colours. Since no global naming convention exists, meanings can alter over time and between countries [10]. The production of brown, grey, and black hydrogen is a significant source of GHG emissions. These types of hydrogen are produced using fossil fuels, such as coal and natural gas. Grey hydrogen is made from fossil fuels, often through steam methane reforming (SMR). This process releases carbon dioxide into the atmosphere. Black or brown hydrogen is made using coal, with the colour representing the type of coal used, bituminous (black) or lignite (brown), respectively. Coal gasification can also produce hydrogen, but it is a highly polluting process that releases carbon dioxide and carbon monoxide into the atmosphere.

While the proportion of black and grey hydrogen is decreasing, brown hydrogen is still the most common type of hydrogen produced in the United States [7]. Brown hydrogen is produced using SMR, which releases carbon dioxide (CO_2) into the atmosphere. While using hydrogen fuel cells can reduce air pollution, producing hydrogen from fossil fuels is not a sustainable solution. Developing technologies that can produce hydrogen without releasing GHG is necessary to achieve a green hydrogen future. Meanwhile, blue hydrogen production emits CO_2, even though it is more sustainable than traditional hydrogen production methods. Consequently, blue hydrogen does not meet international GHG emission reduction targets. Green hydrogen, on the other hand, is a clean technology that aims to produce zero emissions. This technology uses renewable energy sources, such as solar panels and wind turbines, to electrolyse water to generate hydrogen, which removes nearly all carbon emissions. However, green hydrogen production is currently more expensive than blue hydrogen production, likely due to the cost of electrolyser materials.

Although the rate of progress in hydrogen production from renewable sources has been slow in the past, recent advances indicate that significant progress is now being made. Green hydrogen is created by using renewable energy to electrolyse water, making it carbon-emission free and giving it its name. This process converts water into hydrogen gas and oxygen using electricity. In contrast to green hydrogen, blue hydrogen is produced using fossil fuels. However, the carbon dioxide produced is captured and stored underground, known as carbon sequestration. Some companies are attempting to use the captured carbon in a process called carbon capture, storage, and use (CCSU). The blue hydrogen production process is carbon neutral because it emits no carbon dioxide. It is also worth noting that using blue hydrogen is not a requirement to qualify for CCSU. Turquoise hydrogen is produced from methane pyrolysis. It consumes one-seventh of the energy necessary to produce hydrogen from water [7]. It separates carbon into a solid form rather than as a gas. Purple hydrogen is produced by splitting water into hydrogen and oxygen using nuclear power and heat, called combined chemothermal electrolysis. Pink hydrogen is made by using nuclear power to electrolyse water. Red hydrogen is generated through high-temperature catalytic water splitting that uses nuclear thermal energy. Meanwhile, white hydrogen is simply hydrogen that exists naturally.

Table 1 compares hydrogen production technologies, including their strengths, weaknesses, and efficiencies. Based on this comparison, green hydrogen production is the most desirable and promising technology because it has the potential to produce zero emissions during the production and use of renewable energy sources. Meanwhile, blue hydrogen captures and stores carbon emissions but relies on natural gas as a feedstock. This raises concerns about its long-term sustainability, given the world's goal of reducing reliance on fossil fuels. The choice between blue and green hydrogen depends on factors such as cost, availability of resources, and environmental goals. This article will comprehensively overview blue and green hydrogen as renewable energy resources. It will focuson their production technologies, policy and economic aspects, potentials, challenges, and future research directions. Meanwhile, Table 2 summarises the general properties of hydrogen, its advantages and disadvantages based on availability, production, and storage.

4. Hydrogen as a renewable energy resource

Seventy per cent of the universe's matter is comprised of hydrocarbons (oxygen, nitrogen, and hydrogen). A significant amount of hydrogen can be found in both water and plants. Hydrogen is present in the sun. It evaporates from the Earth's atmosphere due to solar radiation due to its lightweight. Hydrogen is the simplest element, consisting of only one proton and one electron. Usually, it is combined with other substances, such as in water, which is two parts hydrogen to one part oxygen. Hydrogen can be a clean energy source when extracted from water, natural gas, or biomass and can be used to power and heat homes. Hydrogen is known for its efficiency and renewability and is the most abundant element in the world. It is also non-toxic and has the potential to generate many employment opportunities in the future. Further hydrogen advantages, drawbacks, and properties are listed in T**able 2**.

4.1. Hydrogen production capacity, market, commercialisation status

European countries have recently emerged as leaders in deploying renewable technologies because of their abundance of renewable energy sources. Jean-Claude Juncker, the European Commission President, has mentioned that the European Union (EU) members' goal is to become "the world's number one in renewables" by 2020, and the EU has set renewable energy targets for all EU countries [18]. Meanwhile, the International Energy Agency (IEA) reported that replacing the world's grey hydrogen with green hydrogen would necessitate 3000 TWh/year, equivalent to Europe's current annual demand for 3000 TWh/year in

Table 1
Different colours of hydrogen defined by the technologies used [11–14].

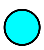
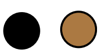
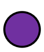
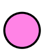
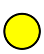
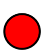
Types of hydrogen colours	Definition by technologies used	Advantages	Drawbacks
	It is naturally occurring hydrogen molecules formed through fracking and found in underground deposits. Hydrogen is a byproduct of the industrial process.	Naturally occurring hydrogen	–
	Hydrogen is produced by water electrolysis using renewable energy sources such as solar, wind, and hydro.	1. Increase recycling 2. Promote bioenergy 3. Does not emit GHGs 4. Produce from clean electricity 5. Emits no carbon dioxide 6. Expected to have a lower price as it becomes more common.	1. High production costs 2. Energy losses 3. Lack of dedicated infrastructure 4. Need to ensure sustainability 5. Lack of value recognition
	Hydrogen is produced by SMR from fossil fuels (other than coal).	The most common form of hydrogen production.	1. Emits carbon dioxide 2. Emits other GHG 3. Continued use of some fossil fuels.
	Hydrogen from natural gas is produced through the SMR process to capture and bury GHGs.	1. Could capture and remove GHGs using carbon capture and storage (CCS) technology 2. Also known as low-carbon hydrogen.	1. Produce carbon dioxide as a byproduct
	Steam methanation of renewable natural gas with CCS.	1. Could capture and store carbon.	1. The process emits a large amount of carbon dioxide.
	Hydrogen is derived from the pyrolysis of methane (thermal splitting).	1. Produce hydrogen and solid carbon. 2. In the future, it may be valued as low-emission hydrogen, depending on several factors.	1. Generate a small number of GHGs
	Hydrogen is produced by coal gasification.	1. Produce liquefied hydrogen for low-emission usage.	1. This process emits large amounts of carbon dioxide, carbon monoxide, and other GHGs. (Opposite of green hydrogen)
	Hydrogen is produced using nuclear power plants. This chemo-thermal electrolysis process uses nuclear power and heat to split water.	1. Low carbon emissions	1. Use very high temperatures from a nuclear reactor. 2. Generate a small number of GHGs
	Hydrogen is produced using nuclear energy to power water electrolysis.	1. The steam generated from the nuclear reactors could be used for other hydrogen productions for more efficient electrolysis	1. Use very high temperatures from nuclear reactors. 2. Generate a small amount of GHGs.
	Hydrogen is produced from the energy grid via water electrolysis.	1. Hydrogen is produced through electrolysis using solar power.	1. Carbon emissions vary greatly depending on the sources used to power the grid.
	Thermal energy generated by nuclear power is used to power high-temperature catalytic water splitting. More minor, modular nuclear power plants are being implemented to augment wind, solar, and battery technology in the power sector.	1. No carbon dioxide emissions	1. Uses very high temperatures. 2. Generate a small amount of GHGs.
	Produced from waste plastics through gasification or pyrolysis with CCS.	1. Low raw material costs 2. Requires less energy.	1. At an early stage, more research is needed.

Table 2
Benefits, drawbacks, and properties of hydrogen [15–17].

Advantages	Disadvantages
Renewable	Expensive to produce
Clean energy source	Its production can produce carbon
Non-toxic	Volatile
Highly efficient	Can be dangerous
Could create thousands of jobs	Unproven technology
Would speed up the use of renewables	Could emit nitrous oxide when burned
The most abundant of all elements in the universe	Difficult to store
Physical Properties	**Chemical Properties**
Average atomic weight = 1 amu	Enthalpy for combustion = - 286 kJ/mol
Symbol = H	$2H_2\ (g) + O_2\ (g) \Leftrightarrow 2H_2O\ (l)\ \Delta H = -572$ kJ
One proton	A mixture of 5–95 % chlorine and hydrogen can cause an explosion
Molecular formula = H_2	Hydrogen autoignition = 500 °C
Not poisonous	An effective reducing agent
Tasteless, non-metal, odourless, colourless, highly flammable	Could react with oxidising elements such as fluorine and chlorine to form hydrogen halides
Boiling point = - 252.87 °C	Could react with more electropositive elements, such as alkali metals
Melting point = - 259.14 °C	Has an intermolecular bonding between nitrogen, oxygen, or fluorine
Density = 0.08988 g/L	Hydrogen isotopes: protium (^1H), deuterium (^2H), tritium (^3H)
Lighter than air	When hydrogen is oxidised, its electron is removed, resulting in the formation of the H^+ ion
The most abundant, especially in stars and planets	In aqueous solutions, H^+ is known as the hydronium ion
Simplest element chemically present	Hydrides are formed when hydrogen bonds to a more electropositive element or group

new renewable energy. The European Commission's strategy for hydrogen stated that €430 billion would be spent in Europe. The division will be as follows: electrolyser (13 %), offshore wind (47 %), onshore wind (25 %), and solar PV (15 %), which will cost €96 billion to make 4.4 million tonnes of green hydrogen, while Ukraine and North Africa will cost €91.5 billion to produce 4 million tonnes of green hydrogen.

Natural gas and coal account for most hydrogen production, which is 95 % of total production. Meanwhile, as a byproduct of chlorine production, electrolysis produces roughly 5 % of the world's hydrogen [12].

With the recent growth of the battery electric vehicle (BEV) sector, it may be tempting to be sceptical about the future of fuel cell electric vehicles (FCEVs) that run on hydrogen and only emit water as a byproduct. However, the demand for hydrogen is projected to increase to 87 million Mt in 2020 and between 500 and 680 million Mt by 2050. The hydrogen production market was valued at $130 billion from 2020 to 2021 and is expected to grow at an annual rate of 9.2 % through 2030 [19]. According to a report by Gupta [20], the market for hydrogen generation surpassed $140 billion in 2019 and is expected to increase at a compound annual growth rate (CAGR) of more than 6.25 % between 2020 and 2026. Rising crude oil consumption and increased investments in expanding existing refining facilities in developing economies will generate considerable market growth prospects for hydrogen makers worldwide.

4.2. Hydrogen applications

Fig. 2 shows that hydrogen can be used in many applications, such as for exploring outer space, industrial processes, electricity, and vehicles. Hydrogen blending also plays a crucial role by allowing for the controlled mixing of hydrogen with other gases, optimising energy efficiency and reducing GHG emissions across various sectors, from transportation to industrial processes. According to the Energy Information Administration (EIA) [21], industry uses nearly all the hydrogen to refine petroleum, treat metals, produce fertiliser, and prepare foods in the United States. Hydrogen is also used in petroleum refineries to reduce the sulphur level of fuels. The National Aeronautics and Space Administration (NASA) used liquid hydrogen as rocket fuel in the 1950s. It was among the first to deploy hydrogen fuel cells to power spacecraft electrical systems.

The oil refining industry is responsible for most hydrogen generation and consumption in the United States. As market demand in this industry has expanded, industrial gas firms have increasingly established hydrogen generation plants on-site or near refineries. Merchant hydrogen, provided by industrial gas firms, now accounts for the vast bulk of hydrogen use at refineries, with 2.4 million Mt in 2014 [22]. In recent years, there has been an uptick in interest in green hydrogen production technologies. The potential applications are expanding across a wide range of industries, including electricity grid stabilisation, refrigeration, cleaning products, green ammonia production for fertilisers, heavy transportation such as shipping, manufacturing processes in industries such as cement and steelmaking production, power generation, and fuel cells for EV.

It may not be easy to be optimistic about the future of FCEVs that run on hydrogen and emit only water due to the recent success of BEVs. However, with their hydrogen fuel cell vehicle, the Mirai, companies like Toyota demonstrate a commitment to this technology. Subsequently, in an inaugural press conference, Honda president and Chief Executive Officer (CEO) Toshihiro Mibe stated that Honda has planned to increase its FCEV and EV model line-up in major electrification markets such as the United States and China to 40 % by 2030. This plan will then be expanded to cover 80 % of the world by 2035 and 100 % by 2040 [23].

5. Hydrogen production technologies

Fig. 3 illustrates two different methods for producing hydrogen: from fossil fuels and renewable sources. Hydrogen produced from fossil fuels is classified as blue hydrogen, and the production methods can be categorised into hydrocarbon reforming and pyrolysis. Hydrocarbon reforming methods include steam reforming (SR), partial oxidation (POX), and autothermal reforming (ATR). Hydrogen produced from renewable sources is called green hydrogen, and the production methods include biomass processes (biological or thermochemical) and water splitting (electrolysis, thermolysis, and photolysis). The biological biomass pathway includes bio-photolysis, dark fermentation (DF), and photo fermentation (PF). The thermochemical biomass pathway includes pyrolysis, gasification, combustion, and liquefaction. Details of these technologies are discussed in subsections 5.1 and 5.2.

Currently, the principal source of hydrogen production is fossil fuels. It has the potential to be marketed as a commercially mature technology that can be employed at low cost while reaching high efficiency [25]. The hydrogen generation efficiency ranges from (65 %–75 %) when employing the SR of methane. Meanwhile, the efficiency of the methane POX process is estimated to be around 50 % [26]. Water electrolysis may also be used to synthesise hydrogen gas from water, accounting for approximately 95 % of total hydrogen production [27].

Table 3 summarises hydrogen production, technologies, economics, roles, and status. The table shows that the demand for hydrogen is increasing as hydrogen has a high heating value (HHV) of 142 MJ/kg, and it is suitable for fuel in aviation, steel, chemical, and electricity storage in the fuel cell. Some car manufacturers, such as Toyota, Honda, and BMW, are willing to encounter issues related to hydrogen production costs and not give up on it just yet.

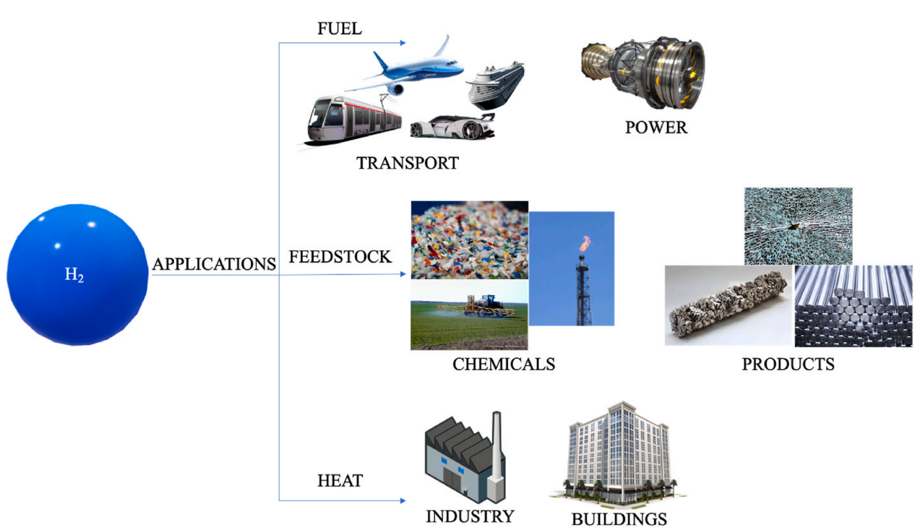


Fig. 2. Hydrogen applications in different sectors.

