Research Article

Challenges Facing Hydrogen as a Strong Sustainable Energy Source

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ABSTRACT

The environmental degradation resulting from the use of non-renewable fuels requires immediate remedies; therefore, sustainable energy sources must be employed. Hydrogen, with net zero carbon emissions, is a crucial sustainable energy resource. It is flexible for use in both portable and stationary systems, providing an advantage over other sustainable fuels. This work presents current knowledge regarding hydrogen, including its classifications, life cycle, production methods, electrolyser technologies, and associated costs. Green hydrogen faces numerous economic and technological obstacles that impede its viable widespread adoption. The cost of green hydrogen significantly exceeds that of grey hydrogen, necessitating a reduction in price to enable competition with grey hydrogen for substitution purposes. Estimates indicate future costs of green hydrogen at \$1–2/kg and electrolysers at \$400–500/kW. This study addresses the issues associated with the extensive utilization of green hydrogen, including the need for inexpensive renewable electricity and reduced electrolyser prices. The cost of renewable electricity has decreased over the years, with wind energy being less expensive than solar energy. The cost of hydrogen should be assessed at the point of production due to its significant dependence on feedstock pricing. Proton exchange membranes (PEMs) appear to be the forthcoming technology for green hydrogen production. Green hydrogen also encounters significant obstacles in storage, transportation, and utilization, as the supply chain lacks adequate infrastructure. This paper focuses on the current state and challenges facing hydrogen for its widespread commercial use. Future research should include substantial reductions in hydrogen cost, advanced electrolyser technologies, hydrogen utilization in engines and NOx reduction during combustion, advanced fuel cells, biological production of hydrogen, and overcoming all hazards associated with hydrogen use due to its properties. These developments would be favorable for all stakeholders, particularly researchers confronting numerous complex subjects. Policymakers should also be actively engaged.

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1. INTRODUCTION

There is no dispute that climate change is occurring globally: sea levels are rising, oceans are becoming more acidic, and temperatures are consistently increasing. If the world fails to maintain the average global temperature increase below 2°C, the imminent implications could be severe. All regions globally will be impacted indiscriminately. The definitive approach is to reduce greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), by approximately 80% by 2050 (Kloesel, 2025).

The significant negative impacts of climate change and global warming have become apparent to everyone. The current situation is critical, and without immediate intervention from the global community, the Earth and life will be jeopardized. The approach involves utilizing renewable fuels with zero or limited carbon emissions to substitute the predominantly used fossil fuels. Hydrogen (H_2), recognized as a clean energy carrier due to its zero carbon emissions and high energy density, shows significant potential as a future sustainable alternative fuel (Tongzhou et al., 2022).

Hydrogen is the lightest and most prevalent element on Earth. It is a colorless gas that does not exist in its free elemental state but is bonded with other molecules, such as O_2 to form water or carbon to produce hydrocarbons. Hydrogen possesses a high calorific value of 120–142 MJ/kg, ranking second among all fuels, surpassed only by U-235 in light water reactors at 500 MJ/kg. Hydrogen has the highest energy-to-weight ratio among all conventional fuels (Rasul et al., 2022). Similar to electricity, hydrogen serves as a secondary energy carrier rather than a primary energy source; however, it uniquely functions as an energy vector, enabling the conversion, storage, and release of energy (Ajanovic et al., 2022).

Hydrogen is exceptionally clean when utilized in fuel cells, as the byproducts are heat, electricity, and water, resulting in no pollution. In addition to being a clean zero-carbon fuel source, hydrogen can be used in mobile systems such as automobiles and trains, as well as in fixed installations, including power stations for electricity generation and industrial plants for ammonia and steel production. Renewable energy sources lack this versatility.

Hydrogen is a flexible energy source for numerous practical applications. In power stations, hydrogen can produce energy through fuel cells and hydrogen gas turbines. It can also serve as an energy reservoir to support various

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auxiliary systems in power stations, including the stabilization of renewable energy output fluctuations, seasonal energy storage, and emergency backup power (Fan et al., 2024). Liquid hydrogen is utilized as rocket fuel due to its high energy density. Substantial advancements have been made in employing H_2 as a fuel for cars and aircrafts (Fan et al., 2024). Hydrogen is presently utilized extensively in industry, including the synthesis of ammonia and methanol, as well as in oil refineries. Hydrogen has considerable versatility, as it can be generated through many technologies and employed across all sectors requiring fuel. It can be delivered to consumers by several methods, including trucks, trains, pipelines, and ships.

Hydrogen could be utilized to fuel internal combustion engines and gas turbines. Its desirable combustion characteristics, such as wide flammability limits, high flame velocity, and high auto-ignition temperature, make it a promising future energy source (Habib et al., 2024). However, extensive research efforts are required to make this commercially viable. In engines, H_2 can be used in two main ways: in fuel cells to generate electricity for electric motors and transportation systems, or in hydrogen internal combustion engines where H_2 is directly burned as fuel. Both methods provide a way to power vehicles and equipment with reduced carbon emissions, though NO_x emissions increase due to the high combustion temperature of H_2. Practically, fuel cells are more developed and provide a more efficient, though less familiar, route to electric power.

Research into hydrogen combustion in engines focuses on adapting internal combustion engines to use hydrogen as fuel, with challenges including pre-ignition, rapid combustion, high heat flux, high NO_x emissions, and material durability issues such as hydrogen embrittlement (Bhuiyan & Siddique, 2025). Key areas of development include modifying engine hardware, optimizing injection and ignition timing, and exploring dual-fuel or hydrogen-doping approaches to reduce emissions. Widespread use of hydrogen-fueled internal combustion engines is hindered by limited hydrogen storage and refueling infrastructure (Bhuiyan & Siddique, 2025). Experiments on a spark-ignition engine fueled with hydrogen under near-real operating conditions showed the critical role of combustion parameters, such as the duration of injection and spark timing, in controlling flame front propagation speed and combustion stability (Sementa et al., 2025). Hydrogen used in direct injection systems increases efficiency by up to 40% in engine tests (Skobiej, 2025).

The increase in NO_x emissions during H_2 combustion requires further research into emission reduction technologies, such as selective catalytic reduction systems (Skobiej, 2025). Development of advanced combustion control technologies is needed to better regulate combustion dynamics and emissions in hydrogen engines (Skobiej, 2025). Combustion of H_2 blended with ammonia and methane results in substantial reductions in CO, HC, and soot emissions. Hydrogen-ammonia blends offer significant reductions in CO_2 emissions (Skobiej, 2025). Ammonia-blended hydrogen-fueled engines are in the early stages, and future research is required (Habib et al., 2024).

Recent advancements in hydrogen-powered engines include the YCK16H engine in China, which demonstrates adaptability to different fuel purities and incorporates innovative technologies such as dual-channel turbocharging and high-pressure direct injection. Additionally, a hydrogen-powered internal combustion engine prototype featuring

intelligent water injection has been developed to enhance performance. This approach aims at transitioning from diesel to a supercharged and lean-burn spark-ignition engine, utilizing hydrogen's unique combustion properties to achieve low NO_x emissions and high efficiency. Despite the significant potential for hydrogen vehicles, numerous challenges remain for widespread implementation, particularly the lack of refueling infrastructure, which is critical for large-scale deployment of hydrogen cars (Markowska et al., 2025).

Hydrogen-fueled gas turbines represent a promising technology, leading the way toward a sustainable energy future (Zhou et al., 2024). However, several challenges remain, including rapid flame propagation, which can cause instability, and increased NO_x emissions. Hydrogen burns faster than natural gas, potentially leading to unstable flames, pressure fluctuations, and mechanical stresses in turbines. Increased moisture content in the exhaust gas from hydrogen combustion can cause hot corrosion, reducing component life. To address these issues, strategies have been developed, including modifications to fuel systems, combustor designs, and nitrogen purge systems. Safe and efficient hydrogen combustion also requires modifications to turbine fuel delivery and ignition systems, as well as the development of advanced control systems. The combustion characteristics of hydrogen influence stability, flame dynamics, and the overall combustion process in gas turbines (Zhou et al., 2024). Further challenges associated with commercial hydrogen gas turbines include the high cost of hydrogen production, achieving effective and efficient hydrogen combustion, and material compatibility (Zhou et al., 2024). Nevertheless, commercial hydrogen gas turbines are considered feasible, and their costs are expected to decrease (Zhou et al., 2024).

Recent developments to enhance H_2 production include the implementation of novel catalysts and materials via pathways such as water splitting, biomass conversion, and microbial processes (Patel et al., 2024). Another emerging area in hydrogen applications is the use of nanomaterials, which offer favorable properties such as high surface area, tunable surface chemistry, and high catalytic activity. These materials could improve hydrogen storage, production, transportation, efficiency, and reduce costs (Shaker et al., 2024).

Consequently, hydrogen is a pivotal contender for worldwide sustainable energy. To generate H_2, it must be extracted from substances containing it, which requires energy input, such as separation from water in electrolysers powered by electricity. The production method dictates the "color" of hydrogen. The three most recognized colors are grey, blue, and green. Grey hydrogen is generated from methane, producing CO_2 emissions; when these emissions are captured, blue hydrogen is formed. Zero-carbon green hydrogen is produced via electrolysers powered by renewable energy. Hydrogen can be produced from diverse feedstocks, and its costs and associated emissions vary depending on the production process and energy source. H_2 manufacturing processes are typically categorized by color, such as grey, blue, green, red, and white (Ajanovic et al., 2022).

Grey hydrogen is currently the predominant production method, with facilities operating in the gigawatt range, whereas green hydrogen is utilized at far lower capacity. Grey hydrogen accounts for 80% of global production, exhibiting an efficiency of 74–85% (Muhammad et al., 2022). Nevertheless, steam methane reforming (SMR) and other fossil fuel-dependent technologies are neither environmentally friendly nor sustainable, generating approximately 830 million

tons of CO_2 annually (Moe and Benjamin, 2023). Green hydrogen contributes about 4% of global energy consumption (Muhammad et al., 2022). The estimated global hydrogen consumption in 2018 was 115 Mt, comprising 70 Mt in pure form and 45 Mt in mixed form, with an average growth rate of 2.8% per year since 1980. The IEA reports that 61% of global hydrogen generation is derived from SMR, 23% from coal, 16% from oil products, and 4% from water electrolysis. Renewables contribute to 25% of global power generation, while only approximately 1% of current green hydrogen is derived from renewable sources (Samuel and Alessandro, 2021). The majority of hydrogen is still produced from fossil fuels. Production of green hydrogen via electrolysers achieves large emission reductions (80–95%) compared with SMR technologies, yet the cost of green H_2 is 0.4–1 orders of magnitude higher (Parkinson et al., 2019).