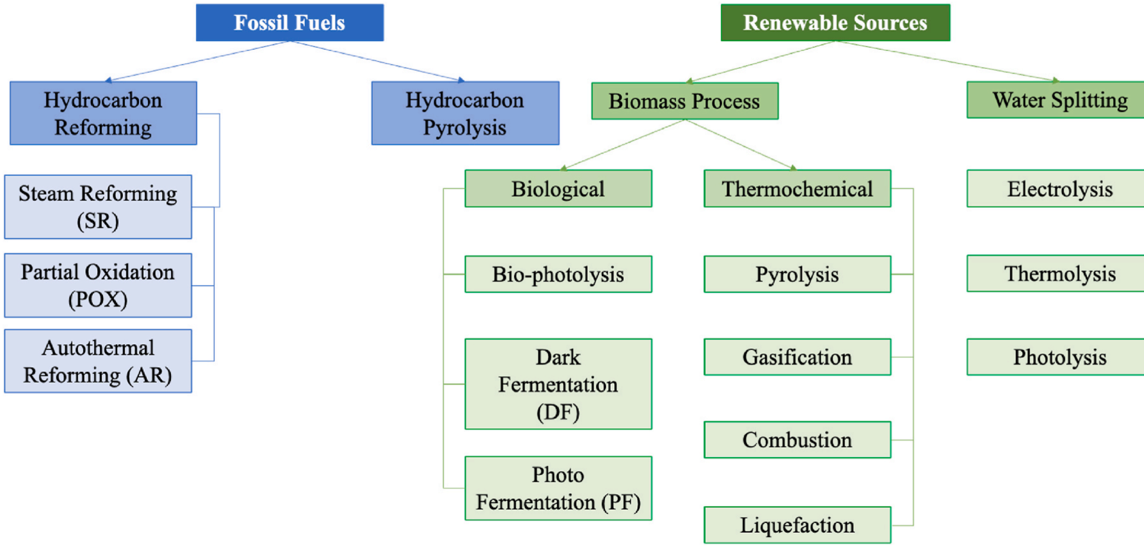


Fig. 3. Hydrogen Production Methods [24].

5.1. Fossil fuel-based production technologies

The synthesis of hydrogen from hydrocarbons necessitates precise energy and temperature requirements. Endothermic reactions are used in industrial operations to produce hydrogen, which requires heat from an external or internal source [43]. Even though hydrogen generation at atmospheric pressure is thermodynamically advantageous at temperatures above 800 °C, temperatures higher than 1000 °C are required to obtain significant conversion rates in systems that do not utilise a catalyst [44]. Fig. 4 illustrates the different hydrogen production methods from fossil fuel-based technologies, including hydrocarbon reforming, steam reforming, partial oxidation, autothermal oxidation, and pyrolysis. Table 4 summarises the current state of these technologies and concludes that adding a catalyst can enhance hydrogen production and control crucial parameters such as temperature and pressure. It is important to note that Table 4 only includes studies published between 2020 and 2022. The following conclusion can be made:

- the addition of catalysts as additives can increase the production of hydrogen
- different catalysts and temperatures can influence the production of hydrogen
- the use of oxidants and high temperatures can increase the concentration of hydrogen
- hydrogen concentration can increase when the process is performed without oxygen during pyrolysis and steam reforming in methane partial oxidation

5.1.1. Hydrocarbon reforming

The use of reforming technology to produce hydrogen from hydrocarbon fuels is explained here. SR of hydrocarbons is considered the most widely used method for hydrogen production, especially in refineries. The hydrogen production process using hydrocarbon fuels is divided into four methods: SR, POX, ATR, and dry reforming (DR) [43]. These methods produce significant amounts of carbon monoxide. Therefore, one or more chemical reactors are used in a subsequent stage to convert carbon monoxide into carbon dioxide through the water-gas shift (WGS) and methanation processes.

5.1.1.1. Steam methane reforming (SMR). SMR is now one of the most common and least expensive methods of producing hydrogen [57]. Its benefit stems from its excellent operating efficiency and affordable operational and manufacturing expenses. SMR is a chemical process that produces hydrogen, carbon monoxide, and other valuable chemicals from natural gas or other hydrocarbon feedstocks. It is a primary hydrogen production method widely used in the chemical and petrochemical industries.

The conventional process of SMR involves using methane and steam to produce a combination of hydrogen and carbon monoxide, which is typically done at high temperatures (700–1000 °C) and pressures (3–25 bar) with the aid of a catalyst (reaction (1)). The catalyst can be either non-precious metals, such as nickel, or precious metals from the Group VIII elements, like platinum or rhodium [58,59]. The CO further reacts with steam in the so-called WGS reaction to form carbon dioxide and additional hydrogen (reaction (2)) [60,61].

$$CH_4 + H_2O \rightarrow CO + 3\ H_2, H^o_{298} = 206\,\frac{\text{kJ}}{\text{mol}}\ \text{(Reforming reaction)} \tag{1}$$

$$CO + H_2O \rightarrow CO_2 + H_2, H^o_{298} = -41\,\frac{\text{kJ}}{\text{mol}}\ \text{(Water–Gas Shift reaction)} \tag{2}$$

The reaction releases heat as a byproduct (reaction (1)), commonly used to create steam for power generation or other industrial applications. Additionally, the process includes a step to remove carbon dioxide [62], and other feedstocks such as lighter hydrocarbons, methanol and oxygenated hydrocarbons can also be used [63]. The network of reforming reactions for feedstocks such as hydrocarbons and methanol can be seen in Eqs. (3)–(6) [64]:

$$C_mH_n + m\ H_2O\ (g) \rightarrow mCO + (m + 0.5n)H_2 \tag{3}$$

$$C_mH_n + 2m\ H_2O\ (g) \rightarrow mCO_2 + (2m + 0.5n)H_2 \tag{4}$$

$$CO + H_2O\ (g) \leftrightarrow CO_2 + H_2 \tag{5}$$

$$CH_3OH + H_2O\ (g)\ \leftrightarrow CO_2 + 3H_2 \tag{6}$$

The SMR process is divided into two stages. In the first stage, hydrocarbon raw material is mixed with steam and fed into a reactor [65], where it produces syngas (an equimolar synthesis gas containing hydrogen and carbon dioxide) with a reduced carbon dioxide content (reaction (3) and (4)). In the second stage, the cooled product gas is sent to a carbon monoxide catalytic converter, where steam helps convert carbon monoxide into carbon dioxide and hydrogen (reaction 5). The catalytic process of steam reforming, which is used to avoid catalyst deactivation, necessitates a feedstock material free of sulphur-containing compounds. The H: C atom ratio in the feedstock

Table 3
Summary of current reviews on hydrogen production, technologies, strategies and policies, and feasibility of commercialisation.

Ref.	Title	Summarised Review Scopes	Categories	Findings
[28]	"Explaining hydrogen energy technology acceptance: A critical review"	Examines the factors contributing to hydrogen energy technology acceptance and suggests that effective communication, public education, policy, and industry standards are crucial.	Hydrogen energy technology	Perceived benefits, costs, risks, and associated emotions are significant drivers of hydrogen energy technology acceptance.
[29]	"Present and projected developments in hydrogen production: A technological review"	Provides a comprehensive overview of methods for producing hydrogen, highlighting the obstacles that need to be overcome.		Producing hydrogen is intricate and involves multiple stages, adding costs and operational losses, especially for hydrogen as a commodity transportation fuel.
[4]	"Economics of converting renewable power to hydrogen"	Discusses the economics of converting renewable power to hydrogen and suggests that hydrogen production from renewable power may become more cost-effective.		Renewable hydrogen is cost-competitive in specific niche applications (USD 3.41 per kilogram) but not yet for industrial-scale supply, particularly in Germany and Texas.
[30]	"Hydrogen on the rise"	Discusses the recent advancements in using hydrogen to store energy despite progress being slower than anticipated.		While battery electric vehicles (BEVs) have dominated the green transportation landscape, fuel cell electric vehicles (FCEVs) fuelled by hydrogen are making significant strides.
[31]	"Green, turquoise, blue, or grey? Environmentally friendly hydrogen production in transforming energy systems"	Compares the environmental impact of four technologies used in hydrogen production and suggests that renewable carbon-free resources are crucial for mitigating the adverse environmental consequences of global warming.		The choice of the most environmentally friendly hydrogen production method depends on geographical and economic constraints.
[32]	"What role does hydrogen have in the future of electric mobility?"	Examines hydrogen's role in fuel cell vehicles, production, market values, the impact of public policy, and the role of hydrogen production in different sectors.		Hydrogen fuel cells might find applications in backup power generation and large-scale storage, but their future depends on competing alternatives like redox flow batteries and their turnaround efficiency.
[33]	"Hydrogen production"	It discusses the importance of hydrogen and production technologies compared to natural gas and crude oil and their applications.		Hydrogen production costs vary based on energy source, feedstock, and capital investment. Wind and solar electrolysis have the highest production cost per kg of hydrogen, and production costs are influenced by technology advancement, existing infrastructure, and feedstock prices.
[34]	"Green hydrogen supply: A guide to policy making"	Examines the policies required to accelerate and support the widespread adoption and commercialisation of green hydrogen.		Proper policies are necessary, including direct grants, feed-in tariffs, tax incentives, and R&D funding. Policies are urgently adopted to ensure the affordable decarbonisation of hard-to-abate sectors and enable the energy transition.
[12]	"Green hydrogen: A guide to policy making"	Guide policymakers on implementing policies that support green hydrogen as a feasible way to decarbonise the energy sector.	Strategies and policies for promoting green hydrogen deployment	IRENA has identified four pillars for green hydrogen policy-making: 1. National Hydrogen Strategies 2. Policy Priorities 3. Guarantee of Origin Systems 4. Enabling Policies
[35]	"Global hydrogen trade to meet the 1.5 °C climate goal: Part II – Technology review of hydrogen carriers"	Evaluates hydrogen transportation through pipelines and three alternative methods: ammonia, liquid hydrogen, and liquid organic hydrogen carriers (LOHC).	Methods and technologies for hydrogen production and transportation	Ammonia ships are the most attractive for a wide range of combinations.
[36]	"Global hydrogen trade to meet the 1.5 °C climate goal: Part III – Green hydrogen cost and potential"	Explores the global cost evolution of green hydrogen up to 2030 and 2050.		Green hydrogen production costs could decrease dramatically, reaching as low as USD 0.65/kg of hydrogen for the best locations in the most optimistic scenario by 2050. Even in a more conservative scenario, the cost could be USD 1.15–1.25/kg H_2 for 74 EJ (EJ) per year demand.
[37]	"Life cycle assessment of biohydrogen production as a transportation fuel in Germany"	Investigates the lifecycle of hydrogen production from biomass for transportation purposes.		Hydrogen production from woody biomass resulted in the lowest emissions, mainly due to the low emissions associated with biomass provision.
[38]	"Green methods for hydrogen production"	Examines environmentally friendly and sustainable hydrogen production methods, categorising them based on the intended uses and power sources.		Green hydrogen production categories include electrical, thermal, biochemical, photonic, electro-thermal, photo-thermal, photo-electric, photo-biochemical, and thermal-biochemical processes.
[39]	"Green hydrogen for industry: A guide to policy-making"	Examines the challenges of green hydrogen in the industrial sector and offers policy options to address those challenges.	Considerations for policymakers and the energy system	The barriers include cost, investment, technicality, lack of value recognition, low demand, and insufficient policy ambition. The policy options include an industrial

(*continued on next page*)

Table 3 (*continued*)

Ref.	Title	Summarised Review Scopes	Categories	Findings
				decarbonisation strategy, technological mandates, and certification systems.
[40]	"Global hydrogen development - A technological and geopolitical overview"	The paper covers the various technical and technological developments related to hydrogen production, refinement, compression, storage, transport, and utilisation.		The technical advancements include purification, compression, transportation, and usage. Green hydrogen's competitiveness depends on extensive development of renewable energies, such as creating large-scale facilities for manufacturing electrolysers and fuel cells and establishing hydrogen refuelling stations, particularly for transportation needs.
[41]	"Global warming consequences of replacing natural gas with hydrogen in the domestic energy sectors of future low-carbon economies in the United Kingdom (UK) and the United States"	It aims to measure the impact of hydrogen as an indirect GHG on the distribution of methane in the troposphere and tropospheric ozone.	Potential benefits and challenges of using green hydrogen	Replacing natural gas with green hydrogen in domestic sectors could substantially reduce the consequences of global warming, provided hydrogen leakage is minimised.
[42]	"Cost-benefit analysis, levelised cost of energy (LCOE), and evaluation of financial feasibility of full commercialisation of biohydrogen"	The article discusses the concept of cost-benefit analysis and uses the LCOE to evaluate the economic viability of biohydrogen technology. The authors examine the costs of biohydrogen production, storage, and transportation and compare them to the potential benefits.	Feasibility and sustainability of biohydrogen commercialisation	Biohydrogen's economic viability is less sensitive to the cost of biomass feedstock but more sensitive to capital and operational expenditures.

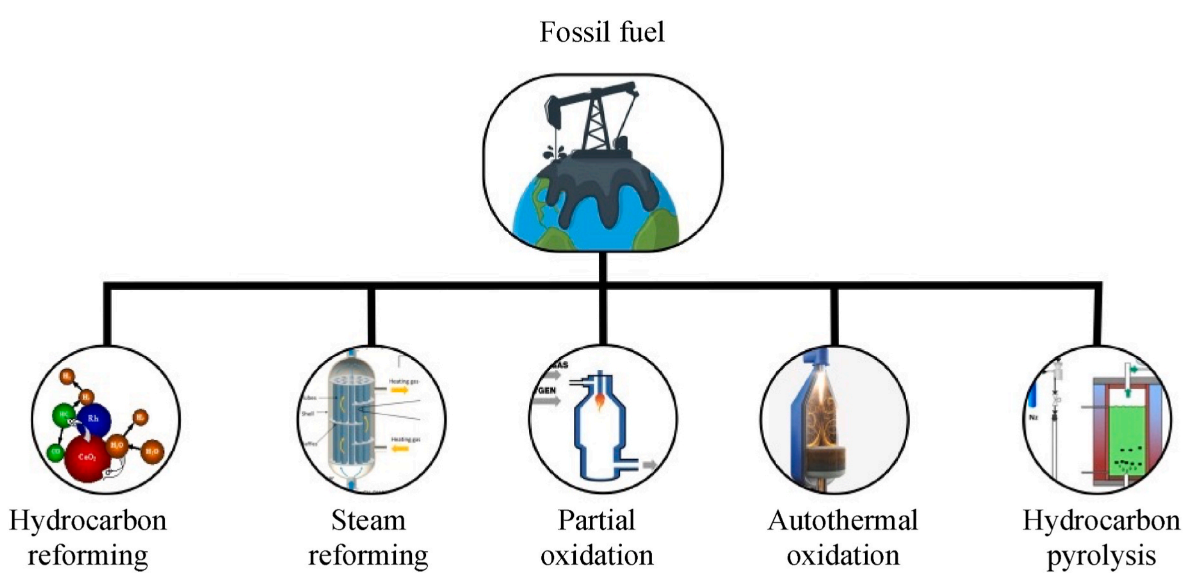


Fig. 4. Fossil fuel-based production technologies.

material is crucial in determining the efficiency of the SR process, with a higher ratio resulting in lower carbon dioxide emissions. A membrane reactor can be used instead of traditional reactors to complete the reaction [66]. In industrial applications, the thermal efficiency of hydrogen synthesis through the SMR is typically around 70–85 % [67].

SMR is a vital process for producing hydrogen, which has many uses, including fuel cell power generation, fuel for transportation, and as a chemical feedstock for producing ammonia and other chemicals. It is also used to produce carbon monoxide, which can be used as a feedstock for many chemicals, including methanol and acetic acid. SR has the potential to achieve both the highest feasible hydrogen efficiency and the lowest possible carbon monoxide content. Meanwhile, steam reformation is an endothermic process that requires much energy. The performance of traditional steam reformers is hindered by the low effectiveness of pelletised catalysts, which typically have an efficacy factor of less than 5 % due to limitations in mass and heat transport [68]. As a result, kinetics is a limiting factor in traditional steam reformer reactors [69], and less expensive nickel catalysts are utilised in industry.

Despite significant progress, industrial SMR remains inefficient regarding energy integration, intensity, and GHG emissions due to the complex multistep process. Therefore, there is a high demand for developing technologies to produce blue hydrogen instead of grey hydrogen using CCSU technology, making the process economically viable. Several new technologies have been proposed to improve the efficiency of SMR while reducing energy input and GHG emissions [70]. These technologies include:

- Membrane technology: This technology uses membranes to separate hydrogen from the other SMR reaction products, allowing for a more efficient process [71].
- Sorption-enhanced steam methane reforming (SESMR): This technology uses sorbents to capture carbon dioxide from the SMR reaction, which reduces GHG emissions [72].
- Chemical looping steam methane reforming (CL-SMR): This technology uses a cyclic process of oxidation and reduction to produce

Table 4
Different studies of fossil fuel-based production technologies for hydrogen production.

Process	Parameters	Findings	References
Supercritical water gasification	Temperature: autoclaved at 750 °C, 30 min Pressure: 24–26 MPa Additives: K_2CO_3/γ-Al_2O_3	H_2 increased by ≈ 20 % by K_2CO_3	[45]
Supercritical water gasification	Temperature: 400–450 °C Time: 1–30 min Pressure: 24–26 MPa Additives: H_2O_2 and KOH	H_2 production (mol/kg OM) increased by ≈ 930 % (0.026–0.37 mol/kg OM) when added KOH	[46]
Supercritical water gasification	Temperature: 350–750 °C Time: 0–90 min Pressure: 16.87–24.87 MPa Additives: K_2CO_3	H_2 yield: increased by ≈ 137 % (from 33.18 to 78.62 mol/kg)	[47]
Electrochemical catalytic coal gasification (ECG)	Enhancement: Ni–Cr wire in ECG Temperature: 800 °C Power: 400 W	CO yield increased 185 % at 800 °C from 0 to 400 W. CO is the main combustible product with a small amount of CH_4 and H_2.	[48]
Autothermal reforming (ATR)	Catalyst: Rh10, Rh20, Rh60 Temperature: 750 °C	Highest H_2 concentration (dry basis): ATR (≈40 vol%, Rh20)	[49]
Autothermal reforming (ATR)	Catalyst: Rh/CeO_2 and Rh/Al_2O_3 Temperature: 850 °C Gas hourly space velocity (GHSV): 5000/h	Highest H_2 concentration: 28 vol%	[50]
Autothermal reforming (ATR)	Catalyst: RhPt Temperature: 700–900 °C Gas hourly space velocity (GHSV): 30,000/h	Highest H_2 concentration: 37 to 39 vol%	[51]
Hydrocarbon Pyrolysis	Catalyst: H-ZSM-11 zeolite Temperature: 500–900 °C Heating rate: 10 °C/min	Gas yield: increased up to 80.8 wt% at 700 °C.	[52]
Hydrocarbon Pyrolysis	Catalyst: chromium wires Temperature: 1200–1475 °C	Conversion efficiency of alkanes to H_2: increased to 100 % at 1475 °C (2.42 %)	[53]
Hydrocarbon Pyrolysis	Catalyst: HZSM-5 Temperature: 500–700 °C	Highest H_2 yield (%): 68.6 % when co-pyrolysis with polyethene	[54]
Hydrocarbon partial oxidation	Oxidant type: Air, enriched air, oxygen Pressure: 0.2–8.0 MPa Temperature: 700–3300 °C	Highest H_2 concentration: 50.2 vol%	[55]
Methane partial oxidation	Oxidant type: with and without oxygen Pressure: 0.101–5.05 MPa Temperature: 500–1300 °C Oxygen/alkane ratio: 1.0–4.0 Post-flame zone: pyrolysis, steam reforming	Highest H_2 concentration (without oxygen): 2.5–3.0 mol/mol CH_4	[56]

hydrogen from methane, which is more efficient and produces fewer GHG emissions than conventional SMR [73].

- Chemical looping sorption-enhanced steam methane reforming (CL-SESMR): This technology combines the benefits of CL-SMR and SESMR to improve the efficiency further and reduce GHG emissions of SMR [74].
- Solar-assisted steam methane reforming (SASMR): This technology uses solar energy to provide the heat required for the SMR reaction, which reduces the need for fossil fuels and GHG emissions [75].
- Electrified steam methane reforming (ESMR): This technology uses electricity to drive the SMR reaction, which is more efficient and produces fewer GHG emissions than conventional SMR [76].

These technologies are still under development, but they have the potential to improve the efficiency and environmental performance of SMR significantly.

5.1.1.2. Partial oxidation (POX) and catalytic partial oxidation (CPOX). Hydrocarbon POX and CPOX have been proposed to produce hydrogen for transport fuel cells and other commercial applications [77,78]. The raw materials used in these methods can be methane or biogas, but they are primarily heavy oil fractions that are challenging to process and utilise [79]. POX is a non-catalytic process that gasifies raw material in the presence of oxygen (reactions (7) and (8)) and possibly steam ((9), ATR) at temperatures ranging from 1300 to 1500 °C and pressures ranging from 3 to 8 MPa. More carbon monoxide is generated (H_2: CO = 1: 1 or 2: 1) when compared to SR (H_2: CO = 3: 1). As a result, the process is completed by converting carbon monoxide with steam into hydrogen and carbon dioxide.

$$CH_4 + O_2 \rightarrow CO + 2H_2 \tag{7}$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{8}$$

$$CH_4 + H_2O\ (g) \rightarrow CO + 3H_2 \tag{9}$$

In order to bring down the working temperature, which is typically in the range of 700–1000 °C, catalysts can be introduced to the CPOX. The employment of a catalyst in a reforming process typically allows for lower operating temperatures and higher hydrogen yields, resulting in higher efficiency and reduced production costs. Maintaining temperature control has been proving difficult due to the exothermic nature of the reactions, which results in the development of coke and hot spots [77,80].

The exact products of POX depend on the type of hydrocarbon being oxidised and the reaction conditions. For example, the POX of methane produces a mixture of carbon dioxide and water, while the POX of propane (C_3H_8) produces a mixture of carbon dioxide, water, and hydrogen. Temperatures between 800 and 1000 °C, an oxygen-to-ethanol molar ratio of 0.6–0.8, and atmospheric pressure are the best operating conditions for POX of ethanol (POE) for hydrogen production.

Under these conditions, complete ethanol conversion and a hydrogen yield of 86–95 % are possible without coke formation [81].

POX is a widely used method for producing hydrogen, and it has several benefits over other methods, such as SR or electrolysis. It has high efficiency, can use a wide range of feedstocks, and does not produce carbon dioxide as a by-product. However, it also has some drawbacks, such as expensive equipment, a specialised catalyst, and water production as a by-product, which can be challenging to separate from the hydrogen gas. Compared to ATR, the POX process in fossil fuel reforming occurs at high pressure. Overall, POX of hydrocarbons is a complex and multifaceted chemical reaction that plays a significant role in many industrial processes.

5.1.1.3. Autothermal reforming (ATR). ATR was developed to solve the problem of reduced hydrogen yield in POX and the endothermic heat of reaction in SR. ATR combines these two processes, making it an attractive option for the onboard reforming of complex hydrocarbons such as kerosene and diesel to provide hydrogen to fuel cells. As previously mentioned, steam is added to the catalytic POX process in ATR. ATR is a combination of both SR (endothermic) and POX (exothermic) reactions [64].

The ATR process is generally defined by the following (Eq. (10)):

$$C_nH_mO_p + x(O_2 + 3.76\,N_2) + (2n - 2x - p)H_2O \leftrightarrow nCO_2 + \left(2n - 2x - p + \frac{m}{2}\right)H_2 + 3.76xN_2 \tag{10}$$

The oxygen-to-fuel molar ratio (x) impacts the hydrogen production, reaction heat, and amount of water required to convert fuel carbon to carbon dioxide [82]. Even after the water/gas shift reaction, the concentration of carbon monoxide in the gas produced by POX of hydrocarbon fuels frequently exceeds 1 % by volume. Other processes are necessary to lower the carbon monoxide level further. The POX must generate enough heat to produce hydrogen endothermically; thus, the (x) must be such that the reaction is exothermic.

ATR is advantageous because it does not call for any additional heat source and is easier and more cost-effective than SR of methane. Fig. 5 is a diagram that illustrates the several modes of operation that a fuel processor can go through to produce hydrogen.

From Fig. 5, a key benefit of the ATR process compared to the SR process is that it may be turned off and restarted relatively quickly while simultaneously creating more hydrogen than POX alone [64]. Even though ATR and POX procedures do not require external heat supplies, they are more expensive than other alternatives [83]. Pure oxygen input and separation equipment, such as an oxygen separation system, raise the cost of these procedures.

5.1.1.4. Dry reforming (DR) (also known as carbon dioxide reforming). DR is a process used to produce hydrogen and carbon monoxide from natural gas and carbon dioxide. The process involves reacting methane (the main component of natural gas) with carbon dioxide to produce syngas [84]. The general reaction is as follows:

$$CH_4 + CO_2 \rightarrow 2CO + 2H_2, H^o_{298} = +247.4\,\frac{\text{kJ}}{\text{mol}} \tag{11}$$

The reaction is typically carried out at high temperatures (700–1100 °C) and pressures (1–10 bar) in the presence of a catalyst, such as nickel or cobalt. The reaction is endothermic, meaning that it requires an input of heat to proceed. This reaction not only helps in waste management through methanation but also has the benefit of combusting methane and carbon dioxide, both greenhouse gases [24]. Additionally, the syngas obtained in this reaction, with a hydrogen/carbon monoxide ratio close to one, is valuable in the chemical industry as it is used in various types of highly specific syntheses to produce a wide range of chemical compounds such as formaldehyde, acetic acid, and liquid hydrocarbons [85].

Ethanol can also be converted into hydrogen through dry reforming. However, it is much less known [86]. The general reaction is as follows:

$$C_2H_5OH + CO_2 \leftrightarrow 2CO + 2\,H_2 + H_2O + C \tag{12}$$

The main disadvantage of this process is that the carbon dioxide reformation produces inert solid carbon, which can deactivate the catalysts utilised [87]. The DR of ethanol for hydrogen synthesis is a complex multiple-reaction system with several unwanted side reactions that affect product distribution [88]. As a result, hydrogen yield is complexly dependent on process variables such as pressure, temperature, and carbon dioxide-to-ethanol molar ratios, to name a few. One of the benefits of DR is that it allows for hydrogen production using a feedstock that is abundant and relatively inexpensive (natural gas). The process also captures and utilises carbon dioxide, which can help mitigate GHG emissions. However, DR can be expensive, energy-intensive, and unsuitable for all applications. The thermodynamics for the DR reaction is not as favourable as the ATR or SMR reactions. However, the fact that 1 mol of carbon dioxide is consumed per mole of methane can lower the carbon footprint, making the consumption of natural gas (and methane) more environmentally friendly.

5.1.2. Hydrocarbon thermal decomposition (TD)

TD is a method for producing carbon dioxide-free hydrogen from natural gas. The reaction can be written as follows:

$$CH_4 \rightarrow C + 2H_2, H^o_{298} = +75.6\,\frac{\text{kJ}}{\text{mol}} \tag{13}$$

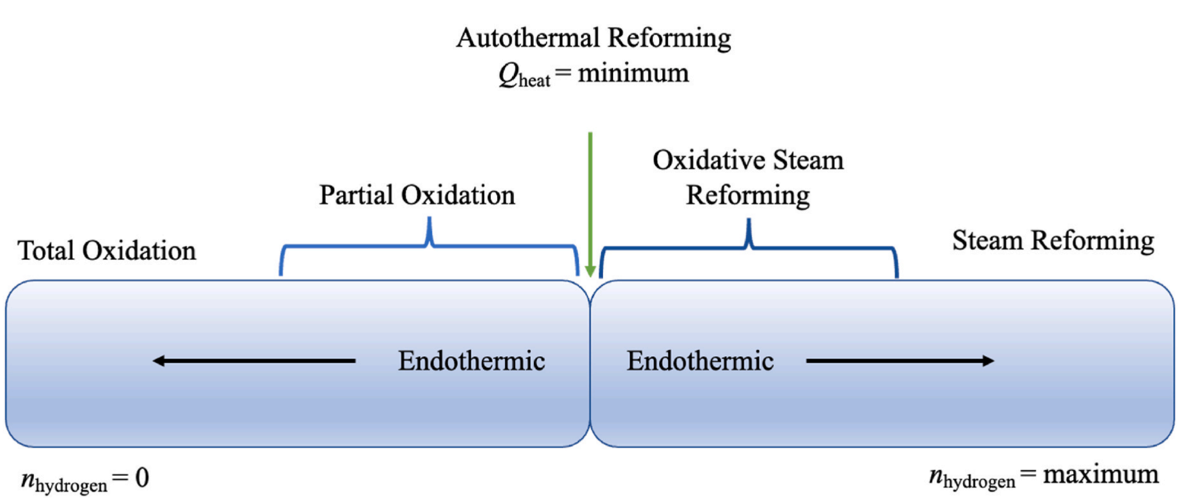


Fig. 5. Operating conditions for POX, ATR, and SR [43].

The temperature of the pyrolysis process can be significantly decreased by utilising a transition metal catalyst such as (Ni, Fe, or Co) [89]. The energy needed to produce 1 mol of hydrogen (75.6/2 = 37.8 kJ/mol H_2) is slightly lower than the SR process. The process is only slightly endothermic, requiring less than 10 % of the heat generated by burning methane to be driven forward. The process also produces a valuable by-product, pure carbon, in addition to the main product, hydrogen. Because the process creates only trace amounts of carbon dioxide (about 0.05 m^3 of carbon dioxide for every m^3 of hydrogen manufactured if methane is used as a fuel), it does not harm the environment [62]. It is worth noting that the process can produce no carbon dioxide if a small portion (about 14 %) of the generated hydrogen is used to fuel the process. However, despite the benefits of pyrolysis, there is a significant potential for fouling from the carbon produced, which can be mitigated using an appropriate reactor design [90].

5.2. Renewable sources-based production technologies

The categorisation of hydrogen production methodologies derived from renewable sources, segregating them into biomass-related and water-splitting processes as presented in Fig. 6. The water-splitting category encompasses techniques such as electrolysis, thermolysis, and photolysis. Conversely, biomass-centric methodologies integrate both biological and thermochemical procedures. Table 5 provides a synthesis of the cutting-edge technologies rooted in renewable sources for hydrogen generation. These techniques encompass dark fermentation, photo fermentation, pyrolysis, photocatalytic water splitting (photolysis), thermolysis, and electrolysis. For each technique, the table enumerates the parameters utilised within the investigation, the employed substrate and inoculum, additives incorporated, and the zenith of hydrogen yield observed. The optimal methodology for green hydrogen generation may exhibit variability contingent upon the bespoke application demands, inclusive of parameters, additive components, and prevailing conditions.

5.2.1. Water-splitting technology

Hydrogen, composed of hydrogen and oxygen, may be produced from water, the most readily available resource [105]. Therefore, if sufficient energy is applied, the water molecule can be broken down into hydrogen and oxygen parts. The process of water splitting can be carried out using a variety of different technologies. Hydrogen can be extracted from water using electricity (electrolysis), photonic energy (photolysis), or thermal energy (thermolysis) [106,107].

5.2.1.1. Electrolysis. Fig. 7 represents the conceptual setup for four electrolyser technologies: alkaline-based electrolysis, PEM, SOEC, and AEM. Electrolysis is one of the most straightforward processes for creating hydrogen from water. The reaction, however, is very endothermic; as a result, the necessary energy input is accomplished through electricity obtained from PV panels or steam turbines [108–110]. It is a process in which electrical energy is converted into chemical energy in the form of H_2 and O_2 as a byproduct. Two reactions occur in each electrode (anode and cathode) [111]. A separator between the anode and cathode electrodes guarantees that the products remain segregated. Water splits when electricity is applied, producing H_2 at the cathode and O_2 at the anode via the following reaction:

$$2H_2O \rightarrow 2H_2 + O_2 \tag{14}$$

The cathode produces hydrogen, while the anode produces oxygen. In an alkaline environment, the following reaction mechanism can be considered [43,108]:

$$\text{Cathode}: 2H_2O\ (l) + 2e^- \rightarrow\ H_2(g) + 2\ OH^-\ (aq) \tag{15}$$

$$\text{Anode}: 4\ OH^-\ (aq) \rightarrow O_2(g) + 2H_2O(l) + 4e^- \tag{16}$$

Although alkaline-based electrolysis is the most prevalent electrolysis technique, more proton exchange membrane (PEM) electrolysers, anion exchange membrane (AEM) electrolysers and solid oxide electrolysis cells (SOEC) units are being developed [112,113]. Water is injected into the PEM electrolyser at the anode. It is split into protons (H^+) that move through the membrane to the cathode to generate hydrogen and oxygen that remain with the water [40]. In alkaline and SOEC, water is supplied at the cathode and split into hydrogen, separated from water in an external separation unit, and hydroxide ions (OH^-), which flow through the aqueous electrolyte to the anode to generate oxygen. AEM electrolysers operate in an alkaline environment, but the typical diaphragms (asbestos) in the alkaline-based method are substituted with anion exchange membranes (immobilised positively charged functional groups on the polymer backbone or pendant polymeric side chains) [114].