The number of low-emission hydrogen production projects is increasing. If all planned projects are executed, by 2030, the output of low-carbon hydrogen could reach 16–24 Mt/y, comprising 9–14 Mt of green H_2 and 7–10 Mt of blue H_2. Achieving all green hydrogen projects would require an electrolyser capacity of 134–240 GW by 2030 (IEA, 2022). Another estimate suggests that yearly production of low-emission hydrogen could reach 38 Mt by 2030, contingent upon the successful completion of all planned projects (IEA, 2023). Currently, electrolysers with a capacity of 14 MW exist, with 50% located in China (IEA, 2023).

Approximately 306×10^6 tons per year of green hydrogen must be generated to attain the targeted net zero carbon objective. To achieve this, a global electrolyser capacity of 3600 GW is necessary, an increase from the existing capacity of approximately 300 MW, along with 14,500 TWh of electricity, representing almost 20% of the world's total electrical supply of 71,000 TWh (Chatenet et al., 2022). These requirements necessitate substantial investments, rendering their fulfillment exceedingly challenging, if not unattainable, in the medium to long term.

The production of hydrogen is far lower than global demand. In 2021, hydrogen demand reached 94 million tons, reflecting a 3% annual increase (IEA, 2022). This constitutes around 2.5% of worldwide final energy consumption. Demand may reach 115 Mt by 2030, while 200 Mt is required to achieve the targeted climate objectives for net zero carbon by 2050 (IEA, 2022). The Statista Research Department (2019) projected global hydrogen consumption of 180 Mt by 2030. A substantial increase of 520 Mt in hydrogen use by 2050 is proposed under a net zero emission scenario (Moe and Benjamin, 2023). The disparity between production and demand for sustainability is substantial. Global hydrogen demand is projected to quadruple from 2021 to 2030 (Statisca Research Department, 2019). The largest portion of the demand surge in 2021 was attributed to grey hydrogen, while the output of blue hydrogen was less than 1 million tons (IEA, 2022). Steady, although constrained, growth in H_2 demand is anticipated until 2030, as existing hydrogen facilities under construction and in operation possess electrolyser capabilities well below 50 MW. However, the infrastructure required for extensive hydrogen utilization, including pipelines and export-import terminals, will require considerable time and investments to achieve.

Hydrogen applications are extensive and versatile. It is utilized in electricity generation, transportation, steel industry, and ammonia synthesis. Approximately 90% of hydrogen produced worldwide is used in the ammonia,

methanol, and oil refining sectors (IEAGHG, 2017). Anticipated applications of hydrogen include (Bird & Bird, 2023): (1) the aviation sector, aiming to decrease CO_2 emissions by 50%; (2) rail transport, where the implementation of fuel cells to power trains will be pivotal for achieving a zero-carbon transition, with one in five train vehicles potentially operating on green hydrogen by 2030; (3) mining, which contributes 4–6% of global GHG emissions, could benefit from green hydrogen by substituting diesel vehicles and electricity generators, facilitating decarbonization; and (4) heavy-duty vehicles powered by hydrogen fuel cells or direct hydrogen fuel, potentially reducing emissions by up to 90% by 2040.

Nevertheless, numerous obstacles confront the utilization of hydrogen. A primary barrier to large-scale adoption is its high cost relative to other available fuels, particularly green hydrogen. The cost of green hydrogen is three to five times greater than that of conventional technologies (Arutyunov, 2021). Numerous forecasts indicate that the prices of green hydrogen will decrease substantially between 2030 and 2050, rendering it economically viable (IEA, 2021; World Energy Council, 2023; Bhashyam, 2023). Cost considerations are presented in detail in section 7.

Hydrogen storage presents significant challenges for large-scale applications. Transportation of hydrogen is a critical aspect, especially for long-distance transit. Both transportation costs and losses incurred during transit are significant concerns. For instance, long-distance pipelines are prohibitively expensive, and considerable losses occur during transportation of cryogenic liquid hydrogen due to boiling (Riera et al., 2023). The primary factors influencing the selection of transmission and distribution technologies are the distance from the production site to consumers and the pattern of hydrogen demand (Sgarbossa et al., 2023). Currently, most hydrogen is produced locally, as long-distance transmission is economically unfeasible due to its low volumetric energy density (Riera et al., 2023). End users obtain hydrogen from terminals in either liquid or gaseous form, depending on the application. High production costs, coupled with the challenges of storage, transportation, and distribution of substantial quantities of hydrogen, remain inadequately addressed.

Notwithstanding the technical considerations related to H_2 generation and storage systems, hydrogen is asserted to be the sole future fuel that meets the criteria for sustainable mobility and the design of hydrogen-based vehicles. Fuel cell vehicles incur lower operating costs than electric automobiles with a 200-mile range and consume 43% less energy than gasoline vehicles (Chakraborty et al., 2022).

The methods of hydrogen refueling, along with challenges associated with rapid refueling and hydrogen storage costs, have been examined. The levelized cost of a refueling station is estimated to range from $1.5 to $8 per kilogram of hydrogen, depending on the station's capacity and location (Halder et al., 2023).

Safety considerations associated with the utilization of hydrogen are significant. Its combustion characteristics, including an extensive flammability range, minimal ignition energy, and high burning velocity, render it an exceptional fuel. However, hydrogen possesses a notably low boiling point and density (0.08 kg/m³), along with a comparatively low ignition temperature of 585 °C, necessitating stringent safety measures for its utilization and storage (Abohamzeh et al., 2021).

The scarcity of green hydrogen production facilities, coupled with inadequate infrastructure for hydrogen storage and delivery, represents a major obstacle to the rapid adoption of H_2 for sustainable energy. Scientific gaps in hydrogen research include the lack of efficient, scalable, and low-cost technologies for production, storage, and utilization. Key areas requiring improvement include electrolyser technology, particularly its ability to manage fluctuating renewable energy input, and the development of integrated, cost-effective, and environmentally friendly storage-delivery systems. Further research is needed in biological hydrogen production for efficiency and scalability, as well as in creating standardized methodologies for life cycle assessments and establishing safety protocols for large-scale deployment. Bridging the gap between academic research and industrial implementation under real-world conditions is crucial.

This research presents a comprehensive scientific overview and thorough thoughtful search on almost all knowledge and aspects about hydrogen. The novelty of this study lies in its coverage of most aspects of hydrogen in a single reference, whereas existing literature typically addresses only one or a few aspects. The primary purpose is to highlight the serious challenges facing hydrogen for widespread commercial feasibility, as it is a strong candidate for future energy sustainability. In addition, crucial future research areas are identified and pinpointed.

This is a state-of-the-art study that addresses various knowledge on hydrogen as a prospective sustainable energy source. Most information regarding hydrogen is provided, and the current state of the hydrogen chain cycle is addressed. An effective assessment is focused on the serious challenges associated with the widespread and feasible utilization of hydrogen, particularly green hydrogen, is presented. The problems in achieving net zero carbon objectives are elucidated. Many opinions and perspectives are provided. The study offers a broad framework for the long-term, feasible adoption of hydrogen for energy sustainability. It may be significant for policymakers, academics, and stakeholders, providing insights into both the opportunities and challenges associated with realizing the full potential of hydrogen energy.

2. STRONG ENERGY SOURCES CANDIDATES FOR SUSTAINABILITY

Table 1 shows some of the strong sustainable energy sources. The table gives the utilization area of each source.

Table 1. Utilization areas of strong sustainable energy sources candidates

Source	Utilization	Remarks
Hydrogen	Electricity, industry, transportation, residential	Versatile in use. Can be used in all sectors, i.e., mobile subjects and fixed installations
Solar thermal	Electricity, heating, cooling, industrial, agricultural (crop drying), and desalination, residential	Fixed installations
Photovoltaic	Mainly electricity	Fixed installations
Wind	Electricity	Fixed installations
Nuclear	Electricity	Fixed installations. It powers ships and submarines

Energy sources can be categorized as those utilized in stationary or land-based installations, such as electricity power stations, those that energize mobility systems, such as transportation facilities, or both. Hydrogen possesses a distinct advantage over all other robust sustainable energy sources due to its wide-ranging functional applications, enabling its use in both stationary and mobile systems. Sustainable energy sources are characterized by their clean, zero-carbon emissions during electricity generation. Nonetheless, the production processes of their components generate significant emissions. No single sustainable fuel can meet the global demand for zero carbon emissions. A combination of several fuels will need to be utilized in varying proportions, depending on the economic and technological conditions of each country.