Catalysts and materials also play a critical role in the development and improvement of electrolysers. Innovations in catalysts and materials

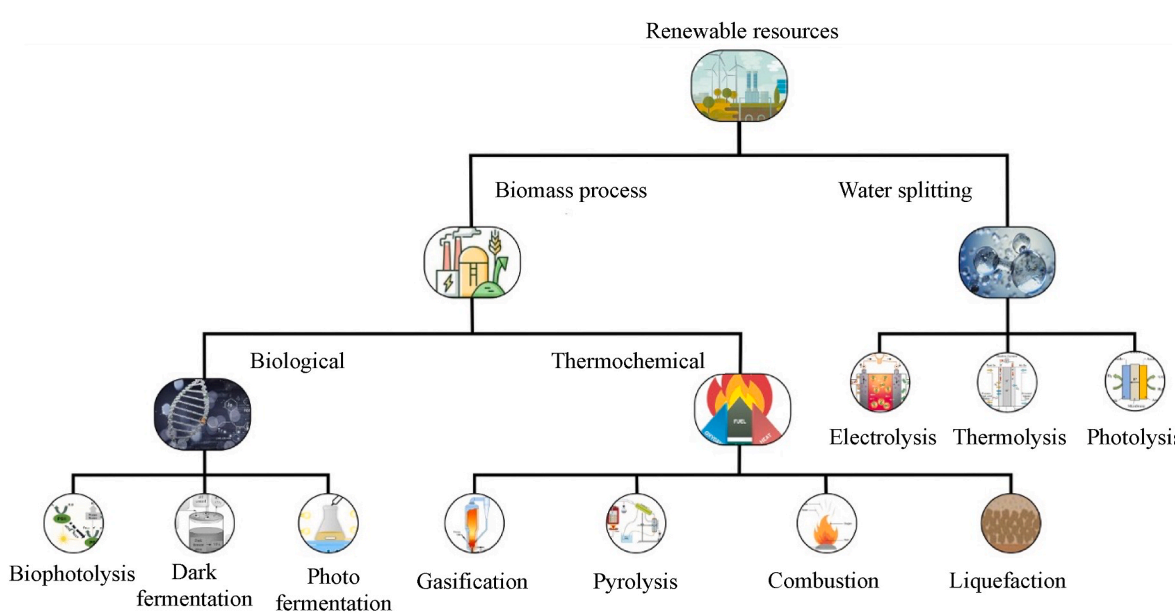


Fig. 6. Renewable sources-based production technologies.

Table 5
Recent studies of renewable sources-based production combining biological, thermochemical, and water splitting technologies.

Process	Parameters	Findings	References
Dark fermentation	Types: exogenous and endogenous Temperature: 37 °C Stirring speed: 220 rpm Nitrogen gas flowrate: 50 mL/min pH: 5.7 Substrate/inoculum heat treatment: 70 °C, 1 h	Highest H_2 production: 8.91 and 8.18 mmol/$L_{reactor}$/hour from heat-treated exogenous fermentation	[91]
Dark fermentation	Additive: Fe_3O_4 nanoparticles as catalyst Temperature: 35–42 °C Stirring speed: 110 rpm Duration: 168 h pH: 6–8 Inoculum: Residual algal biomass Substrate: Glucose	Highest H_2 production: ≈937 mL/L (cumulative) in 168 h, pH 7.5, 40 °C (~37 % higher compared to control)	[92]
Dark fermentation	Temperature: 35 ± 2 °C Duration: until no hydrogen is produced pH: uncontrolled Heat-treated inoculum: Anaerobic digestate Substrate: olive oil mill wastewater and cheese whey	Highest H_2 production: 2.08 L/L when co-fermented 100 % olive wastewater and 20 % cheese whey	[93]
Photo fermentation	Temperature: 20–45 °C Light intensity (Lux): 1000–5000 Inoculation amount: 15–40 % pH: 5.5–8 Photosynthetic bacteria: HAU-M1 (PSB) Substrate: 8 types of shrub landscaping wastes	Highest H_2 production: 73.82 ± 0.06 mL/g TS at 29.78 °C, pH 6.78, 3000 Lux, substrate concentration of 21.49 g/L from *Buxus megistophylla*	[94]
Photo fermentation	Additive: Furfural (0–20 mM) Temperature: 30 °C Light intensity (Lux): 3000 pH: 7 Photosynthetic bacteria: *Rhodobacter capsulatus* SB1003 Substrate: glucose	Highest H_2 production: 2.59 ± 0.13 mol H_2/mol glucose (without furfural); 2.34 mol H_2/mol glucose (with 2 mM furfural)	[95]
Photo fermentation	Temperature: 30 °C Light intensity (Lux): 4000–7000 Duration: 24 and 36 h pH: 7 Photosynthetic bacteria: HAU-M1 Substrate: Giant reed	Highest H_2 production: 5.3 mL/g TS/h (26.2 % higher than no perturbation)	[96]
Pyrolysis	Additive: different types of promoter metals added to Ni–Al_2O_3 (catalyst) Source: biomass, cellulose, lignin Carrier gas: Nitrogen Temperature: 20–600 °C	Highest H_2 yield (H_2 mmol/g biomass): Ce–Ni–Al_2O_3 (1.46-fold increase) H_2 production was directly proportional to the following: i) the porosity and surface area ii) the catalyst material dielectric constant	[97]
Pyrolysis	Source: wood sawdust Carrier gas: Nitrogen Temperature: 550 − 700 °C Additive: Ni/CaO Magnetic field intensity (mT): 0–80	H_2 yield and content: increased by 19.78 % and 9.50 % Highest H_2 content: 63 vol% at 80 mT, 650 °C, 10 wt% Ni/CaO catalyst Highest H_2 yield: 469.2 mL/g at 80 mT, 650 °C, 10 wt% Ni/CaO catalyst	[98]
Pyrolysis	Source: pine sawdust Carrier gas: Nitrogen Temperature: 400 − 850 °C Additive: aluminium dross	H_2 yield: increased by ~ 33 % when added aluminium dross, compared to pure pine sawdust	[99]
Photolysis/photocatalytic water splitting	Time: 0–180 min pH: 6–11 Catalyst: 3.9 mol.% ZnS/CdS photocatalyst	Highest H_2 production: 16.1 mmol/g at 180 min, pH 8	[100]
Thermolysis	Additives: different metal chloride doped sodium-borohydride ($NaBH_4$) Ways: i) ex-situ thermolysis ii) in-situ thermolysis Temperature: 100–500 °C Holding time: 1 h Methods: wet ball-milling, dry ball-milling, facile solution	Highest H_2 production: ~3.68 wt% with 50 $CaCl_2$/$NaBH_4$ as additive at 100 °C using wet ball-milling method	[101]
Electrolysis	Source: lignocellulose (*Bambusa bambos*) Treatment: enzyme (10 % w/w laccase) Voltage: 0.6–1.0 V Mixing: 0–400 rpm Anode: coated with monodisperse iron oxide nanoparticles (IONPs)	Highest H_2 production: 0.02 g (224 mL)/gram biomass, 1.14 times higher efficiency with coated anode compared to uncoated at 0.8 V, 200 rpm	[102]
Combustion	Source: wood pellets + porous media Velocity: 2–8 cm/s Equivalence ratio (φ): 0.8 Temperature: 26.85–586.85 °C	Highest H_2 production: 25.39 % H_2 at 4 cm/s, 199.85 °C with maximum H_2 growth rate reached 142 %	[103]
Gasification	Biomass: sorghum Solvent: THF, NMP, acetone, methanol, tetralin, and xylene Temperature: 250–350 °C Catalyst: K_2CO_3, $NiCl_2.6H_2O$, KOH Stirring rate: 400 rpm	Highest H_2 production: 750 mL H_2, 25.5 ± 0.8 mol H_2/kg feed (yield) using NHF and $NiCl_2$/CaO at 350 °C	[104]

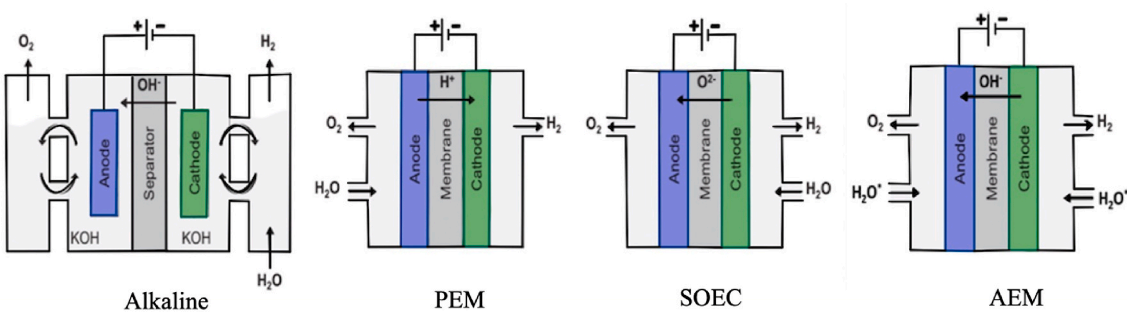


Fig. 7. Conceptual setup of four electrolysis cell technologies.

can significantly enhance electrolysers' efficiency, durability, and cost-effectiveness. For instance, platinum-based catalysts have been studied in PEM electrolysers. However, research has focused on reducing or replacing platinum with more abundant and cost-effective materials such as iridium, iridium oxide, or non-precious metal catalysts such as nickel-iron and cobalt-iron alloys [115]. Meanwhile, since SOEC usually operates at high temperatures, solid oxide electrolyte materials, such as yttria-stabilised zirconia (YSZ), are typically ceramic [116]. Advances in materials science are now focused on developing more conductive and stable electrolytes, such as cathode-supported cell materials [117]. Various catalysts, including perovskite-type materials and transition metal oxides, have also been studied to improve the electrode reactions in SOECs [118,119].

5.2.1.2. Thermolysis/thermochemical water splitting (TWSC). The TWSC, also known as thermolysis, employs the direct application of thermal energy to set in motion a series of iterative chemical reactions, which break apart water molecules [106,107,120]. One of the prerequisites for the breakdown of water is for Gibbs's energy to be equal to zero ($\Delta G = 0$), requiring a temperature around 2500 °C; however, materials that are stable at this temperature and sustainable heat sources are not readily available [83,121]. Thus, thermochemical water splitting cycles with oxidation/reduction chemicals are proposed to lower the temperature [122]. Many technologically feasible procedures such as copper-chlorine (Cu–Cl), iodine-sulphur (I–S), cerium-chlorine (Ce–Cl), magnesium-chlorine (Mg–Cl), magnesium-iodine (Mg–I), vanadium-chlorine (V–Cl), iron-chlorine (Fe–Cl), hybrid chlorine, hybrid sulphur (HyS), and copper-sulphate (Cu–SO_4) have recently been studied [123]. One significant disadvantage of most of the stated cycles is their necessity for high process heat, which can be around 800 °C, except for the Cu–Cl cycle, which requires significantly less (540 °C) [124]. Two types of TWSCs are two-step and multi-step [125]. According to studies, increasing the number of steps in a particular thermochemical cycle reduces the needed maximum temperature for the entire cycle. As a result, the cycle can incorporate more diverse heat sources. More than 300 thermochemical cycles for water splitting have been studied since the 1960s. However, few proposals for large-scale hydrogen synthesis have been made [112,126].

5.2.1.3. Photo-electrolysis/photolysis. Photo-electrolysis is a technique that uses sunlight to create hydrogen from water in a photo-electrochemical cell [127]. It is now the most cost-effective and efficient technique for producing hydrogen from renewable resources. The systems employed in photoelectrolysis are identical to those used in PV; semiconductor materials are utilised in both types of technology. Photoelectrolysis involves using a photoelectrode, a photo-electrochemical device that collects light, to perform water electrolysis. The photoelectrode is a semiconducting material that absorbs solar energy and generates the voltage needed to split water molecules into H_2 and O_2 [43]. If a photoelectrode is immersed in an aqueous electrolyte and exposed to solar radiation, it will generate enough electrical energy to produce H_2. The reaction can be presented as follows:

$$H_2O \xrightarrow{h\nu} H_2\,(g) + \frac{1}{2}\,O_2(g) \tag{17}$$

The reaction is affected by the semiconductor material types and the intensity of sunlight, producing a current density ranging from 10 to 30 mA/cm^2. Electrolysis requires a voltage of around 1.35 V when these current densities are present.

5.2.2. Biomass technologies

Biomass is a renewable energy source from plant and animal-based materials, including energy crop leftovers, forest waste, industrial by-products, animal and human waste, and various other sources [128,129]. Using biomass as clean alternative energy is becoming increasingly popular because it is renewable, produces low carbon dioxide emissions, and has a low sulphur content [130]. Biomass conversion technologies can be divided into two pathways: thermochemical and biological. Thermochemical techniques allow biomass conversion into hydrogen and hydrogen-rich gases through pyrolysis and co-pyrolysis, gasification, combustion and liquefaction [131,132]. Meanwhile, bio-photolysis (direct and indirect), photofermentation, dark fermentation, and biological shift reactions are all possible pathways for biological hydrogen synthesis.

5.2.2.1. Thermochemical. As previously stated, thermochemical techniques that convert biomass fuel into hydrogen or even hydrogen-rich gaseous streams are the most practicable [133]. Hydrogen or syngas produced from biomass could be a practical step towards achieving a climate with zero GHG emissions, which is critical in developing sustainable RE systems [134].

5.2.2.2. Pyrolysis and co-pyrolysis. Pyrolysis is one of the processes suited for producing hydrogen because it possesses benefits such as easy storage and transportation and is compatible with equipment such as turbines, incineration machines, containers, and appliances. The biological matter is heated and degassified at a pressure of 0.1–0.5 MPa to a temperature of 500–900 °C in an oxygen-free atmosphere during pyrolysis [135]. Although biomass pyrolysis was developed as a bio-oil production option, it could also produce hydrogen independently. Pyrolysis is a thermochemical process that produces bio-oil (liquid oil) and charcoal (solid) inside a gaseous stream by heating biomass without oxygen. In an atmosphere devoid of O_2, biomass conversion is a multi-step process involving nitrogen gas.

During the transformation process, temperatures might range from 300 – 500 °C to 700–800 °C [128,136]. The pyrolysis results go through secondary reactions, which, depending on the reactor settings, produce hydrogen gas and other by-products [137]. The pyrolysis also yields CH_4 and CO in addition to H_2, which can be turned back into H_2 by SR and WGS processes [112,126]. In addition to hydrogen, the gaseous stream contains significant amounts of CH_4 and light hydrocarbons, which might be steam-reformed to make more hydrogen. Furthermore, the CO contained in the gaseous steam might be transformed into hydrogen and carbon dioxide by a subsequent WGS process [138,139]. The co-pyrolysis of a coal blend with organic waste has recently gained attention in industrialised nations. The reason for this process is that it has the potential to reduce and alleviate the waste management problem [140].

5.2.2.3. Gasification. Gasification is considered one of the most successful technologies for converting biomass into power, heat and chemical compounds [141]. In gasification, biomass is heated by a gasifying agent such as air, oxygen or steam, which produces syngas. This process happens at high temperatures, ranging from 500 to 1400 °C, and is divided into pyrolysis and gasification. The first stage, pyrolysis, involves thermally breaking down the fuel to create volatile hydrocarbons and char, while the second stage, gasification, involves converting these products to syngas [142].

The composition of the resulting syngas is determined by various factors, including the composition of the biomass, the gasification technology, and the gasifying agent [139]. Because it is less expensive than oxygen, air is the most commonly used gasifying agent. When air is used, the resulting syngas has a lower energy content due to the nitrogen dilution effect, with an HHV of 3.7–6.4 MJ/m^3 at standard temperature and pressure (25 °C/1 atm) [143]. Gasification with oxygen and steam yields syngas with an HHV ranging from 9.2 to 16.5 MJ/m^3 at STP [139].

Unlike combustion, which converts the chemical energy of carbon in biomass into heat and light in one step, gasification converts the chemical energy into a combustible gas in two phases. The resulting syngas are comprised of carbon monoxide, hydrogen, carbon dioxide, methane, water, and traces of other components like tars and dust [144]. Syngas is more versatile and easier to use than the original biomass. They can be used to power gas engines and gas turbines or as a chemical feedstock for liquid fuels such as ammonia, methanol, hydrogen and diesel [145].

Gasification includes biochemical and thermochemical processes, with the former utilising microbes at room temperature under anaerobic conditions, i.e. anaerobic digestion, and the latter utilising air, oxygen, or steam at temperatures greater than 800 °C [144,146]. Supercritical gasification may convert agricultural and other wastes to high-pressure gas quickly and cheaply, removing the need for downstream operations [147]. The process's main by-products are H_2 and CO_2 [148]. Supercritical water is an organic solvent, so nonpolar groups in biomass (feedstocks) and gases are readily soluble. Supercritical biomass gasifiers typically require 600–800 °C without a chemical catalyst or less than 600 °C with a chemical catalyst [149].

5.2.2.4. Reforming. Biomass can be converted into bio-oil or syngas, typically used as low-quality fuels due to their complex compositions and low hydrogen content using pyrolysis and gasification. Several reforming processes, such as SR, DR, ATR, POX and chemical looping reforming (CLR), can produce high hydrogen yields over catalysts. The previous section discussed these reforming processes, except for CLR. The concept of CLR is based on the process of chemical looping combustion (CLC), which uses an oxygen carrier (OC) catalyst to transfer oxygen from the air to fuel without direct contact between fuel and air [150].

CLC is a revolutionary combustion method with intrinsic carbon dioxide separation that employs an OC to deliver oxygen from the air to fuel while avoiding direct contact between them [151]. The CLR process is comprised of two reactors: an air reactor (AR) and a fuel reactor (FR). The OC is continually moving between the two reactors. In the FR, the OC particles are reduced by the fuel, and the fuels are first oxidised to produce carbon dioxide and water before undergoing reforming and WGS reactions with steam. In the AR, oxygen oxidises the OC to its original state.

5.2.2.5. Biological. Bio-hydrogen research has risen dramatically in recent years due to a greater emphasis on sustainable development and waste minimisation. Production of hydrogen gas from biomass materials can be derived from a range of organic waste materials, including biodegradable plastic, agricultural waste and sewage sludge. Biological hydrogen production utilising carbohydrate-rich biomass as a renewable resource can be achieved using different approaches, such as bio-photolysis, dark fermentation, photo-fermentation, biological WGS and biocatalysed electrolysis.

5.2.2.6. Bio-photolysis. A bio photolytic process might theoretically yield a 2:1 ratio of H_2 to O_2 without carbon dioxide fixation or other intermediary metabolic-producing events [152]. Clean and sustainable energy from renewable resources can be produced through cyanobacteria and green microalgae biophotolysis of water. These organisms can use sunlight to split water into H_2 and O_2 molecules [153]. The hydrogen production process through biophotolysis or photoautotrophic process uses sunlight and carbon dioxide as the only source of energy to generate hydrogen gas through the hydrogenase enzyme process by bacteria and algae [154].

The benefit of biophotolysis is that there is no need to supply substrate as nutrients. Water is the principal electron donor required for hydrogen gas generation. Sunlight and carbon dioxide are the primary inputs required for this process. Photobiological hydrogen generation is possible through both direct and indirect bio-photolysis. In direct bio-photolysis, a photosynthetic device absorbs light. The recovered energy is utilised to link water splitting to create a low-potential reductant (ferredoxin), which inhibits hydrogenase and creates hydrogen. In comparison, water is split by photosystem II, and photosystem I (PSII and PSI) and ferredoxin reduction are employed to fix carbon dioxide in indirect biophotolysis [152].

5.2.2.7. Dark fermentation. Dark fermentation is another biological process to produce hydrogen, where anaerobic microorganisms such as microalgae or specific bacteria are kept in the dark at temperatures between 25 and 80 °C or higher, depending on the strains. These bacteria or microalga perform a series of intricate biochemical events to create hydrogen gas throughout several phases. The first phase is the enzymatic hydrolysis of high molecular weight organics into water-soluble organics, followed by the hydrolysis of simple organics into volatile fatty acids (VFA), hydrogen, and carbon dioxide [155,156]. Hydrogen is primarily created by the anaerobic metabolism of pyruvates produced during carbohydrate catabolism [157]. The reactions that produce hydrogen via dark fermentation are as follows:

$$C_6H_{12}O_6 \rightarrow 2H_2 + CH_3CH_2CH_2COOH + 2CO_2 \tag{18}$$

$$C_6H_{12}O_6 + 2H_2O \rightarrow 4H_2 + 2CH_3COOH + 2CO_2 \tag{19}$$

$$C_6H_{12}O_6 + 4H_2O \rightarrow 8H_2 + CH_3COOH + 4CO_2 \tag{20}$$

$$C_6H_{12}O_6 + 6H_2O \rightarrow 12\ H_2 + 6CO_2 \tag{21}$$

Because of the minor gases, the hydrogen yield is reduced compared to photolysis [158]. Dark fermentation techniques offer advantages and are more profitable than photo-fermentation procedures because they can continuously produce hydrogen and do not rely on solar energy [159].

5.2.2.8. Photo fermentation. Photo fermentation technology is still in the R&D phase for producing hydrogen. The metabolic conversion of organic molecules to biohydrogen by different photosynthetic bacterial species is known as photo fermentation. Photo fermentation is distinct from dark fermentation in that it occurs only in the presence of light. In a nitrogen-deficient media, nitrogenases in purple non-sulphur bacteria catalyse the conversion of organic acids or biomass into hydrogen via photosynthesis. The global reaction performed on glucose as the model substrate is represented by Ref. [160]:

$$C_6H_{12}O_6 + 6H_2O \xrightarrow{h\nu} 12\, H_2 + 6CO_2 \tag{22}$$

Photo fermentation can be accomplished in a single step or two stages. The single-step process is less expensive but has several limitations, such as high energy consumption from nitrogenases and limited solar energy conversion. The two-stage fermentation method starts with dark fermentation and then proceeds to photo fermentation to produce more hydrogen. However, this method has the disadvantage of being challenging to operate due to the management of different bacteria and parameters between the different phases [161,162]. Photo fermentation is currently considered the least commercially competitive biological approach for hydrogen production [163].

5.2.2.9. Biological water gas shift reaction (BWGS). The BWGS process can produce hydrogen from the synthesis gas. The capacity of photoheterotrophic bacteria belonging to carboxydotrophic hydrogenogens within the family *Rhodospirillaceae* to use carbon monoxide as a carbon source is required for the BWGS reaction [152]. These microbes can generate hydrogen (along with carbon dioxide) in the dark by oxidising carbon monoxide and reducing water via an enzyme route through Equation (23) [164]:

$$CO + H_2O \leftrightarrow CO_2 + H_2, H^o_{298} < 0\ \frac{kJ}{mol} \tag{23}$$

Other widely used microorganisms include *Rhodospirillum rubrum* and *Carboxydothermus hydrogenoformans* [165,166]. Lower temperatures and pressures (30–70 °C depending on the strain and ambient pressure) are advantageous over a thermochemical WGS reaction. Nonetheless, various parameters must be optimised. Carbon monoxide produced by the feedstock must be controlled because it reduces bacterial activity. Furthermore, microorganisms must be improved to boost concentration in the bioreactor. Finally, difficulties affecting gas-to-liquid mass transfer should be addressed [166].

5.2.2.10. Biocatalysed electrolysis. Biocatalysed electrolysis is a unique biological hydrogen production technology that efficiently converts a broad spectrum of dissolved organic compounds into wastewater. Biocatalysed electrolysis does this by deploying electrochemically active microorganisms capable of generating electrical current from the oxidation of organic materials. Hydrogen is produced when this biological anode is connected to a proton-reducing cathode through a power supply. Microbial Fuel Cells (MFCs) and Microbial Electrolysis Cells (MECs) are the two basic types of biocatalysis electrolysis-based bio-electrochemical systems (BESs). MFCs use cathodes exposed to air, resulting in electricity production and an oxygen reduction reaction [167]. Meanwhile, MEC requires a tiny additional electrical energy input from an external power supply to enhance the hydrogen production process on the cathode [168]. Acetate can be biocatalytically electrolysed by the following reaction [169]:

$$CH_3COO^- + 4H_2O \rightarrow 2\, HCO_3^- + H^+ + 4H_2 \tag{24}$$

Under typical conditions, hydrogen synthesis from acetate requires 104.6 kJ/mol of energy input, according to Gibbs free energy estimates [170]. As a result, in theory, hydrogen synthesis by biocatalysed acetate electrolysis requires only 0.14 V of applied voltage.

Various hydrogen production technologies exhibit varying levels of efficiency and maturity. Steam reforming, a commercialised method, achieves an efficiency range of 70–85 % [171,172]. Similarly, partial oxidation and autothermal reforming, also categorised as commercial methods, showcase efficiencies within the 60–75 % range. Meanwhile, plasma reforming, considered a long-term prospect, presents a broader efficiency range of 9–85 % [173]. Aqueous phase reforming, anticipated in the mid-term, demonstrates an efficiency range of 35–55 %. Biomass gasification, an already commercialised approach, displays 35–50 % efficiencies. Additionally, dark fermentation, photo fermentation, and MEC, representing long-term prospects, exhibit varied efficiencies of 60–80 %, 0.1 %, and 78 %, respectively. Alkaline and PEM electrolysers, at a commercial maturity level, have efficiency ranges of 50–60 % and 55–70 %, respectively [174]. SOECs, which are expected to reach maturity in the mid-term, showcase an efficiency range of 40–60 %. Lastly, photoelectrochemical water splitting, a long-term option, demonstrates an efficiency of 12.4 % [174]. Overall, these diverse technologies present a spectrum of efficiencies that are crucial for considering their integration into the hydrogen energy landscape.

5.3. Recent green hydrogen production technologies

Green hydrogen is produced using renewable energy sources, such as solar and wind power, to electrolyse water into hydrogen and oxygen. Water electrolysis is an electrochemical process that uses electricity to split water into hydrogen and oxygen [175]. It is a zero-emission technology that can produce green hydrogen, which is hydrogen produced from renewable energy sources. Electrolyser cells can be powered by renewable energy sources, such as solar cells and wind turbines, as well as waste heat from industrial processes, to produce hydrogen in an environmentally friendly manner [176]. Four water electrolysis technologies have been developed based on their electrolyte, operating conditions, and ionic agents (OH^-, H^+, O_2^-): alkaline, AEM, PEM, and solid oxide electrolysers [175,177]. All four technologies operate on the same principle of using electricity to split water molecules into hydrogen and oxygen.

SOECs have several advantages over PEM and alkaline electrolysers, which operate at lower temperatures. SOECs can produce hydrogen at a higher electrochemical reaction rate and lower electrical energy requirements [178]. SOECs can split steam and CO_2 into H_2 and CO [179]. They can also be operated in co-electrolysis mode, which converts a mixture of H_2O and CO_2 into syngas. In electric steam methane reforming (ESMR), the primary reformer in an SMR plant is modified to remove the burners and use electric heating instead of combustion heating [76]. High-purity green hydrogen can be produced from the air through a direct air electrolysis (DAE) process. In this process, moisture is directly absorbed by a hygroscopic electrolyte and split in situ into H_2 and O_2 [180,181]. DAE units can operate under low humidity conditions, comparable to deserts. Microbial bioelectrochemical systems (BESs) can generate electricity or other value-added products, such as H_2. BESs use microorganisms to catalyse electrochemical reactions at the anode and cathode. There has been a growing interest in developing BESs for H_2 production in recent years. MECs are a type of BES that can produce H_2 from various organic substrates [182–184]. MECs typically use heterotrophic bacteria attached to an anode to oxidise organic matter and generate electrons and protons. The electrons are transferred to the cathode, reducing protons to H_2.

In recent years, there have been several advancements in green hydrogen production technologies, which have the potential to make the production of green hydrogen more efficient, cost-effective, and scalable. At the moment, the cost of green hydrogen is around $2.50–6.80 per kilogram [185]. However, due to the combined impacts of cheaper renewable energy and reduced electrolyser cost, the price of green hydrogen is falling so rapidly that it will soon be competitive with blue hydrogen. In the United States, the DOE has announced a goal of reducing the cost of hydrogen production to $1 per kilogram by 2030. Table 6 lists several recent hydrogen production technologies. The source, process, advantages, disadvantages, and technology maturity are presented. The life cycle assessment or techno-economic study will not be discussed in this study due to data limitations such as the materials used, process, and transportation costs of each technology, as well as the GHG emissions data. Meanwhile, Fig. 8 summarises recent green hydrogen production technologies based on Table 6, which is covered in this review.

Fig. 8 demonstrates that, to date, SOEC, ESMR, AEM, DAE, and BPV

Table 6
Recent advancements in green hydrogen production methods.

Methods	Source/Feedstock	Process	Advantages	Disadvantages	TRL	Ref.
Solid oxide electrolyser cells (SOECs)	Steam Heat source: 1. Industrial waste heat. 2. Solar thermal and geothermal heat systems. 3. Nuclear power	650–1000 °C, <25 bar	1. Could sustain very high electrochemical reaction rates (current densities >1 A cm^{-2}). 2. Has a good load-following capability, hence excellent technology to integrate with intermittent renewable energy sources. 3. Lead to compact systems with smaller footprints than liquid-alkaline electrolyte systems. 4. Ideal for on-site. 5. Low material costs (use ceramics as the electrolyte). 6. Can be operated in reverse mode.	1. Cell component degradation. 2. Loss of gas tightness (electrolyte/sealant failure). 3. Mechanical instability due to heat stress. 4. Longer start-up/break-in periods.	6–7	[186–188]
Methane pyrolysis/ splitting	Energy source: Electricity Feedstock: Methane	>800 °C	1. No direct CO_2 emissions. 2. Creates solid carbon in the form of carbon black.	1. Significant thermal losses could reduce its efficiency. 2. Requires high-temperature plasma.	3–6	[3,187]
Electrified steam methane reforming (ESMR)	Natural gas (methane)	1. Pre-reforming 2. Reforming 3. Shift conversion 4. CO_2 capture 5. Compression and purification 6. Utilisation	1. Can combine with carbon capture, utilisation and storage (CCUS) to reduce CO_2 emissions. 2. Can reduce the cost of decarbonising hydrogen production.	1. The process is currently more expensive than traditional SMR. 2. Potential for methane leaks.	3–4	[187,189]
Anion exchange membranes (AEMs)	Membrane: solid polymer electrolyte	Use a transition metal catalyst (CeO_2–La_2O)	1. Does not require platinum. 2. The AEM acts as a solid electrolyte, preventing corrosive electrolytes. 3. Can operate under alkaline conditions. 4. Has a low internal resistance and high conductivity.	1. Less durable. 2. Less stable. 3. Low performance at high pressures and temperatures.	6–7 (for lab scale system)	[187,190, 191]
Hydroxide exchange membrane water electrolysers	High-purity water as the feedstock	Use a hydroxide exchange membrane as the electrolyte to split water into hydrogen and oxygen	1. Platinum group metals-free catalysts can be used. 2. Can use less expensive non-titanium stack components (e.g., stainless steel) while maintaining the benefits of membrane-based technologies.	1. Requires supporting electrolytes instead of liquid water operation. 2. The immaturity of the solid-state ionomers. 3. Poor durability. 4. Less mature technology. 5. Fast ionomer degradation.	3–5	[192–194]
Direct air electrolysis (DAE)	External supply: For example, solar panels, tidal, geothermal or wind Source: Water Source of oxygen: Air Electrolyte: Alkaline solution (e.g., KOH)	Use an electrochemical process to capture and convert CO_2 from the ambient air into hydrogen directly	1. Uses renewable energy sources. 2. Can be scaled up. 3. High efficiency. 4. Lower cost as it does not require expensive membranes or electrodes.	1. High capital cost. 2. Requires careful control of several factors, including catalysts, pressure, and temperature. 3. Low hydrogen output.	4–6	[195]
Biophotovoltaics (BPV)/ Biophotoelectrolysis cell (BPE)/Microbial electrolysis cells (MEC)	Using photosynthetic microorganisms such as algae and cyanobacteria	Solar energy is converted into electricity using biological photosynthetic materials	1. Waste CO_2 from industrial processes can be used as a feedstock for microorganisms, making it an attractive option for sustainable and low-cost hydrogen production. 2. The technology is environmentally friendly and produces no harmful emissions or pollutants.	1. To extract electrons into a solid-state anode from the microbial electron transport chains. 2. The experimental setup lacks comparability and standardisation. 3. The current outputs of the devices are very low.	1–3	[182, 196–198]
Membrane-less electrolysers	Source: Various aqueous high conductivity electrolyte	There is no diaphragm or membrane divider between the H_2- and O_2-evolving electrodes	1. Has a lower number and types of parts (only anode, cathode, and a device body are needed), hence low manufacturing and assembly cost. 2. Minimising device complexity.	1. Due to higher ohmic solution (IR) losses, high operating current densities (≥0.5 A cm-2) occurred, hence producing a lower voltage efficiency. The longer distance for ion transport in most membrane-less electrolysers leads to a higher overall ohmic resistance of the	1–3	[199,200]