3. HYDROGEN COLORS

All hydrogen production methods can be classified using color designations. Although hydrogen is colorless, these designations are commonly used as identifiers. Figure 1 illustrates the different hydrogen colors and the feedstocks for their production . The colors of hydrogen are explained below.
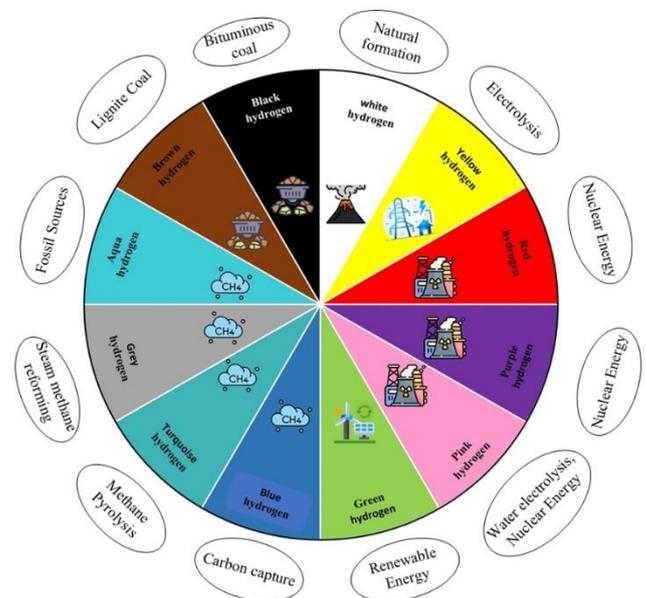

Figure 1. Hydrogen colors as produced from different feedstocks and energy resources

- Green H_2: produced by water electrolysis powered by renewable energy sources, such as wind, solar, or possibly hydropower.
- Pink H_2: produced from water electrolysis using nuclear electricity.
- Purple (violet) H_2: produced by utilizing nuclear energy and heat through combined electrolysis and thermochemical water splitting.
- Red H_2: produced by high-temperature catalytic water splitting systems powered by nuclear energy.
- Yellow H_2: produced by electrolysis powered by electricity from the grid. Further research is needed to clarify the distinction between green and yellow hydrogen (Ajanovic et al., 2022).
- Grey H_2: produced via steam methane reforming, partial oxidation, or autothermal reforming.
- Turquoise H_2: produced from methane through methane pyrolysis, with solid carbon as a byproduct that can be stored, used, or sold.

- Brown and Black H_2: produced from lignite coal (brown) and bituminous coal (black), representing the least environmentally friendly hydrogen. Each kilogram of brown or black coal produces approximately 20 kg of CO_2 (Jose et al., 2023). These forms are the most widely used due to large coal reserves worldwide.
- Blue H_2: grey hydrogen with carbon capture and storage, representing a low-emission variant.
- Aqua H_2: combines features of green and blue hydrogen, with production not resulting in CO_2 emissions like green hydrogen, yet derived from fossil sources like blue hydrogen. Canadian researchers have developed an economical, commercial technology to produce aqua hydrogen from oil sands (natural bitumen) and oil fields at low cost without carbon emissions (Minli et al., 2021).
- White H_2: occurs naturally as a free gas in layers of the continental crust, deep oceanic crust, and volcanic gases (Jose et al., 2023).

In the foreseeable future, the hydrogen industry will predominantly utilize grey hydrogen, transitioning to blue hydrogen. Green hydrogen may require additional time to reach a significant share of production, primarily dependent on reducing costs associated with renewable energy and electrolysers. Hydrogen is expected to become a crucial energy source across all sectors.

According to Jose et al. (2023), aqua hydrogen is currently the most economical variant, though still in early development stages. Less expensive options include grey, black, and blue hydrogen, derived from natural gas and coal and thus dependent on feedstock pricing. Black hydrogen is the most environmentally harmful, followed by grey hydrogen, while blue hydrogen demonstrates substantially lower emissions.

Turquoise hydrogen is economically promising; however, its production process requires further research, and the solid carbon byproduct can be marketed without generating emissions. The most expensive variants are purple and pink hydrogen, generated through electrolysis, while green hydrogen remains associated with high production costs. Significant cost reductions are necessary to establish green hydrogen as a feasible production technique.

4. HYDROGEN SUPPLY CHAIN CYCLE

An effectively constructed hydrogen supply chain is essential to support a future hydrogen economy. A hydrogen supply chain consists of several technological components and functions, each exhibiting a distinct level of scientific and technological maturity. Some components are highly advanced, while others require additional time for development. The considerable diversity of technologies across the various systems in the chain makes its construction a complex and challenging endeavor.

Figure 2 illustrates the hydrogen supply chain cycle, from production to end-use consumption. The components of the chain begin with the feedstocks used for hydrogen production, followed by hydrogen generation, storage, transportation, and final applications. Methane (CH_4) is employed to produce grey and blue hydrogen, whereas renewable resources and water serve as feedstocks for green hydrogen production. Hydrogen can be stored in either gaseous or liquid form. Various transportation methods exist, depending on factors such as storage state and distance. Hydrogen applications are numerous, encompassing transportation, electricity generation, industrial use, and domestic purposes. Hydrogen production methods are discussed in the following section.

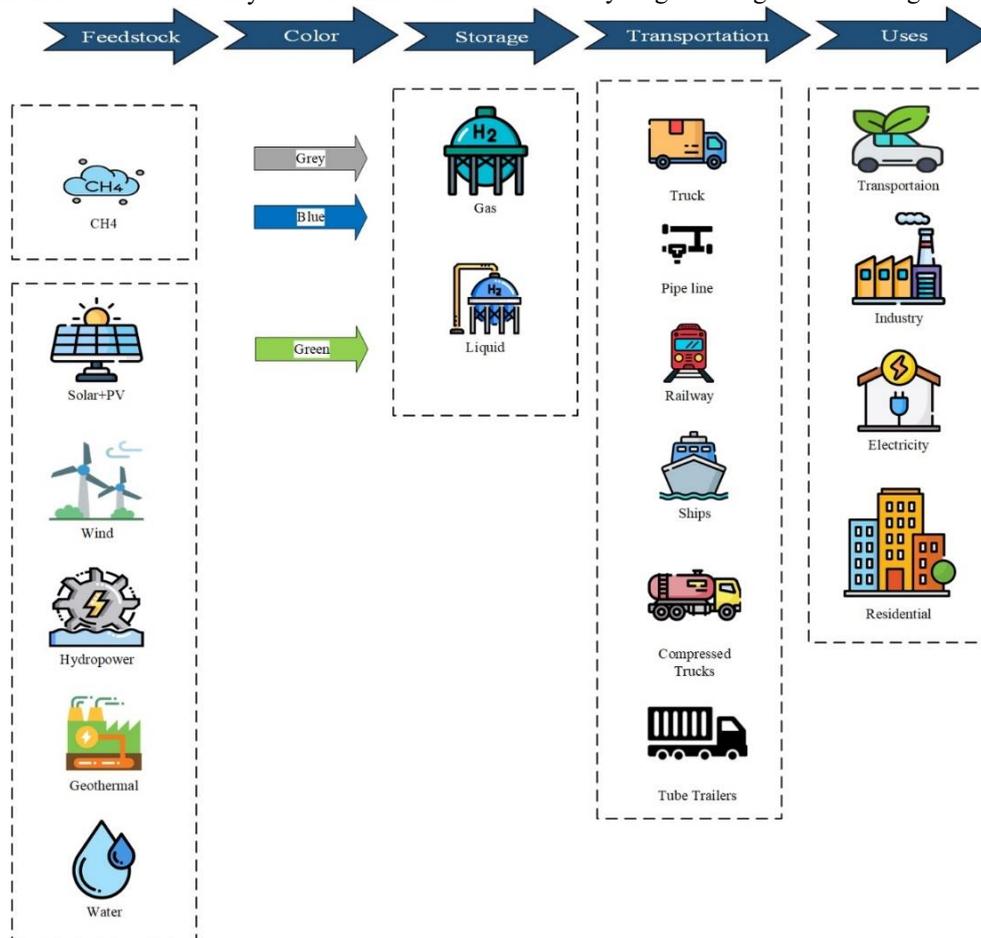Hydrogen storage can be categorized as either physical or

Figure 2. Hydrogen supply chain cycle from feedstocks to end uses for different colors, storage forms, and transportation facilities.

material-based. In physical storage, hydrogen is contained by altering its physical state, either through increased pressure (compressed gaseous hydrogen storage), reduced temperature below its boiling point (liquid hydrogen storage), or a combination of both approaches (cryo-compressed hydrogen storage). The alternative approach is material-based storage, much of which remains in experimental stages. In this method, additional materials are incorporated to interact with hydrogen molecules or atoms, either physically or chemically, to enhance storage density and safety compared to physical storage systems (Miao et al., 2023). Underground storage systems demonstrate the lowest storage costs, followed by compressed hydrogen and liquid hydrogen storage (Halder et al., 2023).

Table 2 presents the storage conditions and methodologies for hydrogen, along with the respective advantages and disadvantages of each method. No single method is inherently superior; the choice depends on specific practical applications and economic considerations.

Table 2. Advantages and disadvantages for different hydrogen storage conditions and modes (Leonardo and Rui, 2021).

Storage conditions	Storage mode		
	Compression	Liquifaction	Chemical
Pressure, bar	600	1	9.9
Temperature, ^{0}C	25	>- 252.9	25
Hydrogen state for use	Pressure reduction	Evaporation	Catalytic
Advantages	Ambient temperature, low cost	Atmospheric pressure, lighter storage tanks	Small safe storage, atmospheric temperature and pressure
Disadvantages	High pressure, expensive tanks, gas volatility, quick tank degradation	High energy consumption, very low temperature, strong insulation	New technology, high temperature, high cost

Hydrogen transportation can occur in various forms, including as a compressed gas, liquid, or within a hydrogen carrier such as ammonia. Transportation modalities include road, pipeline, and maritime shipping. In road transport, hydrogen is delivered either as compressed gas or liquid. Pressurized gaseous hydrogen can also be transported via pipelines, which is cost-effective for moving large volumes of hydrogen. Maritime shipping enables the transfer of hydrogen in substantial quantities (Miao et al., 2023). Facilities for transporting liquid hydrogen include tanker vehicles, rail tankers, and ships. Hydrogen can also be carried as a gas through pipelines, tube trailers, or rail tanks.

Hydrogen transport is generally categorized into transmission and distribution. Transmission refers to the movement of hydrogen over long distances from production facilities to storage terminals across regions or countries, using all available infrastructure, whereas distribution involves delivery to end consumers (Muhammad et al., 2022). Compressed gaseous tube trailers are suitable for short-distance transport and modest volumes due to their lower complexity. Cryogenic liquid tanker trucks are preferable for longer distances and larger volumes, as they can carry more hydrogen per trip than tube trailers. Pipelines can transport large volumes across long distances, despite higher construction costs (Fan et al., 2024).

Hydrogen fuel cells have numerous practical applications. They are currently used to power spacecraft electrical systems and provide electricity on Earth. In 2022, the United States operated approximately 205 fuel cell electric power generators, totaling around 350 MW in capacity. Compact fuel cells are also employed to power electronic devices, including laptops and mobile phones. Many automotive manufacturers have developed hydrogen fuel cells for zero-emission vehicles. Fuel cells can achieve two to three times the efficiency of gasoline-powered internal combustion engines. However, the high cost of fuel cells and the limited availability of hydrogen fueling infrastructure have constrained the widespread adoption of hydrogen-fueled vehicles (EIA, 2023). Hydrogen fuel cell-powered trains are operational in Germany, and initiatives to utilize hydrogen in shipping have been established (IEA, 2022).

The use of hydrogen for electricity generation and space heating, either as pure hydrogen or blended with natural gas, represents another prospective application. Globally, approximately 55% of hydrogen is used in ammonia synthesis, 25% in refining processes, around 10% in methanol production, and the remaining 10% in other applications, including renewable energy (WHA INTERNATIONAL, 2023), as illustrated in Figure 3. The potential capacity for hydrogen use in ammonia production and the electricity sector could reach 3.5 GW by 2030 (IEA, 2022).
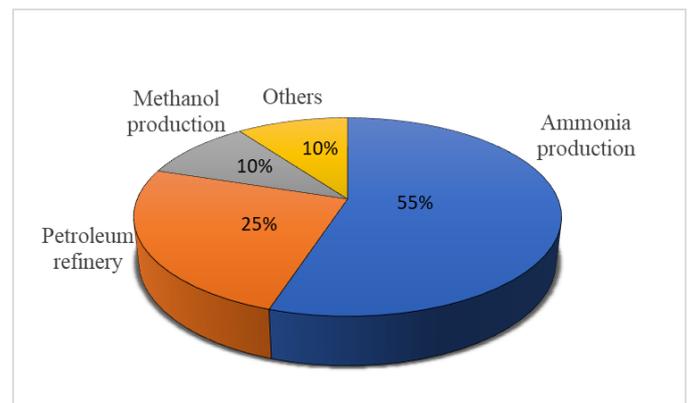

Figure 3. Global hydrogen utilization share in different industrial sectors (WHA INTERNATIONA 2023).

5. HYDROGEN PRODUCTION METHODS

The production of hydrogen requires an initial energy input to extract it from its naturally occurring chemical compounds. Once separated, hydrogen can serve as a supplementary energy source through combustion or be employed in fuel cells. The design of hydrogen production facilities requires careful consideration of technical, economic, and environmental factors to optimize operations and maximize production benefits. Key criteria include feedstock cost, availability of renewable energy sources, process efficiency, and environmental impact. Hydrogen

production is a critical phase in the hydrogen supply chain, utilizing various methodologies for generation. The following sections describe the technologies employed for grey, blue, and green hydrogen.

5.1. Grey hydrogen

Grey hydrogen is produced via steam methane reforming (SMR). The process begins with the removal of contaminants from both steam and natural gas (NG), followed by mixing and subjecting the mixture to high pressure and heating to approximately 900 °C over a nickel-based catalyst. This yields syngas composed of carbon monoxide and hydrogen. The water-gas shift (WGS) reaction is then employed to generate additional hydrogen and CO_2, which is currently released into the atmosphere.

The heat required to drive the SMR reaction is supplied through NG combustion. The SMR reaction at high pressure and temperature is:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$
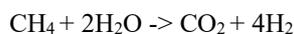
This reaction requires 164.7 kJ to produce 4 moles of H_2 when water is in vapor form and 252.7 kJ when water is in liquid form. Approximately 9 tons of CO_2 are emitted per ton of H_2 produced to obtain high-purity hydrogen (Samuel and Alessandro, 2021). Hydrogen is separated from the CO_2–H_2 mixture using pressure swing adsorption (PSA). This method increases CO_2 emissions due to the additional energy required for operation.

An alternative approach to provide heat for the SMR reaction is partial oxidation of methane, which generates heat during the reaction. This method, combined with SMR, is referred to as autothermal reforming (ATR).

$$2CH_4 + O_2 \rightarrow 2CO + 4H_2$$

In the ATR reaction, syngas is produced by combining CH_4 with a sufficient quantity of oxygen or air. Additional hydrogen can be generated by processing the syngas through the WGS reaction. This reaction produces heat that can sustain the SMR process.

The ATR process can be further enhanced by optimally mixing steam, methane, and oxygen at high temperature and pressure:

$$3CH_4 + O_2 + H_2O \rightarrow 3CO + 7H_2$$

This reaction does not require external heat input, making it an efficient reforming method with lower capital investment and reduced carbon emissions.

5.2. Blue hydrogen

Blue hydrogen is produced from grey hydrogen, but with CO_2 removed using carbon capture and storage (CCS) systems. As a result, blue H_2 is cleaner and more environmentally friendly than grey H_2.

Carbon emissions are a principal contributor to the global climate crisis. Therefore, mitigating climate change requires reducing carbon emissions from all sources. Carbon capture technologies offer an effective solution to this problem.

CCS systems can capture CO_2 from a variety of sources, including power plants, factories, and natural gas processing facilities. The efficiency of CO_2 capture varies depending on the technology employed. Captured CO_2 can then be transported and stored underground in geological formations or utilized in various industrial applications. Blue hydrogen production relies on the integration of carbon capture and storage. CCS technologies have been implemented in practice

for several years in many countries. For instance, the USA operates more than 70 CCS projects, storing over 500 million tons of CO_2 in oil fields (Samuel and Alessandro, 2021). Underground CO_2 storage does not pose significant health, safety, or environmental risks in the short or long term, as CO_2 is neither flammable nor explosive and can be safely handled. All risks associated with its use have been managed or mitigated (Samuel and Alessandro, 2021).

Although modern SMR hydrogen plants achieve efficiencies that reduce CO_2 emissions by roughly 10% beyond the theoretical minimum, further reductions are achievable only through CCS (IEAGHG, 2017). CO_2 capture is a commercial process and a primary source of industrial and food-grade CO_2.

Currently, only three facilities worldwide integrate CO_2 capture with CO_2 transportation and storage (IEAGHG, 2017). Capture technologies can remove 56–90% of CO_2 (IEAGHG, 2017). However, implementing a CO_2 capture system increases total plant costs by 18–79% compared to a facility without CCS and raises the levelized cost of hydrogen (LCOH) by 18–45% (IEAGHG, 2017). Research indicates that blue hydrogen could serve as an alternative to green hydrogen despite the additional costs associated with installing carbon capture systems (Tomonori and Mika, 2022).

Numerous carbon capture technologies exist, each with specific advantages and limitations, and the suitability of a particular technology depends on the application. Nonetheless, all of these technologies serve the common goal of capturing carbon to mitigate the severe impacts of global warming. Most of these technologies are discussed in the following sections.

5.2.1. Carbon capture systems

1.   Adsorption

In adsorption, which is a complex separation process, the gas encounters porous particles capable of adsorbing it due to surface affinity, and separating it from the gas mixture. This method is costly, has low efficiency, and requires large operating energy (Silvio et al., 2022).

2.   Absorption

In absorption processes, CO_2 should be capable of later separation. This is possible due to the presence of materials that can absorb CO_2 and transport it from one phase to another. Absorption is one of the most promising technologies for its efficiency and economic feasibility, however, it requires high operating energy (Silvio et al., 2022).

3.   Membrane separation

This technology relies on the selectivity of the material in relation to the gas. CO_2 permeates through membranes and separates itself from other gases. This technology is the most effective among current ones (Silvio et al., 2022).

4.   Chemical capture

This technology depends on the use of chemical reactions with CO_2 to obtain final organic or inorganic products, mainly carbonates. The great interest in this technology stems from the fact that the produced carbonates have high boiling point, low toxicity, and are biodegradable. Carbonates could offer added value to industrial and agro-industrial chains (Silvio et al., 2022).

5.   Bioenergy with carbon capture and storage (BECCS)

BECCS relies on capturing CO_2 from biomass energy production and storing it. This is a double acting process that captures emissions and generates electricity.

6.   Chemical looping

Here, metal-based particles acting as catalysts are used to make CO_2 react with them and separate it from the fuel. The

captured CO_2 is stored, while the fuel is left for further combustion. This technology is still in the experimental stage, but is categorized as promising.

7. Cryogenic carbon capture (CCC)

CCC is a relatively new technology, with limited applications, that depends on cryogenic cooling to capture and remove CO_2 from gases. It can extract CO_2 at a higher rate than conventional systems and can store it at a reduced volume. It is a promising technology with high potential.

8. Carbon capture using nanotechnology

Here, nanomaterials are used to capture and store CO_2 at much lower pressures than other technologies. This method is in its research phase but holds great promise for its scalability and high efficiency. In addition, it utilizes few resources and energy, and produces low waste.

9. Aqueous amine-based CO_2 capture

This technology uses amines to absorb CO_2 from industrial processes before it is emitted into the environment. CO_2 is then separated from the amine and transported for storage or reuse. Despite being a mature technology, it has limitations such as high cost and high energy consumption. Recently, absorption processes have emerged as sustainable and economically favorable methods for capturing GHG emissions (Khan et al., 2023).

5.2.2. Carbon storage, transportation and uses

The technologies for CO_2 capture and storage have been in practice for many years in many countries. Currently, the global amount of CO_2 captured is about 40 $MtCO_2$/year, and if all announced projects are implemented, then the global CO_2 capture potential will be about 130–150 $MtCO_2$/year (Madejski et al., 2022). Underground CO_2 storage does not result in health, safety, or environmental hazards in the short or long term. CO_2 neither burns nor explodes. CO_2 has also been handled successfully for decades, and any risks associated with its use have been effectively managed or mitigated. Pipelines remain the most feasible transportation method for large volumes of CO_2 (Dennis et al., 2014). Captured CO_2 is transported for geological storage or utilization. CO_2 can be used in industry, agriculture, food and beverages, refrigerants, fire extinguishing gases, and energy production. A demonstration plant in China produces 160 t/day of ammonia and urea utilizing captured CO_2. Currently, CO_2 utilization represents as little as 2% of emissions, but predictions suggest that the chemical industry could capture 700 megatons of CO_2/year (Dennis et al., 2014).