(continued on next page)

Table 6 (*continued*)

Methods	Source/Feedstock	Process	Advantages	Disadvantages	TRL	Ref.
			3. Potential to be durable devices with greater resilience to extreme operating conditions that would harm a membrane, high tolerance to impurities, and long operating lifetimes. 4. Able to operate using various aqueous conductive electrolyte	electrolytic solution (Rs) and, hence, a higher ohmic voltage loss. 2. Hard to maintain a significant pressure difference between electrodes; hence cannot electrochemically compress hydrogen. 3. Cannot produce 99.99 % hydrogen purity compared to PEM. 4. Materials-related challenges. 5. Issues with scaling-up.		
Redox decoupling	Source: Water/ alkaline solutions	1. Split water into hydrogen and oxygen using electricity 2. Involves two steps: (i) Oxygen formation: oxygen evolution reaction (OER) (ii) Hydrogen formation: hydrogen evolution reaction (HER)	1. Could produce high-purity hydrogen from alkaline solutions using redox-mediated HER and OER reactions through a pair of electrochemical–chemical cycles. 2. Demonstrates a sustained and fast hydrogen production and almost unity steady-state faradaic efficiency	Since OER and HER are usually connected, any enhancement/ justifications made will impact the other.	2–4	[201,202]

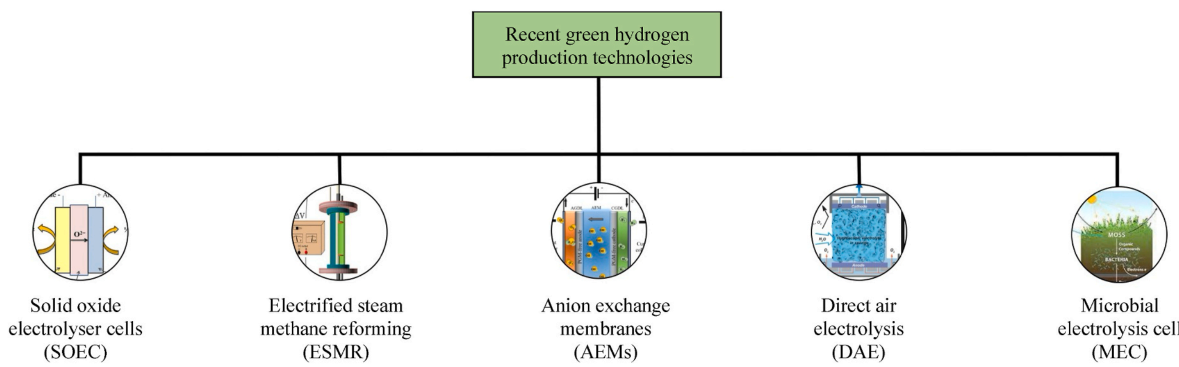


Fig. 8. Recent green hydrogen production technologies.

are the most recent technologies of green hydrogen production. Electrolysis using wind- or hydro-generated electricity is considered one of the best green H_2 production sources [203]. Among the three electrolysis methods, SOECs can generate H_2 with the highest efficiency compared to other electrolysis cells [204]. Table 6 shows that the SOEC method currently outperforms other methods. The SOECs excel in terms of efficiency. SOECs have the highest efficiency of any hydrogen production technology, with efficiencies of up to 90 % [204]. This is significantly higher than other technologies, such as alkaline electrolysis cells (50–60 % efficiency) and PEM electrolysis cells (60–80 % efficiency) [205–207]. Despite having a longer start-up time, SOECs have lower material costs as they employ ceramic as the electrolyte instead of hydroxide exchange membrane electrolysers. SOECs method also has a TRL 6–7 technology maturity, indicating that it is ready for technology demonstration and commercialisation. The commercialisation of SOECs is hindered by their relatively short lifespan of less than two to three years, compared to 10 and 20 years for PEM and alkaline electrolysis technologies. This limitation is a primary focus of ongoing R&D efforts [208].

Meanwhile, for AEMs, solid electrolytes are a recent advancement in the ongoing quest for a high-performance, industrially viable energy device. The membrane has excellent mechanical, thermal, and chemical properties. The solid membrane reduces fuel crossover problems and carbonation associated with aqueous KOH used in conventional alkaline fuel cells [191]. The TRL for AEMs is in the stage of technology viability for demonstration and commercialisation. The ESMR is also one of the promising technologies that can potentially reduce GHG emissions associated with hydrogen production. However, since the method uses methane, any leaks during production could result in significant GHG emissions, offsetting the technology's benefits. Moreover, ESMR requires significant energy to generate high temperatures and pressure, which can be expensive and energy-intensive. Hydroxide exchange membrane water electrolysers also have the potential to become a promising technology for hydrogen production due to their high efficiency, low cost, scalability, and safety advantages. However, challenges still need to be overcome to improve its durability, performance, and commercial viability.

Research on BPVs is in its early stages, lacking standardisation in biomass generation, growth techniques, and system configurations, making comparisons between studies challenging [209]. Enhancing power outputs may benefit from thoroughly comprehending microbes and targeted optimisations. Potential future approaches may involve leveraging synthetic biology to enhance electron transfer efficiency, potentially by introducing alternative electron transfer pathways. All the processes discussed above are related to various forms of electrolysis or reforming processes that have the potential to play a significant role in reducing emissions and enhancing energy efficiency in specific sectors. Alkaline electrolysers are a mature technology that is well-suited for large-scale H_2 production. Alkaline electrolysis can produce high-purity hydrogen used in various sectors such as transportation, chemical processing, and industrial processes. This can be powered by renewable energy sources like wind or solar power, providing a clean and sustainable way to produce hydrogen and reducing overall emissions.

AEM and PEM electrolysis can produce high-purity hydrogen suitable for fuel cell applications, such as transportation and stationary power generation. These types of electrolysers have the potential to be more efficient and cost-effective than traditional alkaline electrolysers. AEM and PEM electrolysis offer higher efficiency and faster response times than alkaline electrolysis, making them suitable for applications where rapid response and efficiency are crucial. PEM electrolysers are well-suited for producing H_2 for grid balancing applications. SOECs are the most efficient type of electrolyser, but they are also the most expensive. SOECs are still under development, but they have the potential to revolutionise H_2 production. The high-temperature operation of solid oxide electrolysis can be integrated with industrial processes, utilising waste heat and improving overall efficiency. ESMR is a process for producing H_2 from methane using electricity instead of natural gas for heat. ESMR is more efficient and less polluting than traditional SMR. ESMR is well-suited for applications with a reliable source of low-cost electricity, such as renewable energy. SMR can be integrated with carbon capture technologies to reduce GHG emissions by capturing and utilising the CO_2 produced during the reforming process.

DAE is a process for producing H_2 directly from the air. DAE is still under development, but it has the potential to be a very efficient and low-cost way to produce H_2. DAE helps achieve carbon neutrality by utilising CO_2 from the atmosphere for fuel production, offsetting emissions. MECs are a type of bioelectrochemical system that can be used to produce H_2 from wastewater and other organic matter. MECs are still under development. These can be applied in wastewater treatment facilities and food processing plants to treat organic waste and produce hydrogen simultaneously. MECs offer a potential route to produce hydrogen from waste streams, reducing waste and providing a clean energy source. Overall, these technologies have the potential to significantly reduce emissions and enhance energy efficiency in a variety of sectors. As these technologies continue to develop and become more cost-effective, they are expected to play a significant role in transitioning to a clean energy future.

6. Hydrogen policy and economy

6.1. Green hydrogen strategy of different countries

The World Bank Group is adopting various initiatives in Brazil, Panama, Costa Rica, Colombia, and Chile to establish green hydrogen as a fuel and promote green hydrogen as energy storage. Countries including Australia, India, China, Japan, Bangladesh, and Germany also plan their energy transitions, strongly focusing on green hydrogen. Fig. 9 shows global green hydrogen production potential by regions, with Sub-Saharan Africa having the highest potential in green hydrogen production (2715 EJ), followed by Middle East and North Africa (2023 EJ), North America (1314 EJ), Oceania (1272 EJ), South America (1114 EJ), rest of Asia (684 EJ), Northeast Asia (212 EJ) and Southeast Asia (64 EJ) [210]. Meanwhile, Table 7 summarises some countries' green hydrogen policies.

Based on Table 7, the National Hydrogen Strategy found that Australia has abundant natural resources required to manufacture clean hydrogen, placing Australia in an excellent position to become a significant hydrogen producer. The National Hydrogen Strategy plans for Australia to break through market obstacles, ensure regulatory uniformity, and establish global trade alliances to become a key participant in the hydrogen sector by 2030. The plan provides an adaptable framework enabling Australia to scale up as the hydrogen industry expands quickly [218]. In contrast, as a step towards the National Hydrogen Mission, the Indian government announced the first phase of its Green Hydrogen Policy [213]. The project intends to assist India in achieving its climate goals while establishing it as a green hydrogen centre. By 2030, it aims to produce five MMTPA of green hydrogen and the corresponding growth of RE capacity. The policy provides various incentives to entice investors to place bets on producing green hydrogen and green ammonia.

India now has 6.7 million tonnes per year of hydrogen consumption, which is anticipated to almost double by 2030 [213]. Most of it is used as a process fuel by steel mills, fertiliser factories, and oil refineries to create final goods. Grey hydrogen is created using fossil fuels like natural gas or naphtha. Although the cost of renewable electricity has

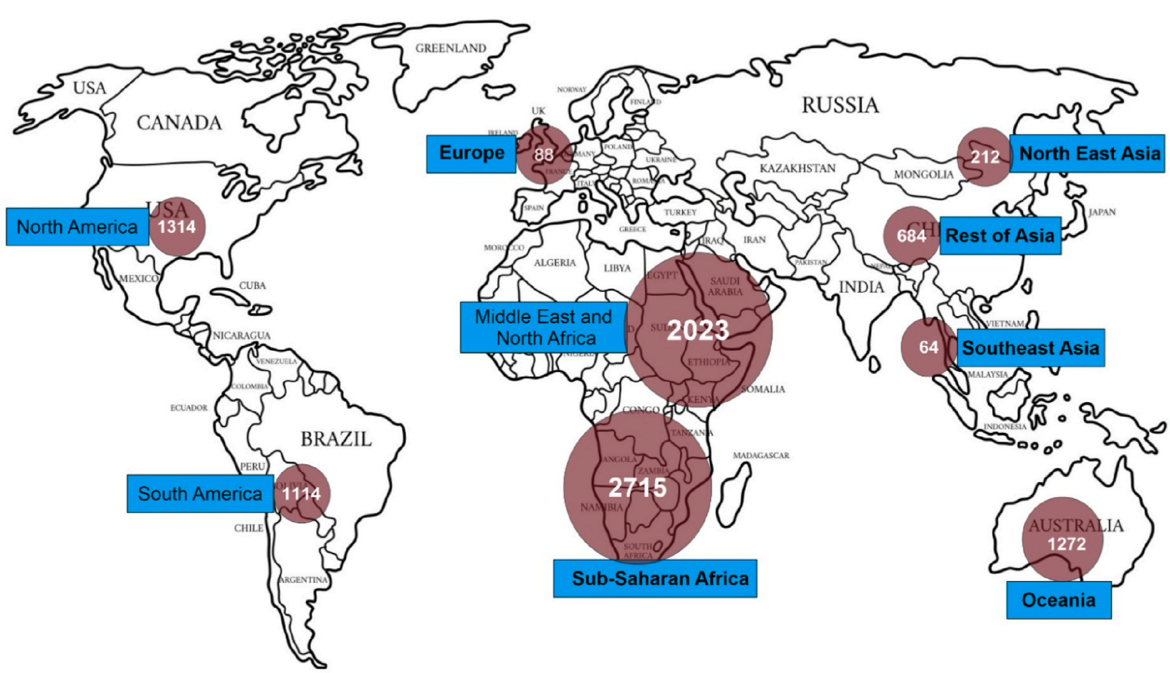


Fig. 9. Global green hydrogen production (in EJ) potential by region [210].

Table 7
Countries that harness green hydrogen for decarbonisation.

Countries	Green hydrogen policies	Ref.
Brazil	1. To develop and consolidate the Brazilian hydrogen market and to boost the country's economic competitiveness on a global scale. 2. Examine existing national rules and regulations to subsidise incorporating hydrogen as an energy vector and fuel in the Brazilian energy matrix. 3. Encourage government authorities to regulate the production, transportation, quality, storage, and use of hydrogen and associated technologies.	[211,212]
India	1. To produce five million metric tonnes per year (MMTPA) of green hydrogen by 2030 (Green Hydrogen Policy). 2. The growth of RE capacity	[213]
China	1. 100,000–200,000 tonnes/year of green hydrogen (3.3–6.7 TWh) in 2025. 2. Advance demonstration projects in urban districts, storage and transport, and the chemical and metallurgy industries. 3. Begin preparing learners for careers in the hydrogen industry, engage in global standardisation and cooperation, and encourage research and development in key core technologies. 4. There will be 50,000 fuel cell vehicles by 2025.	[214]
German	1. By 2030, Germany's hydrogen demand is expected to be 90 to 110 TWh. 2. By 2030, the first green hydrogen generation plants with a total capacity of up to 10 GW will be built, including the required offshore and onshore infrastructure. 3. Extensive funding for hydrogen use (€445 million for the industry until 2024, €2 billion allocated in the 'global arena', €7 billion will be used to improve the entire hydrogen value chain, up to 2022, €100 million per year will be made available in the research and development field, focusing on hydrogen technologies).	[215]
Japan	1. Significantly reduce hydrogen delivery cost. 2. Expanding domestic hydrogen demand. 3. Develop hydrogen storage and supply chain.	[216,217]
Australia *South Australia* *Queensland* *Western Australia* *Victoria* *Tasmania* *New South Wales (NSW)* *Northern Territory*	1. Treating a clean, creative, safe, and competitive hydrogen sector, development indicators, and success metrics. 2. Consider the effects of hydrogen on exports, transportation, industrial usage, gas networks, electrical systems, and other intersecting concerns, including safety, skills, and the environment. The South Australia Hydrogen Action Plan lists 20 steps in five key categories to enhance renewable hydrogen production for domestic and international distribution. These five categories are: 1. Encouraging investment in hydrogen infrastructure 2. Setting up a superior regulatory system 3. Strengthening trade partnerships and supply abilities 4. Promoting innovation and improving workforce expertise 5. Incorporating hydrogen into South Australia's energy network. The Queensland government published the Queensland Hydrogen Industry Strategy 2019–2024 in May 2019. The strategy focuses on the following: • supporting innovation • facilitating private sector investment • ensuring a practical policy framework • building community awareness and confidence • facilitating skills development for new technology The Western Australian Renewable Hydrogen Strategy outlines the critical areas on which the State Government will concentrate to advance the sector in Western Australia: • Export • Remote applications • Hydrogen blending in natural gas networks • Transport Victoria's Renewable Hydrogen Industry Development Plan, published in 2021, offers a roadmap for the state's transformation into an energy superpower and accelerating the renewable hydrogen industry. The Renewable Hydrogen Action Plan was released in March 2020 with a $50 million funding initiative to boost investment in the hydrogen industry. The government aims for Tasmania to become a significant producer of renewable hydrogen and a major global supplier by 2030. The NSW Government published the NSW Hydrogen Strategy in October 2021. The Strategy provides decarbonisation incentives of up to $3 billion to establish commercial hydrogen supply networks and considerably lower the price of green hydrogen. The NSW Hydrogen Strategy's primary initiatives include: • establishing green hydrogen hubs, beginning in the Illawarra and Hunter regions • exempting green hydrogen producers who connect to portions of the network with available capacity from 90 % of electricity network use fees • establishing a new Renewable Fuel Scheme with a legislated hydrogen target reaching 8 PJ (67,000 tonnes) by 2030 • and providing exemptions for green hydrogen production from government electricity schemes. The Northern Territory government released its Renewable Hydrogen Strategy in July 2020. The Strategy sets out a five-point action plan, addressing: • Local industry development • Resource management • Growing and harnessing demand • Supporting innovation • Responsive regulation	[218]
Bangladesh	1. Initiative to produce hydrogen, utilising waste and biomass as feedstock as an alternative energy source in Bangladesh. 2. To produce 10 % of the nation's electricity from renewable sources.	[218–220]
The UK	1. By 2030, a leader in the hydrogen industry, with 5 GW of low-carbon hydrogen production capacity, will accelerate the economy's transition to a low-carbon economy. 2. Future scale-up towards Carbon Budget 6 and net zero. 3. The First Hydrogen project will have refuelling stations for light, medium, and heavy vehicles that can produce 40–80 MW of green hydrogen. 4. To generate up to 10 GW of low carbon hydrogen production capacity by 2030, at least half of this coming from electrolytic hydrogen.	[221,222]

dramatically decreased due to the growing deployment of renewable power generation, green hydrogen is still too expensive to be competitive with grey hydrogen. The policy's incentives will assist in bringing down the price of producing green hydrogen. However, the biggest obstacle will still be making it as inexpensive as grey hydrogen, which is now four to six times less expensive. Lower production costs will be possible thanks to eliminating central open access fees, but state-level open access fees can undermine the desired policy incentives. As a result, cooperation is needed to eliminate this difference in fees and improve policy incentives.