5.3. Green hydrogen

Green hydrogen is the cleanest and is of zero carbon. Thus, if it becomes dominant, it will be a key fundamental future energy source for sustainable energy. It is produced by electrochemical water splitting by means of electrolysers that obtain their driving energy from renewables. Like fuel cells, electrolysers consist of an anode and a cathode separated by an electrolyte. Different electrolysers operate in different ways, mainly due to the different types of electrolyte materials used and the employed ionic species. During water electrolysis, the hydrogen evolution reaction (HER) takes place at the cathode and the oxygen evolution reaction (OER) occurs at the anode.
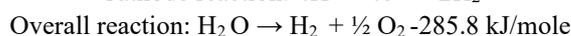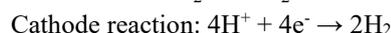
There are many types of electrolysers of different designs and operating conditions: alkaline water electrolysers (AWE, also AEL), proton exchange membrane (PEM) electrolysers, solid oxide electrolysers (SOE), and anion exchange membrane (AEM) electrolysers.

The principal leading water electrolysers in use in the green hydrogen production industry are the PEM, AWE, and SOE. The favorable one among these for producing H_2 of high purity is the PEM. PEM electrolysis, also named polymer electrolyte membrane electrolysis, is adopted as a modern efficient technology for H_2 production.

In a PEM electrolyser:

(1) oxygen and positively charged hydrogen ions (protons) are formed at the anode,

(2) electrons flow through an external circuit and H_2 ions selectively move across the PEM to the cathode, and

(3) at the cathode, H_2 ions combine with electrons from the external circuit to form H_2 gas.

Figure 4 shows a PEM electrolyser. The reactions are:

$$\text{Anode reaction: } 2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$
$$\text{Cathode reaction: } 4H^+ + 4e^- \rightarrow 2H_2$$
$$\text{Overall reaction: } H_2O \rightarrow H_2 + \tfrac{1}{2}O_2 \ \text{-285.8 kJ/mole}$$

Thus, electrolysis of water produces H_2 by this highly endothermic reaction. This reaction needs 4.5–7 times the energy of the SMR reaction per one kg H_2 produced (Samuel and Alessandro, 2021).
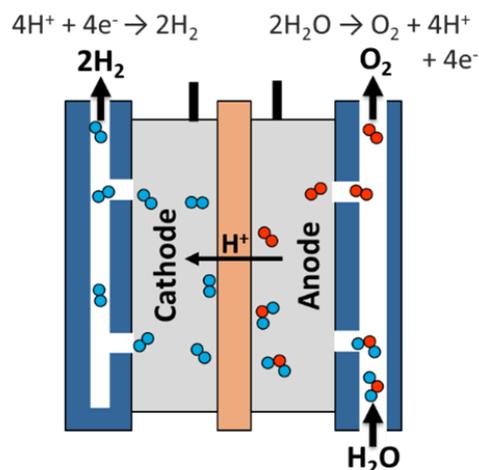

Figure 4. A PEM electrolyser showing cathode and anode reactions .

In theory, 1.23 V is sufficient to operate the water electrolyser to produce H_2. Practically, a higher 1.8–2.0 V is required because of the overpotentials encountered on the cathode and the anode. Thus, different designs of electrocatalysts were developed to lower such overpotentials.

Splitting a mole of liquid water to obtain a mole of H_2 at 25 °C requires 285.8 kJ of energy, of which 237.2 kJ is supplied as electricity and 48.6 kJ as heat. In PEM and alkaline electrolysis cells, the required heat is obtained from the extra heat generated from the internal resistance due to the flow of the electric and ionic currents in the cell. This heat requirement is directly traceable back to the electricity supplied, meaning that 285.8 kJ, not 237.2 kJ, of electricity is the minimum energy needed to split water in these electrolysers. This explains the higher actual cell potential compared to the theoretical one, as indicated by Eq. (1) below.

The electrochemical potential (standard potential) corresponding to the high heating value (HHV) is 1.481 V/cell, which represents the neutral voltage to produce H_2 and O_2 with 100% thermal efficiency, which means that no waste heat is generated from the reaction. This can be calculated from Faraday's Law as:

$$E° = \frac{\Delta H°}{nF} \qquad \text{V/cell} \tag{1}$$

where $E°$ is the standard potential, $\Delta H°$ is the HHV= 285.84 J/mole, n is the number of electrons required to generate a molecule of hydrogen = 2, and F is the Faraday constant= 96.485 Coulomb/mole.

Substituting in Eq. (1), we have: E° = 1.481 V/cell. This explains the difference from the 1.229 volts, which is based on using a HHV of 237.2 kJ in Eq. (1) instead of 285.8 kJ.

The cell efficiency is given by:

$$\text{Cell efficiency} = \frac{\text{Thermal neutral voltage}}{\text{Cell operating voltage}} \tag{2}$$

Substituting in Eq. (2), the cell efficiency= 1.229/1.481= 83%.

6. ELECTROLYSERS: TECHNOLOGIES, CHARACTERISTICS, DERIVING POWER, AND COST
6.1. Technologies and types

Electrolysers can be classified into two categories, mature or experimental, in terms of technology. AEL and PEM electrolysers are available for commercial use. However, AEL is more established, having been in existence for almost 100 years, whereas PEM is less developed but has been available for about 50 years. PEM (acidic) electrolysers are the most appropriate available technology for integrating intermittent renewable energy sources. Their high expense remains an obstacle to extensive commercial utilization. Although AEL systems are less expensive, they are significantly larger and their relatively high minimum load renders them less compatible with renewable electricity sources, as they favor stable working conditions. AEM electrolysis is an emerging technology aimed at circumventing the limitations of alkaline and PEM electrolysers. The primary issues confronting this technique are its low stability and the brief lifespan of the employed polymer membranes (30,000 hours) (Kumar and Lim, 2022).

Solid oxide electrolysers (SOEs) are emerging entities in technology and are distinguished by their superior efficiency. The primary problem is to enhance the insufficient durability of these electrolysers. This can be achieved by enhancing the electrolyte's conductivity, improving the chemical and mechanical stability of the system, and optimizing the electrochemical surface characteristics and compatibility of the electrode materials (Kumar and Lim, 2022).

The high temperature electrolyser (HTEL) is also present. HTEL requires a temperature exceeding 600 °C, therefore it is powered by steam. The electrolyte is a ceramic substance that conducts negative oxygen ions (Lange et al., 2023). The electrolyte in AEL is a potassium hydroxide (KOH) aqueous solution, and the membrane conducts hydroxyl cations. In PEM, pure distilled water is utilized for electrolysis, and the membrane is conductive for positive hydrogen ions. AEMs function with either water or KOH solution, and the membrane conducts hydroxyl ions.

Investment costs for alkaline electrolysers, sized between 1.8–5300 kW, range from 800 to 1500 USD per kW, which is 2 to 2.5 times lower than those of PEM electrolysers (Patonia and Poudinch, 2022).

PEM electrolysers are distinguished by their ability to generate high-purity hydrogen. AEL electrolysers are extensively utilized in commercial applications. AEMs generate hydrogen at a comparatively low cost by substituting the costly electrocatalysts utilized in PEM and AEL electrolysers with more economical alternatives. SOE generates hydrogen with great efficiency, low cost, and reduced emissions. The disadvantage is the elevated operating temperature, which results in prolonged startup duration (El-Shafie, 2023).

AEL, PEM, and SOE are the primary methods for the production of green hydrogen through water electrolysis. PEM electrolysers were developed to address issues of partial load, low current density, and insufficient operating pressure associated with alkaline ones. PEM electrolysis is the most efficient technology for producing high-purity hydrogen and is compatible with the variability of renewable energy sources (Tongzhou et al., 2022).

A hydrogen generation facility has numerous systems with distinct relevant designations. These are addressed in the subsequent discussion.

Stack: The term "stack" in green hydrogen production systems refers to the cell units, porous transport layers, bipolar plates, end plates, and numerous ancillary components, including spacers, seals, frames, and bolts. The primary factor influencing electrolyser technologies is stack costs. The cell unit constitutes the central component of the stack where the primary electrochemical process of water splitting occurs. The cell unit comprises the membrane onto which the catalyst layers are applied as electrodes in PEMs, as well as the electrodes and diaphragms in AELs. Typically, stacks constitute 40–60% of the overall electrolyser costs. In AEL and PEM systems, stacks typically account for around 50% and 60% of the total electrolyser expenses, respectively (Patonia and Poudinch, 2022). The difference mostly arises from the utilization of precious platinum-group metals in PEMs, which obstructs their widespread commercial adoption.

Power electronics: Power electronics in electrolyser technology relate to the utilization of solid-state electronics for the regulation and conversion of electric power when interfacing renewable energy systems, which generate DC, with the grid, which produces AC. The primary function of power electronics is to convert alternating current (AC) from the grid into the direct current (DC) necessary for operating the electrolysis cell stack. Rectifiers execute this conversion. The cost contribution of power electronics for both alkaline and PEM systems is approximately 15%. It is higher for other technologies (Patonia and Poudinch, 2022).

Gas conditioning: Gas conditioning in electrolysers is important for H_2 compression to achieve the requisite storage pressure, as well as for drying to purify raw hydrogen. Hydrogen is refined to 99.5–99.9999% and compressed to over 50 bar to minimize its volume for storage. The gas-conditioning share is around 10% for PEM systems and about 6% for solid oxide systems (Patonia and Poudinch, 2022).

Balance of plant: The plant system's balance consists of heat recovery and rejection equipment, process material delivery systems (including pumps, valves, and piping), control mechanisms, safety systems, waste collection and disposal systems, maintenance and repair tools, heating, cooling, ventilation, air conditioning, power supply, and distribution, among others. The proportion of this cost component in current alkaline and PEM electrolysers is 15–20% (Patonia and Poudinch, 2022).

General Electric of the USA developed PEM electrolysis technology over 60 years ago, utilizing a solid sulfonated polystyrene membrane as the electrolyte at that time (Kumar and Lim, 2022). In PEMs, water electrolysis occurs in a cell

containing a solid polymer electrolyte (SPE), which facilitates proton conduction, separates product gases, and provides electrical insulation for the electrodes. The membrane in the PEM electrolyser functions both as the electrolyte and as a gas separator. Electrolysis employs exclusively pure deionized water within the cell.

PEM electrolysis offers numerous advantages, including high current density, enhanced energy efficiency, low gas permeability, a broad operational temperature range (20–80 °C), ease of use and maintenance, and a compact mass-volume profile (Kumar and Lim, 2022). AEL stacks are significantly larger than PEM stacks, measuring 2.6 m² compared to 0.5 m² for PEM. PEM stacks have significantly greater power density (6.3 W/cm² compared to 2.3 W/cm²) and pressure capability (30 bar against 5 bar). These characteristics demonstrate increased efficiency attributable to reduced electricity use and lower expenses for post-compression (Subramani et al., 2023).

PEM electrolysers function efficiently at elevated current densities, enabling low operational costs, especially in systems linked to variable energy sources such as wind and solar, where abrupt peaks in energy input may occur. PEM electrolysers provide superior performance at varying ramping rates (Subramani et al., 2023). Their solid structure allows for a minimal gas-crossover rate, yielding very high hydrogen purity, which is crucial for storage, safety, and direct application (safety thresholds at typical settings are 4 mol-% H_2 in O_2).

In conclusion, PEMs possess numerous advantageous characteristics:
1. increased efficiency,
2. substantial current densities at minimal applied cell voltages,
3. exceptional dynamic performance with fast startup response, and
4. significant resistance to duty cycles.

These characteristics render PEMs suitable for operation with either grid electricity or direct input from renewable sources (Bazarah et al., 2022).

Table 3 presents the energy required by various electrolysers to generate 1 kilogram of H_2. PEM is the predominant energy consumer. This must be decreased to diminish the cost of green hydrogen.

Table 3. Energy consumption by different electrolysers to produce 1 kg H_2 (Patonia and Poudinch, 2022).

Electrolyser	Energy consumption, kWh/kg H_2
AEM	57-69
Alkaline	50-78
PEM	>78

Although technologically matured, alkaline electrolysers are engineered to function with grid electricity rather than with intermittent renewable energy sources that are not grid connected. It is advantageous to modify them for compatibility with changeable renewable energy sources.

The significant problem associated with PEMs is the high cost of the system. The primary component of the PEM electrolyser is the membrane, which requires significant enhancements to achieve greater efficiency and extended lifetime, hence reducing costs. A membrane with reduced thickness and enhanced mechanical properties could improve its effectiveness and durability (Kumar and Lim, 2022). A significant aspect of PEMs is the utilization of costly

electrocatalyst materials, like Pt, Ir, and Ru, which renders them more expensive than alkaline electrolysis. Consequently, in contrast to AEL stacks, PEMs utilize essential basic materials. In 2018, the worldwide output of platinum and iridium was 135 and 8.5 tons per year, respectively (Subramani et al., 2023). If the complete targeted PEM installed capacity of 91 GW is to be achieved by 2030, the current global output of iridium will not meet this need, given the existing use of iridium in PEM electrolysers (Subramani et al., 2023). Intensive efforts must be undertaken to identify more economical alternatives to decrease expenses and facilitate expansion. A further problem contributing to the elevated cost of PEMs is the utilization of porous transport layers and bipolar plates composed of costly platinum or gold coated titanium materials. There is a necessity to explore the use of significantly less expensive materials to accomplish the same duty in this field. Currently, significant scientific efforts are dedicated to the advancement of high efficiency, low cost PEM electrolysers (Tongzhou et al., 2022).

The overall efficiency of PEM electrolysers is influenced by the efficiencies of various components and elements within the system, including assembly procedures and the characteristics of the materials employed. The elements influencing efficiency are categorized as static (e.g., design and pressure clamping) and dynamic (e.g., working conditions and energy expended in gas bubble removal), all of which exert considerable influence (Bazarah et al., 2022).

Increasing the stack sizes from the present 1 MW to 20 MW may yield a 30% decrease in original costs. AEL and PEM electrolysers, now sized at 1 MW, are the leading prospects to achieve this objective, in contrast to SOE and AEM electrolysers, which have significantly smaller capacities of 0.005 and 0.0025 MW, respectively. Scaling up the entire hydrogen facility, rather than merely increasing the stack size, is anticipated to yield the most significant cost reduction in the balance of plant, power electronics, and gas conditioning (Patonia and Poudinch, 2022). Augmenting stack size encounters physical and technological constraints. Larger stacks may be more susceptible to increased leakages and mechanical instability (Patonia and Poudinch, 2022).

Extending the lifespan of electrolysers allocates the expenses of the entire hydrogen production facility across a greater production volume, resulting in a reduced cost per unit of H_2 generated. At present, alkaline electrolysers exhibit the longest lifespan owing to their advanced technology, as indicated in Table 4. PEMs have the second longest lifespan, whereas SOEs have the shortest.

Table 4. Lifetime of different electrolysers (Patonia and Poudinch, 2022).

Electrolyser	Life time, h
AEM	30000
Alkaline	60000-100000
PEM	50000-90000
Solid oxide	20000

AELs have less suitability for low load operation than PEMs. This is why, when they are stopped and flushed due to insufficient power supplies, they require a minimum of 50 min, and even an hour, for a cold startup (Patonia and

Poudinch, 2022). As depicted in Table 5, PEMs have the least start up time, which is an advantage for them.

Table 5. Startup times of different electrolysers (Patonia and Poudinch, 2022).

Electrolyser	Startup time, min
Alkaline	30-60
AEM	30-60
PEM	Few minutes-30
Solid oxide	>60

Table 6 depicts the primary attributes of PEM, AEL, and SOE electrolysers (Leonardo and Rui, 2021). AELs exhibit a superior production rate and function at reduced pressure relative to PEMs. Nonetheless, PEMs have superior current density and hydrogen purity. The values for SOEs are incomparable, as they are in the demonstration phase and require further development to achieve commercialization. Table 7 represents further properties of PEM, AEL, and the under-development HT electrolysers (Lange et al., 2023). PEMs offer significant benefits due to their great load adaptability, minimal warm-up duration, and favorable startup load gradient. AELs exhibit a rapid heating rate and comparatively superior efficiency relative to PEMs, along with reduced maintenance expenses. HTs, although having significantly greater efficiency, require substantial enhancements in other attributes to achieve commercial viability. The efficiency of AELs and PEMs must be substantially enhanced above current levels.

Table 6. Main operating conditions and performance characteristics of different electrolysers (Leonardo and Rui, 2021).

Item	Electrolyser		
	AEL	PEM	SOE
Operating temperature, ^0C	40-90	20-100	600-1000
Operating pressure, bar	<30	<200	<20
Current density, A/cm^2	0.2-0.4	1.8-2.2	0.3-2
Voltage, V	1.8-2.4	1.8-2.2	0.7-1.5
Production rate, m^3/h	<1400	<400	<10
Hydrogen purity, %	>90.5	>99.99	>90.9
Energy consumption, kWh/m^3	~5.55	~5.4	~3.6
Efficiency, %	51-60	46-60	76-81
Stack degradation rate, %/y	0.25-1.5	0.5-2.5	3-50
Maintenance cost, % of investment cost	2-3	3-5	--

Table 7. Some operational characteristics of different electrolysers (Lange et al., 2023).

Item	Electrolyser		
	AEL	PEM	HT
LHV efficiency	63-71	60-68	96
Load flexibility, %	20-100	0-100	
Warm up time, 0-100% load	1-5 min	<10 s	15 min
Heating up rate, K/min	0.4-1.5	0.3-1	0.51
Startup load gradient, %/s	10-50	10-90	
Shut down load gradient, %/s	10	40.6	3

The future of hydrogen production will significantly depend upon electrolysis, however, alternative technologies like thermolysis and photolysis could enable a more efficient utilization of thermal or solar energy (Phuoc-Anh et al., 2023). There is a strong belief in shifting from AEL to PEM systems by 2030 to become the preferred electrolyser technology fed by renewable energy (Schmidt et al., 2017). Table 8 shows the anticipated future performance of electrolysers. It is essential to minimize electricity consumption, reduce stack degradation, and increase current density. Accomplishing these objectives is crucial for lowering the cost of hydrogen generation, which is vital for the widespread adoption of green hydrogen.

Table 8. Projected future working characteristics of different electrolysers (Lange et al., 2023).

Item	Electrolyser	Year			
		2020	2024	2030	2050
Electricity consumption, kWh/kg	AEL	50	49	48	<45
	PEM	55	52	50	<45
	SOE	40	39	37	<40
	AEM				<45
Stack degradation, %/1000 h	AEL	0.12	0.11	0.1	
	PEM	0.19	0.125	0.12	
	SOE	1.9	1.2	0.5	
Current density, A/cm^2	AEL	0.7	0.7	0.8	>2
	PEM	2.2	2.4	2.5	4-6
	SOE				>2
	AEM				>2

6.2. Driving energy for electrolysers

Electrolysers are significant energy consumers. Electricity for electrolysers can be sourced from independent renewable sources, primarily wind and solar, or directly from the national grid. The minimum theoretical energy requirement

for an electrolyser to operate is about 39.3 kWh/kg H_2 (HHV H_2 at ambient temperature); however, the practical value is 50–60 kWh/kg H_2 (Parkinson et al., 2019). In 2050, the electricity consumption for all electrolyser methods is projected to be 44.4 kWh/kg H_2, assuming a plant efficiency of 75% (Samuel and Alessandro, 2021). Table 9 indicates that the primary cost determinant for green hydrogen is predominantly electricity, followed by the capital expenditure (CAPEX) of electrolysers.

Table 9. Share of cost drivers for green H_2 (Patonia and Poudinch, 2022).