As for the Japanese, their government has ambitious goals for a carbon-free future and energy security [223]. In order to decrease the cost of hydrogen by 2030 and promote the use of ammonia as a low-carbon transition fuel, it aims to establish a comprehensive global hydrogen supply chain. The "Basic Hydrogen Plan" (the Basic Strategy) and the "Strategic Roadmap for Hydrogen and Fuel Cell" were released by the Ministry of Economy, Trade and Industry (METI) in 2017 and 2019, respectively, outlining the policy framework for the growth of the Japanese hydrogen economy.

Meanwhile, Bangladesh has entered the battle for hydrogen energy by establishing a research and test processing facility. The initiative is part of a more extensive government initiative to diversify the nation's energy mix, which is still primarily dependent on coal and gas. The prototype plant produces hydrogen, utilising waste and biomass as feedstock. A study of the Hydrogen Energy Storage Based Green Power Plant (Solar-Wind hybrid model) in Bangladesh's coastline reveals that the system's cost per unit is $0.09/kWh [219]. It establishes that the green hydrogen production scheme can be used to store renewable energy in a manner that is safer for the environment. However, the study does not separately analyse hydrogen production costs [220].

Germany is actively implementing a cutting-edge hydrogen policy, with the government contributing a significant portion of state financing for hydrogen initiatives. The country prioritises green hydrogen, produced from renewable sources, as the most sustainable long-term option but is also researching the potential use of low-carbon hydrogen (blue and turquoise) as a bridge technology. Germany aims to lead in developing and exporting green hydrogen technology and is forming international partnerships to secure future hydrogen supply as the country continues to rely on energy imports. The National Hydrogen Strategy includes a 38-point action plan to launch the market ramp-up by 2023 [224].

China recently released a plan for the development of hydrogen energy for the years 2021–2035 to meet its targets for reducing carbon emissions [225]. The plan, jointly released by the National Development and Reform Commission and the National Energy Administration, aims to establish a comprehensive hydrogen energy industry development system by 2025, with improved innovation capabilities and mastery of core technologies and manufacturing processes. By 2025, annual hydrogen production from renewable energy is expected to reach 100, 000 to 200,000 tonnes, significantly contributing to the consumption of new hydrogen energy and reducing one to two million tonnes of carbon dioxide emissions. To support the goal of reducing carbon emissions by 2030, China plans to develop a well-organised industrial structure and increase the use of hydrogen produced from RE sources. By 2035, hydrogen produced from renewable energy is expected to contribute significantly to the nation's transition to green energy.

To create a hydrogen economy in the UK, it is vital to establish clear and consistent guidelines while remaining flexible to learn from early initiatives and make decisions that provide the most decarbonisation and economic benefits in the long run. The policy direction and goals outlined in this strategy align with the UK's overall framework and will guide actions throughout the 2020s for a long-term approach. By 2030, the UK aims to be a leader in the hydrogen industry with 5 GW of low-carbon hydrogen production capacity to support the transition to a low-carbon economy. The plans also include future scaling towards the Carbon Budget 6 and net zero goals, leading to job creation and clean growth throughout the UK [221,222]. The strategy also highlights the importance of keeping alternative options open and adapting to changing market conditions, as there are still questions about the use of hydrogen in 2030 and beyond, including the scale of demand and the anticipated division of production techniques. Various technologies are being considered to support the 2030 objectives, CB6 and net zero ambitions, to provide multiple realistic routes to 2050.

6.2. Hydrogen investment

Since hydrogen has gained attention as a potential clean energy source, technology investment has grown globally. Countries like South Africa, South Korea, China, Canada, and India have invested significantly in hydrogen technology development and deployment. Countries like the EU, the United States and Australia have also explored and invested in the technology. Fig. 10 shows that in 2021, South Korea invested $38 billion compared to South Africa and Namibia, with $8.5 billion and $9.4 billion in hydrogen investment, respectively. In 2022, the graph showed that countries such as Canada, India, and Australia had been the top investors in hydrogen technology, with each country investing billions of dollars in research and development, infrastructure, and deployment. Investment in South Africa significantly increased to $17.8 billion in 2022 compared to 2021 as the government focused on the green hydrogen pipeline. The United States and China have also made significant investments in hydrogen technology. The investment varies by country every year and is expected to rise, depending on the needs of government initiatives and plans.

6.2.1. Australia

Australia's expanding hydrogen industry has a pipeline of investments of A$133 – A$185 billion ($92 – $128 billion), or 35 % of the nation's overall investment in non-RE and mineral resources [226]. By the end of 2021, there were 83 Australian hydrogen projects, up from 58 at the end of 2020. Several pilot, demonstration, and small-scale hydrogen projects are now in various operation phases thanks to the government's A$1.2 billion investment in such endeavours. The first hydrogen projects in the nation started small-scale production in 2021, and in February, the Hydrogen Energy Supply Chain project shipped a test shipment of liquid hydrogen to Japan. Jemena's Western Sydney Green Gas Project, which generates 53 metric tonnes of green gas annually by electrolysis utilising renewable energy, is the largest active project.

To assist the development of an Australian hydrogen economy that is clean, inventive, safe, and competitive, the Clean Energy Finance Corporation (CEFC) Advancing Hydrogen Fund plans to spend up to $300 million. The CEFC and Australian Renewable Energy Agency (ARENA) collaborate to remove investment roadblocks to develop Australia's hydrogen economy. Projects chosen for investment in the ARENA Renewable Hydrogen Deployment Funding Round will be the focus of the Advancing Hydrogen Fund [218].

A news release by ARENA has reported that the Australian Government has recently allocated $20.9 million to support Hysata, a startup based in Wollongong [227]. The funding aims to enable Hysata to showcase its advanced hydrogen electrolyser technology commercially. Hysata's innovative technology has already demonstrated an impressive 95 % efficiency in producing hydrogen (equivalent to 41.5 kWh/kg), outperforming existing technologies that typically operate at around 75 % efficiency (equivalent to 52.5 kWh/kg) [227]. This breakthrough has the potential to significantly lower the costs associated with renewable hydrogen production by reducing the amount of electricity needed. Moreover, the technology offers the added benefit of reduced balance of plant expenses by minimising electrical resistance and lowering cooling requirements.

In the Pilbara area of Western Australia, ENGIE company will construct one of the world's first large-scale renewable hydrogen plants [228]. The Yuri project, at A$87 million, entails the following:

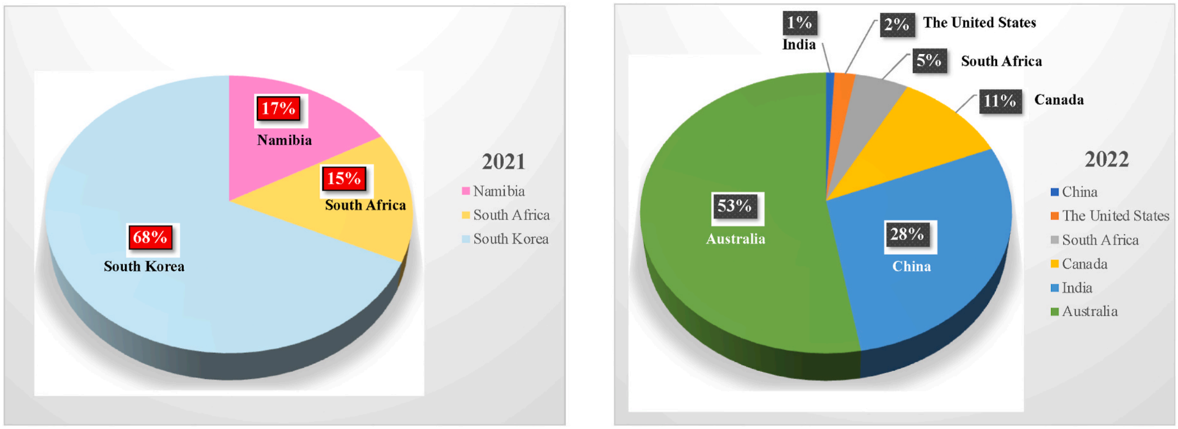


Fig. 10. Hydrogen investment in different countries between 2021 and 2022 covered in this review.

- a 10-MW electrolyser that creates renewable hydrogen
- an 18 MW solar power plant to run the electrolyser
- an 8 MW/5 MWh lithium-ion battery.

The electrolyser will be the biggest in Australia when it is finished. In the Pilbara area of Western Australia, Yuri will construct the plant close to the world-scale ammonia manufacturing facility of Yara Australia. The facility will produce up to 640 tonnes of renewable hydrogen per year. The project will receive A$2 million from the Renewable Hydrogen Fund as part of the Western Australian Government's Renewable Hydrogen Strategy. More than $500 million is being invested by the South Australian government to speed up new hydrogen projects, shipping infrastructure, and modelling tools for investors and developers [229].

The Hydrogen Jobs Plan aims to establish a large-scale, environmentally friendly hydrogen manufacturing facility and power plant. This includes projects such as the Australian Gas Infrastructure Group's (AGIG) Hydrogen Park South Australia (HyP SA). This $14.5 million demonstration project includes the largest electrolyser in Australia at the Tonsley Innovation District in Adelaide's southern suburbs, the Eyre Peninsula Gateway Project at Cultana, developed by Hydrogen Utility™ (H2U), which combines more than 75 MW of water electrolysis to create renewable hydrogen and ammonia, the Green Hydrogen Project by Trafigura Group Pte Ltd and Nyrstar to construct a commercial-scale green hydrogen manufacturing facility, and the construction of a Hydrogen Hub at Port Bonython to create a substantial, clean hydrogen production hub for both domestic and international markets.

6.2.2. Canada

The Canadian government expects the clean fuel sector to be valued at CAD 50 billion (approximately $38 billion) and provide 350,000 employees by 2050 [230]. It established a CAD 1.5 billion Clean Fuels Fund in June 2021 to develop low-carbon fuels such as hydrogen. Canada is eyeing hydrogen export as much as domestic consumption. Already a world leader in hydrogen technology, Canada's new Bill C-12, which established net zero objectives, will encourage more investment and research. First Hydrogen is constructing 100 MW + green hydrogen generation stations in Quebec and Manitoba. These ideas are being created with a North American and Canadian automotive strategy.

Meanwhile, World Energy, a company based in Newfoundland and Labrador, is making a final investment decision, expected by late 2023, to construct what they call Canada's first commercial facility for green hydrogen and ammonia production. This innovative project, known as Project Nujioqonik, is planned for Bay St. George in western Newfoundland and is designed with a substantial capacity to produce 250,000 metric tons of green hydrogen annually, which will then be converted into approximately 1.2 million metric tons of green ammonia per year [231].

Furthermore, developer EverWind Fuels disclosed that initial construction efforts have begun for their green hydrogen and ammonia project. This facility is slated to commence production in 2025, making it the second green hydrogen facility to go online in Atlantic Canada during that year. Vice President Sam Imbeult emphasised that EverWind Fuels has outlined a phased development strategy, with the initial phase already having received permits and is geared to produce and export 200,000 MT of green hydrogen annually. Subsequently, there are plans for this production to increase to 1 million MT per year in the following year [232].

One of the established companies in Canada, Hydrogenics, is a subsidiary of Cummins Inc. that produces alkaline and PEM electrolysers for various applications. Cummins has introduced the HyLYZER, a proven modular water electrolyser system designed for convenient on-site installation indoors or outdoors that is commercially available in the market. It offers user-friendly features that facilitate easy scalability and has a stellar reputation for reliability, minimal maintenance requirements, and on-site safety assurance. The HyLYZER is well-suited for projects with hydrogen production needs ranging from 1000 to 10,000 normal cubic meters per hour (Nm^3/h) [233].

6.2.3. The United States

The States' DOE has made $7 billion available to support the creation of regional clean hydrogen hubs (H2Hubs) throughout the country, which will serve as a crucial power source in the nation's future clean energy economy. The DOE also released a draft of the National Clean Hydrogen Strategy and Roadmap for public comment as part of the Department's commitment to accelerate the national deployment of clean hydrogen fuel. The H2Hubs will play a significant role in the Department's efforts to support local governments nationwide in embracing clean hydrogen and achieving President Biden's goal of a net-zero carbon economy by 2050. This is one of the largest investments in DOE history, and the Office of Clean Energy Demonstrations will fund the H2Hubs under the Bipartisan Infrastructure Law (BIL) of the President [234].

The BIL includes $500 million for clean hydrogen manufacturing and recycling initiatives, $8 billion for regional clean hydrogen hubs that will support equipment manufacturing and strong domestic supply chains, and $1 billion for a clean hydrogen electrolysis program that will reduce the cost of hydrogen produced from clean electricity [235]. Additionally, the country's Energy Earthshots Initiative, created to accelerate affordable, clean energy solutions, has set its first goal or "Shot" to reduce the cost of clean hydrogen to $1 per 1 kg within a decade.

6.2.4. China

China Petroleum and Chemical Corp, better known as Sinopec, is the largest refiner in the world by volume and has already created four green hydrogen projects. These initiatives include a 100,000 tonnes per year renewables-based project in Ulaanqab, Inner Mongolia, a 10,000 tonnes per year solar-based project in Kuqa, Xinjiang Uygur autonomous region, and a 10,000 tonnes per year wind and solar-based project in Ordos, Inner Mongolia autonomous area [236]. These are a part of its $4.6 billion investment plan through 2025 for the hydrogen sector, which intends to boost its capability for annual hydrogen production to 500,000 tonnes by that year.

State Power Investment Corp. Ltd.'s ambitious hydrogen plans include a hydrogen demonstration project in Tibet's autonomous region that employs hydrogen to address the intermittent nature of RE sources. Private companies are also relocating. The largest producer of iron ore in the world, Fortescue Metals Group and Envision Group, a Chinese green technology company, have agreed to work together to create 10 million tonnes of green hydrogen by 2030 [237]. China Energy Engineering (CEEC), a provider of green energy solutions, has begun construction on one of the nation's biggest green hydrogen production zones in Lanzhou, Gansu province.

The three-phase project, which will cost 15 billion yuan ($2.23 billion), will include the engineering, procurement and construction of facilities for the entire hydrogen industry chain, including production, storage, transportation, and refilling as hydrogen cells and hydrogen-powered vehicles. In the first phase, CEEC will invest 3 billion Yuan ($ 442.32 million) in building facilities on a 2.83-km site to produce 20,000 tonnes of green hydrogen annually and store 100,000 cubic meters of hydrogen in partnership with fuel cell expert Wuhan Troowin Power System Technology.

A centre for green hydrogen for transportation and the manufacture of hydrogen equipment are among the other facilities in the first phase. Green hydrogen will be created using clean renewable energy sources like solar or wind, which emit no glasshouse gases. By 2025, the Chinese government wants 50,000 fuel cell vehicles on the road and a green hydrogen production capacity of between 100,000 and 200,000 tonnes per year [238].

6.2.5. India

The Indian government proposes investing INR 800 Cr. (approximately $96 million) to encourage the switch to green hydrogen by 2024 on pilot projects, supply chain and infrastructure, R&D, legislation, and public awareness [239]. Under the recently established Green Energy Corridor Project, any new renewable energy facilities for green hydrogen generation before July 2025 will be eligible for 25 years of free power. The seven states included in the project—Gujarat, Himachal Pradesh, Karnataka, Kerala, Rajasthan, Tamil Nadu, and Uttar Pradesh—would initially receive funding for the construction of 20 GW-capacity renewable energy power plants. In the Indian state of Rajasthan, Avaada Group would invest over $5 billion to construct an integrated green hydrogen and ammonia factory with captive RE capacity. By 2025 and 2030, Avaada hopes to attain 11 GW and 30 GW [240]. With backwards integration into polysilicon, ingots, and wafers, it intends to increase the size of its PV production to 10 GW by 2030.