Cost item	Share, %
Electricity	73
CAPEX (without finances)	14
Finance	8
Operating and maintenance (O & M)	5
Total	100

Affordable energy is crucial for the economical production of green hydrogen, as any decreases in electrolyser costs cannot offset high electricity prices (IRENA, 2020). Available renewable electricity is essential for the competitiveness of green hydrogen. Thus, it would be advantageous to generate green hydrogen in nations with abundant renewable resources. In order to achieve the desired cost effectiveness, reductions in power costs should be coupled with decreases in the cost of electrolysers, which represent the second greatest cost component. Costs within the supply chain, particularly those associated with storage and transportation, should be minimized. The average global levelized cost of electricity (LCOE) for onshore wind farms decreased by 5% from 2021 to 2022, falling from $0.035/kWh to $0.033/kWh, which is 52% lower than the least expensive fossil fuel alternative. In 2022, the LCOE for offshore wind decreased by 2%, falling from being 258% more expensive than the least expensive fossil fuel alternative to merely 17% more costly (IRENA, 2022). Capital investment in offshore wind exceeds that of onshore wind. In 2022, the average global LCOE for utility-scale photovoltaic systems decreased by 3% year-on-year, reaching $0.049/kWh (IRENA, 2022). From 2010 to 2022, the reduction in LCOE was 89% for solar photovoltaic (PV), 68% for onshore wind, and 59% for offshore wind (IRENA, 2022). Therefore, there are assurances that renewable electricity costs will be significantly lower in the future.

6.3. Cost of electrolysers

The cost of green hydrogen production is highly influenced by the costs of electrolysers, which rank as the second most significant expense after the cost of input electricity. The current costs of commercial electrolysers, specifically AEL and PEM, are high. Efforts are underway to develop sophisticated AEL and PEM systems. The costs of advanced AEL and PEM stacks are expected to be similar; however, the uncertainty associated with advanced PEM is greater than that of advanced AEL stacks, due to the greater challenges encountered in implementing the advanced PEM design compared to the advanced AEL design. The primary reason is the exorbitant cost of iridium used in PEMs. The

costly components in AEL stacks include the membrane, bipolar plate, and electrodes, as well as the membrane, bipolar plate, and mattress for advanced configurations.

Table 10 shows the approximate cost proportions of the components in various electrolyser systems. The predominant expense for AEL and PEM plants is the stack, with the proportion being higher in PEM electrolysers. In SOE and AEM systems, the primary cost component is attributed to the BOP. Consequently, for the two commercial AEL and PEM systems, it is imperative to reduce the stack cost to lower overall expenses. For the underdeveloped SOE and AEM systems, primary cost reductions should target the BOP, as well as the stack and power electronics.

Table 10. Approximate cost shares for 1 MW electrolysers (Patonia and Poudinch, 2022).

Cost component	Share of cost, %			
	Alkaline	PEM	Solid oxide	AEM
Stack	50	60	30	19
Power electronics	15	15	30	18
Gas conditioning	15	10	6	15
Balance of plant	20	15	34	48
Total cost range, $/kg H_2	540-900	667-1450	2300-6667	>931

The current efficiency of electrolysers is inadequate, resulting in high costs. The material expenses for a 1000 Nl/h AEL electrolyser, with an efficiency of 65%, amount to €740, equating to approximately €140 per kW, which is considerably lower than the current cost of an alkaline stack, around €12,500 (Marcelo and Alessandro, 2008). Reports indicate a projected 50% reduction in the CAPEX of electrolysers, attributed to decreases in raw material costs (Badgett et al., 2021). The estimate in Badgett et al. (2021) is corroborated by forecasts suggesting that the cost of electrolysers will decrease by 50% by 2040–2050, reaching approximately $420/kW (IRENA, 2019).

The CAPEX for AEL and PEM electrolysers with capacities of 5–6 MW is approximately €1000/kW, and it is anticipated to decrease by 25–30% for increased capacities of 100 MW. Additional reductions are expected for larger capacities of 1000 MW (Samuel and Alessandro, 2021). Technological developments and increased demand may lower the cost to €360–€500/kW by 2030 and €160–€250/kW by 2050 (Samuel and Alessandro, 2021).

A cost model for PEM and AEL electrolysers, incorporating the influence of plant size and technological advancements, forecasts a substantial reduction in the CAPEX disparity between AEL and PEM electrolysers by 2030 for capacities ranging from 1 to 10 MW. Furthermore, marginal cost reductions are anticipated, with CAPEX projected to reach $320–400/kW for larger plants exceeding 100 MW, along with potential further decreases. The model indicates that PEM will be more cost-effective than AEL for capacities up to 10 MW by 2030 (Anita et al., 2022).

Anticipated reductions in the overall stack costs of AEL and PEM from the 2020 figures of €242–388/kW and €384–1071/kW to €52–79/kW and €63–234/kW by 2030,

respectively, will mostly result from increased current density and significant reductions in the cost of expensive materials. Additional, though smaller, reductions will result from decreases in manufacturing and labor costs due to the mass production of GW-scale systems. The maturation of AEL technology will render its cost reduction less pronounced than that of PEM (Subramani et al., 2023).

During the 1990s, the CAPEX for AEL and PEM systems varied from €870–2350/kW and €310–4750/kW, respectively. The 2030 forecasts are €790–910/kW and €400–960/kW, respectively. Projected costs are €700–1000/kW for alkaline and €850–1650/kW for PEM (Joris, 2019). Current capital expenses for alkaline electrolysers are reported to be between $500 and $1000/kW, while PEM electrolysers range from $700 to $1700/kW (Ajanovic et al., 2022). Leonardo and Rui (2021) provide capital costs for AEL, PEM, and SOE electrolysers as €740–1390, €1300–2140, and over €2000 per kW, respectively. Other reported values for electrolyser CAPEX range from $300–1300/kW (Parkinson et al., 2019).

Electrolyser capital costs are estimated to drop to $88/kW for alkaline and $60/kW for PEM under an optimistic scenario by 2050, or $388/kW and $286/kW, respectively, under a pessimistic scenario, with PEM potentially dominating the market. With a combination of declining electrolyser costs and LCOE, the global LCOH of green H_2 is projected to fall below $5/kg H_2 for solar, onshore, and offshore wind energy sources under both scenarios by 2030. A quicker transition requires the implementation of financial policies, such as a hydrogen carbon credit system, an oxygen credit system, and a carbon tax (Zun & McLellan, 2023).

It is projected that potential cost reductions for alkaline and PEM electrolysers are 77% and 79%, respectively, with expectations that PEM will overtake alkaline. With current electrolyser costs, electricity prices need to be less than $22/MWh for green H_2 to compete with grey H_2 produced from natural gas at about $20/MWh. Nevertheless, blue H_2 appears to be the most cost-effective production pathway, with or without a carbon tax, making it the most suitable option in the short- to medium-term (Zun and McLellan, 2023). It has been suggested that blue H_2 assets deployed within the next few decades are likely to be significantly underutilized unless the cost of green hydrogen remains at the high end of projections (Reza et al., 2025).

Table 11 presents recent values of Electrolyser operational expenditure (OPEX), efficiency, and lifetime for different electrolysers. PEM has higher CAPEX than AWE, owing to the greater maturity of the latter. Both have similar efficiency, while AWE has a much longer lifetime than PEM. Although SOE has higher efficiency, its lifetime is shorter and its CAPEX is larger. AEM has the lowest CAPEX, but the lowest efficiency and shortest lifetime of all. It should be noted that OPEX values will vary in the future, mainly decreasing as technologies develop and mature. OPEX is heavily dominated by energy costs rather than fixed $/kW values. Key factors include electricity prices, electrolyser efficiency, plant size, and maintenance, which vary significantly by technology and application, making a single $/kW OPEX value misleading. In practice, OPEX can be approximated as a percentage of CAPEX, as shown in Table 11. AWE and PEM have almost similar OPEX, but with higher capital costs than AEL and shorter stack lifetimes. SOEC has a much higher OPEX.

Table 11. Recent data of CAPEX, OPEX, stack lifetime and efficiency for different electrolysers (Aminaho et al., 2025).

Electrolyser type	CAPEX, $/kW	OPEX, % of CAPEX	Efficiency, %	Stack lifetime, h
AWE	1816	2	60-70	80000
PEM	2147	2	60-70	40000-60000
SOE	~ 3000	12	70-90	25000-30000
AEM	< 1500	-	50-65	2000-8000

Consequently, there is no reliable cost estimate for electrolysers, particularly for PEMs. The literature has a multitude of varying future cost estimates and ranges. Nonetheless, all forecasts indicate significant reductions in costs from 2030 to 2050.

7. LEVELIZED COST OF HYDROGEN (LCOH)

The main cost consideration for hydrogen is the feedstock cost. The price of natural gas applies to hydrogen produced using SMR. The primary expense for green hydrogen is the cost of power. The LCOH for blue and green hydrogen is mostly influenced by the pricing of NG and electricity, respectively. From this perspective, these technologies exhibit minimal decreases in the production cost of H_2 under novel innovation scenarios that account for high plant efficiency and significant reductions in investment costs (Peter, 2022).

The LCOH for grey and blue hydrogen may differ from one country to another based on NG prices. Data from (Riera, 2023) indicate that the LCOH for grey hydrogen in 2016 was $1–$1.25/kg H_2 at low natural gas prices of $2.5–$3.5/GJ, whereas higher natural gas prices above $7/GJ led to an LCOH of $1.60/kg H_2 and above. The price of green hydrogen production is significantly influenced by the availability of renewable resources and their input in electrolysers powered entirely by renewable electricity. The electricity cost constitutes around 90% of the overall running expenses of green hydrogen (Ajanovic et al., 2022). When compared to nuclear and wind power, PV solar electricity produced the highest LCOH for the PEM electrolyser (Riera, 2023). The cost of grey H_2 varies from €1 to €2.7 per kilogram H_2, primarily influenced by local natural gas prices (Samuel and Alessandro, 2021). A recent study gives the cost range of grey H_2 from $1.3–1.5/kg H2, with efficiency of 70–85% (Habib et al., 2024).

The price of green hydrogen varies between €3 and €7.5/kg H_2, principally influenced by the expenses associated with renewable electricity, the annual capacity factor, and the type of electrolyser employed (Samuel and Alessandro, 2021).

The implementation of carbon capture and storage for the production of blue hydrogen increases the cost of grey hydrogen by 25–30%. The cost of hydrogen generation via gasification and pyrolysis of biomass varies between $10 and $14/GJ, rendering it non-competitive with SMR hydrogen (Kalamaras and Efstathiou, 2013).