6.2.6. Other countries

Germany will invest $10.6 billion, while France and Portugal will each contribute $8 billion. Britain expects to spend $16.6 billion, Japan $3 billion, and China (the world's biggest producer of green hydrogen) to invest $16 billion by 2020 to green their businesses. Following the passage of a hydrogen law, government-backed corporate consortia in South Korea agreed in 2021 to invest $38 billion in enhancing the country's hydrogen industry by 2030. In 2021, Namibia launched an estimated $9.4 billion green hydrogen project, which is planned to commence production in 2026 [241]. The first goal is to produce 2 GW of renewable energy for regional and worldwide markets. The $8.5 billion pledged at the 26th United Nations Climate Change Conference in Glasgow (COP26) to assist South Africa's Just Energy Transition Partnership in transitioning to a low-emission development path includes an aim of "developing new economic prospects such as green hydrogen" [242]. South Africa announced intentions in February 2022 to support a pipeline of green hydrogen projects valued at around $17.8 billion over the following decade [243]. Similarly, Kenya, Morocco, and Nigeria are developing strategies to include green hydrogen in their energy mixes [244].

Other commercially available green hydrogen electrolyser systems on the market include Siemens' Silyzer and ITM Power. Siemens' Silyzer is known for its ability to scale up to double-digit megawatt levels and employs PEM electrolysis technology, consistent with the industry standard. Siemens offers a range of electrolyser options in their portfolio, with the Silyzer 300 being their latest and most powerful product line, featuring power consumption ranging from double-digit megawatts and production capacity from 100 to 2000 kg per hour. Siemens has established itself as a leading PEM electrolyser manufacturer for green hydrogen production [233].

Meanwhile, ITM Power has gained market recognition and secured partnerships with industry leaders, such as Linde and Shell, in green hydrogen initiatives. Linde, a global gas company, has formed a joint venture focused on the green hydrogen gas business. ITM Power designs and manufactures modular PEM electrolysers to facilitate green hydrogen production. Shell, an energy company, has chosen an ITM 10 MW electrolyser for their green hydrogen facility at the Energy and Chemicals Park Rheinland refinery in Wesseling, Germany, with support from the European Commission's Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) [233].

7. Potentials and challenges of hydrogen production technologies

The concept of a world that runs on hydrogen has been discussed for many years. Despite the seemingly slow progress that has been made, people have the impression that it is and always will be a fuel of the future. This is particularly true regarding the development of infrastructure as well as the cost-cutting measures. Fig. 11 summarises the current potentials and challenges of hydrogen production technologies. Current hydrogen production is mainly involved in electrolysis and fossil fuel reforming. The former process is energy-intensive and expensive in terms of power consumption and requires renewable energy sources. These have become a barrier to the growth in energy markets.

In certain hydrogen production technologies, such as electrolysis, it has been reported that around 9 kg of water is required to produce 1 kg of hydrogen [245]. This can be problematic in water-scarce regions such as Pakistan and Turkey, leading to competition for water between hydrogen production and other essential needs. Moreover, the quality of water used is crucial, as impurities can affect production efficiency. The environmental impact includes potential harm to aquatic ecosystems and increased energy consumption. However, ongoing research aims to develop more water-efficient methods, such as drip irrigation in agriculture, and regulations may encourage responsible water use in the hydrogen industry to address these concerns and make hydrogen production more sustainable for the future.

Hydrogen can power internal combustion engines, but it emits nitrogen oxides and is less efficient than fuel cells. The high cost of fuel cells and limited availability of hydrogen fueling stations have limited the number of hydrogen-powered vehicles on the road today. Lack of accessibility to hydrogen refuelling stations discourages people from purchasing hydrogen-fuelled vehicles, and companies are hesitant to install refuelling stations without a market for hydrogen-fuelled vehicles [246].

Although hydrogen can be delivered in compressed form as a liquid at – 253 °C or at high pressures, the logistics of long-distance transport in

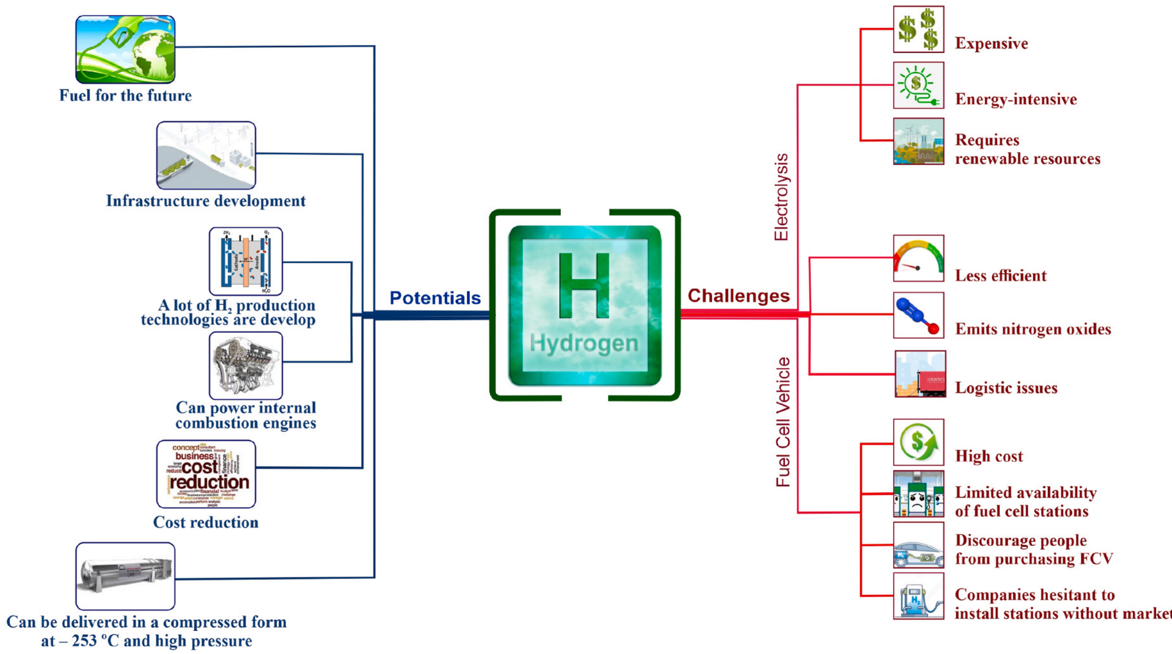


Fig. 11. Current potentials and challenges of hydrogen production technologies.

this form remain a considerable barrier [186]. Liquid hydrogen storage requires specialised equipment and insulation to maintain extremely low temperatures. The development of technology that converts hydrogen generated via electrolysis (made by in situ or external steam/water electrolysis for carbon dioxide conversion) into liquid fuels, such as diesel, dimethyl ether (DME), methanol, and ammonia, is the subject of intense effort. This would facilitate transportation from areas with a high concentration of RE to areas with limited renewable resources and fossil fuels [247]. As the industry expands, it is anticipated that several new deployments will be made for these products.

Moreover, substantial concerns have also been raised about hydrogen safety due to its high flammability, as it can ignite over a broad range of conditions [248]. Hydrogen is colourless, odourless, and lighter than air, making it difficult to detect leaks. Developing safe and efficient hydrogen storage technologies remains a significant challenge. Gaseous hydrogen must be stored at high pressures or cryogenic temperatures, which can also pose safety risks. Therefore, building a robust hydrogen infrastructure, including production facilities and distribution networks, as well as specialising firefighting equipment and training, requires careful consideration of safety measures and regulations. Public awareness and education about hydrogen safety are crucial for successfully deploying hydrogen technologies.

8. Future hydrogen energy development directions

Future research directions should focus on scaling up and developing green hydrogen technologies to at least meet the technology readiness level (TRL) 5–6 (technology development and viability demonstration). Fig. 12 summarises the roles of hydrogen producers, governments, and researchers in developing future hydrogen directions. While researchers work on green hydrogen production to combat climate change, industries must find ways to transport, store, distribute, and increase fuel stations, including in rural areas. Meanwhile, governments should carefully consider and implement policies that will position green hydrogen to play an essential role in the long-term global effort to achieve a cost-effective, resilient, secure, and clean global energy

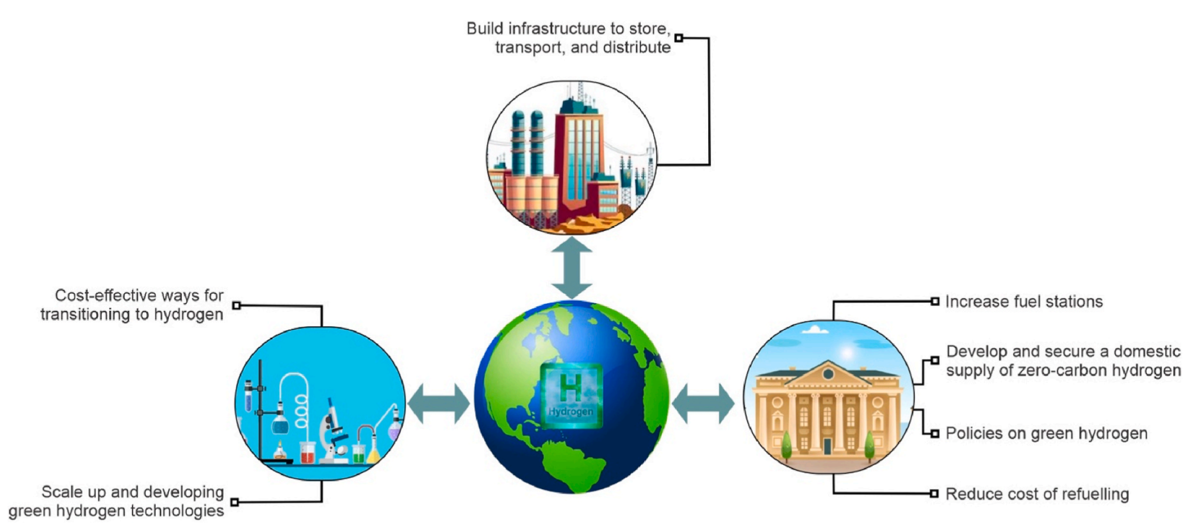


Fig. 12. The roles of government, hydrogen producers, and researchers in mapping the future of green hydrogen development.

system. They should develop and secure a domestic supply of zero-carbon hydrogen because producing green hydrogen is still prohibitively expensive and can only be done on a small scale. There is currently insufficient infrastructure to store large amounts of liquefied hydrogen for extended periods, transport it over long distances, and distribute it [215]. As a result, governments in every country must import a large portion of their demand for carbon-neutral and zero-carbon hydrogen.

In the future, the success of a hydrogen energy system will depend on factors such as market competition and demand. For example, hydrogen-powered equipment must be competitive with alternative fuel options. Challenges such as a lack of refuelling infrastructure and high costs for hydrogen refuelling are currently hindering the widespread adoption of fuel cell vehicles. However, if there is a high demand for hydrogen, the cost of refuelling could decrease with economies of scale. Hydrogen has more potential for powering heavy vehicles such as buses, trains, and trucks used in industries such as mining. Fuel cell systems are particularly effective when the energy storage per unit of mass is high [249]. Additionally, traditional uses of hydrogen such as methanol production, gas networking, and oil refining will likely see only modest growth by 2050, while demand for hydrogen as a fuel is projected to increase significantly starting in 2030, accounting for 35 % of all hydrogen demand by 2050 [250].

The infrastructure supporting the world's energy supply has evolved into a complex system, including extraction, processing, and transportation over the past century. Making significant changes to this system can take many years. For hydrogen to become a successful fuel, it must overcome challenges such as rebuilding or modifying much of the existing infrastructure and competition with other energy sources. The process of integrating hydrogen into the energy delivery system is likely to take place over several decades. It may be slowed down by factors such as economic downturns caused by the COVID-19 pandemic. Additionally, policymakers should focus on finding cost-effective solutions for transitioning to hydrogen and exploring ways the hydrogen and natural gas industries can complement each other.

9. Conclusions

This review provides a comprehensive overview of the progress made globally in green hydrogen production technologies and associated policies, with a particular emphasis on electrolysis and the potential of emerging green hydrogen technologies, including solid oxide electrolyser cell (SOEC), electric steam methane reforming (ESMR), anion exchange membrane (AEM), direct air electrolysis (DAE), and microbial electrolysis cell (MEC). The potential of green hydrogen to substitute current high-carbon fuels, especially those derived from blue or grey hydrogen, is highlighted, showcasing its potential to reduce emissions across industrial sectors and serve as an energy source for power, heat, and transportation.

Green hydrogen has garnered significant attention and investment within various industries due to its versatility along the manufacturing chain, from renewable electric energy generation to water electrolysis and hydrogen synthesis. Recent efforts have been directed toward developing green hydrogen technologies that rely on renewable energy sources for hydrogen production. These technologies encompass renewable electrolysis, utilising electricity from renewable sources such as solar, wind, or hydro to power the electrolysis process for hydrogen production, and bio-based hydrogen, which employs organic waste and biomass through gasification, fermentation, or pyrolysis.

Data gathered from this review underscores that green hydrogen remains relatively expensive compared to non-renewable alternatives as an input for businesses or an energy source. Governments across the globe, including those of Australia, Canada, India, and China, have made substantial investments in green hydrogen technologies. The United States Department of Energy (DOE) has set an ambitious target to reduce hydrogen production costs to $1 per kilogram by 2030. Electrolysis is the most mature green hydrogen technology, utilised across various applications based on its technological maturity. Among newer methods, SOECs exhibit considerable promise, albeit with drawbacks like a longer start-up period and mechanical instability due to heat stress, offset by their low material costs. SOECs prove practical on-site and integrate effectively with intermittent renewable energy sources. While other technologies are in early development stages, they are anticipated to gain viability in the years ahead.

Advancements in green hydrogen production are important to policymakers, industries, and researchers in various countries. Policymakers are focused on enhancing economic competitiveness, decarbonisation, and regulation to support the growth of the green hydrogen sector. Government support and incentives, including subsidies, tax credits, and grants, are anticipated to increase globally to promote green hydrogen production. Governments worldwide will also introduce stricter environmental regulations, encouraging industries to adopt clean energy sources like green hydrogen. Consequently, industries stand to benefit from the energy transition, export opportunities, and innovation driven by green hydrogen technologies. Researchers play a critical role in advancing technology simultaneously. Continued research and development efforts will likely enhance the efficiency and cost-effectiveness of green hydrogen production technologies.

However, several challenges remain and are expected to last over the next decade. These include high production costs, extensive infrastructure development, intermittent production due to reliance on renewables, market development, and global cooperation. Addressing the hydrogen challenges and issues requires a multidisciplinary approach involving collaboration between industry, government agencies, researchers, and standards organisations. Additionally, ongoing research and technological advancements are crucial to improving the safety of hydrogen throughout its entire lifecycle, from production to end-use applications. Overcoming these challenges will be essential to realise the potential benefits of green hydrogen in terms of economic growth, environmental sustainability, and energy security.

The limitations in this review stem from data scarcity, particularly in assessing the availability and sustainability of required resources such as renewable energy sources (e.g., solar, wind) and water for green hydrogen production in specific regions and obtaining comprehensive environmental impact data for all stages of the hydrogen production life cycle, including emissions, water use, and land use. The review emphasises the limitations of green hydrogen production technologies by focusing on their life cycle assessment and techno-economic study. Recent studies have focused on developing stable, reliable, practical, and cost-effective green hydrogen production technologies. Each method presents its advantages and disadvantages, and the optimal choice of technology depends on the specific requirements of each application. Future studies should concentrate on reducing the environmental impact of green hydrogen production, such as minimising water usage, optimising renewable resources, and developing carbon capture and utilisation technologies. Moreover, further analysis is warranted to explore the circular economy concept within the hydrogen production context, considering options for recycling, reusing, or repurposing materials and byproducts within the hydrogen value chain.

In summary, green hydrogen, derived from renewable sources, offers a sustainable solution to decarbonise the energy sector, reducing reliance on fossil fuels and enhancing climate resilience. Its applications in various sectors enable significant reductions in GHG emissions, promoting environmental sustainability. Rapidly declining production costs position green hydrogen as a cost-effective alternative, pivotal for mitigating climate change and aligning with global sustainability goals like UN SDGs and ESG principles.

Credit author statement

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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

Data will be made available on request.

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