Numerous assessments are presented in the literature regarding the expenses associated with various hydrogen colors. Nonetheless, irrespective of the cost metrics, grey H_2 remains the least expensive, succeeded by blue H_2, while green H_2 is the most costly. Reference (IRENA, 2021) indicates that the cost of green hydrogen is $4–6/kg H_2, which is 3–4 times greater than the price of grey hydrogen. Given that the production cost of hydrogen is mostly influenced by feedstock costs, it is advisable to assess the LCOH in the nation of production. Importers of hydrogen should evaluate locations with advantageous natural gas and renewable energy costs. The estimated LCOH for green hydrogen generated from onshore wind energy in Chile is €2–2.4/kg H^2, while in

Sweden it ranges from €5–7/kg H_2 (Torun, 2022). Consequently, the cost of hydrogen production is contingent upon the quality of renewable resources. Wind energy in Chile appears to have greater potential than in Sweden.

A minimum cost of €2.53/kg H_2 for onshore wind energy is documented for a capacity of 50 MW. The minimum price for PV is €3.14/kg H_2 for a PV capacity of 50 MW (Andreas et al., 2023). Estimates for green hydrogen generated from wind energy cost between $4.61 and $10.01/kg H_2, while that produced from solar energy ranges from $7.10 to $14.87/kg (Parkinson et al., 2019). This illustrates that wind energy is a more cost-effective source than photovoltaic systems for generating green hydrogen.

The levelized costs of grey, blue, and green hydrogen are given at $0.5–1.7, $1–2, and $3–8/kg H_2, respectively. The projected cost of green hydrogen in 2030 is $1.3/kg H_2, depending upon optimal renewable resources (IEA, 2021). The costs for grey, blue, and green hydrogen are given at $0.98–2.93, $1.80–4.70, and $4.50–12/kg H_2, respectively (Kamala, 2023). The costs for blue and green hydrogen are €2.24 and €3.44/kg H_2, respectively (Peter, 2022). Alternative estimates of the LCOH for grey and blue hydrogen are $1.03–2.16 and $1.93–2.26/kg H_2, respectively (Parkinson et al., 2019). The cost of grey hydrogen ranges from $0.80 to $1.20/kg H_2. The price of hydrogen derived from coal gasification varies between $1.2 and $2/kg H_2. The production costs of biomass gasification range from $1.6 to $3/kg H_2 (Peter, 2022). The LCOH values for grey and blue hydrogen are established to range from $0.50 to $1.70 and $2.10 to $2.60/kg H_2, respectively (Moe and Benjamin, 2023).

A recent work reported costs for blue hydrogen ranging from $5–7/kg H_2 in the US to $7–11/kg H_2 in Europe and Australia. The cost of green hydrogen ranges from $10 to $15/kg. Grey hydrogen produced from inexpensive NG costs $2/kg in the US (Reda et al., 2024).

The cost of hydrogen production from fossil fuels with optimal methods ranges from $0.8 to $3.5/kg H_2, depending upon the country of production (Halder et al., 2023).

The average levelized cost of blue hydrogen is 59% lower than that of green hydrogen for projects in 2023. By 2028, green hydrogen will be less expensive than new blue hydrogen facilities utilizing Chinese alkaline electrolysers, and by 2033, this will apply to those employing Western electrolysers (Bhashyam, 2023).

Green hydrogen is anticipated to replace new grey hydrogen in over 90% of markets by 2035. By 2030, a new green hydrogen facility will be more cost-effective than operating current grey hydrogen reactors in numerous countries. By 2050, the levelized cost of green hydrogen plants will eliminate the minor cost disparity with grey hydrogen plants (Bhashyam, 2023).

Projected cost estimates for blue and green hydrogen by 2050 are $1–2 and $1–2.50/kg H_2, respectively (Chatenet et al., 2022).

The current global production cost of green hydrogen varies between $2.7 and $8.8/kg H_2, with projections indicating a substantial reduction by 2030 to a range of $2–6/kg H_2, primarily attributed to declining renewable electricity prices and advancements in hydrogen production technologies. The anticipated cost reductions of green hydrogen are linked to declines in solar electricity, which now achieves levelized costs of $17.5/MWh. The expense of electrolysers is anticipated to decrease substantially over time. By 2050, the projected price of green hydrogen is anticipated

to be between $1.5 and $5/kg H_2, with certain predictions of $1 per kilogram or lower in areas with superior renewable resources (World Energy Council, 2023). A decrease in electrolyser costs may lower the price of green hydrogen to $2/kg by 2030. The costs associated with renewable energy sources are consistently declining. The cost of green hydrogen ranges from $2.2 to $8.2/kg H_2 (Peter, 2022). Green hydrogen generated by advanced electrolysis systems, possessing a technology readiness level of approximately 7–8 (demonstration/system development) and a commercial readiness index of around 4–5 (application), would be priced at approximately $4–7/kg H_2 (Rasul et al., 2022). Green hydrogen, produced via electrolysis with 55–80% efficiency, remains expensive at $2.28–7.39/kg, compared to grey hydrogen at $0.67–1.31/kg, which generates 8.5 kg CO_2 per kg of hydrogen production (Bhuiyan & Siddique, 2025).

As the electrolyser's efficiency improves, the production cost of green hydrogen diminishes. The production cost decreases from $10.3 to $6.36/kg H_2 for electrolyser efficiencies of 52% and 79.2%, respectively (Muhammad et al., 2022). This signifies a nearly 62% reduction in costs for a 27.2% enhancement in efficiency.

An analysis of various H_2 production costs determined that the cost of grey H_2 rises over time, while the cost of green H_2 has been gradually decreasing since 2015 (Tomonori and Mika, 2022).

Even under the unrealistic assumptions of 100% electrolysis efficiency and negligible capital expenses for equipment, the energy price must not exceed $47/MWh to achieve a competitive production cost of green hydrogen at $1.6/kg H_2 (Moe and Benjamin, 2023). Achieving this low cost for green hydrogen appears challenging in the short term. The persistent substantial decline in the cost of renewable electricity in recent years augurs well for the economic viability of green hydrogen. Photovoltaic and wind energy production decreased by 60% and 40%, respectively, over the past decade (IRENA, 2021).

A relevant question is when green H_2 will overtake blue H_2. Costs of blue and green H_2 become equal when cheap renewable electricity reduces electrolyser costs and increases the competitiveness of green H_2, while carbon pricing or regulations for blue hydrogen's residual emissions make it less attractive, potentially leading to a blue-to-green switching point. The precise timing and cost parity depend on factors such as declining electrolyser costs, cheap NG prices for blue hydrogen, and increasing carbon costs (Kloesel et al., 2025). Higher residual emissions of blue H_2 can reduce its competitiveness much earlier than the cost parity of green H_2. In regions with high NG prices (€40/MWh), such competitiveness vanishes. In regions where NG prices drop to €15/MWh, blue H_2 can compete until at least 2040, depending upon achieving 90% CO_2 capture and <1% CH_4 leakage. In the short term (2030), green and blue H_2 costs are close, with only a slight advantage for green H_2 due to lower emissions. However, from 2035 onward, the competitiveness advantage of green H_2 can become substantial due to cost improvements (Ueckerdt et al., 2024). Therefore, there are no precise expectations for when green and blue H_2 costs will equalize or when one will become cheaper, due to the dependence on feedstock costs, which vary based on multiple factors, such as region and global political issues.

Numerous studies give varying estimates for the eventual cost of green hydrogen. Irrespective of the specified numerical values, it is evident that the cost of green hydrogen could fall

below \$2/kg H_2, and perhaps even \$1/kg H_2, facilitating its extensive practical application across many sectors.

8. CHALLENGES FACING HYDROGEN ECONOMIC AND TECHNOLOGICAL FEASIBILTY

The large-scale utilization of hydrogen as a sustainable energy source continues to encounter numerous hurdles. Many initiatives require substantial research and investment for implementation, which may exceed current estimations and forecasts in terms of duration.

The viability of supplying electrolysers solely with intermittent renewable electricity is questioned due to its detrimental impacts on minimum running load, frequent cold starts, time required to achieve operating power, load factor, and electrolyser efficiency (Samuel and Alessandro, 2021). Besides its variability, solar and wind energy exhibit low capacity factors (average energy during a specified duration/rated design energy) in comparison to thermal and nuclear energy. In 2018, the annual capacity factors in the EU were 23% for wind energy and 13% for solar energy (Samuel and Alessandro, 2021). Capacity factors fluctuate regionally based on meteorological conditions; still, they remain modest, typically between 15% and 30% (Samuel and Alessandro, 2021). Capacity factors also exhibit daily, weekly, monthly, and yearly fluctuations due to the rapid variability of wind and solar energy. In contrast, the capacity factors for thermal and nuclear energy range from 80% to 90%.

Moreover, photovoltaic and wind energy systems possess shorter lifespans of 20 to 30 years, whereas contemporary thermal and nuclear power facilities have lifespans of 50 to 70 years. The issue is that electrolysers powered exclusively by renewable electricity experience intermittency and low variable capacity factors of the input energy sources. Operating under such adverse conditions impairs the plant's performance and efficiency, thereby impacting the cost of H_2. Consequently, it is imperative to build storage solutions of varying capacities and durations that cannot be accommodated by electric battery storage.

The primary purpose of H_2 storage is to manage variations in supply and demand. Thus, seasonal storage is essential to manage the fluctuations of renewable energy sources. Hydrogen storage is crucial for bridging the gap between intermittent supply and demand (Sgarbossa et al., 2023). The variability of renewable electricity supplied to electrolysers, coupled with the unpredictable demand for hydrogen in the distribution network, necessitates hydrogen storage to provide supply during peak demand and act as a resource reservoir during low demand, while production persists (Sgarbossa et al., 2023).

The substantial capacity of underground hydrogen storage renders it suitable for seasonal storage. Despite its high energy density, the liquefaction of hydrogen is technically challenging and expensive. Therefore, exploring alternatives or strategies to mitigate challenges and decrease underground storage expenses is advisable. Solid-state storage of hydrogen by physical adsorption or chemical reactions may provide both secure storage and elevated storage density (Fan et al., 2024).

Presently, considerable energy losses occur during hydrogen generation, transit, and conversion. Mitigating these losses would significantly lower hydrogen supply costs (IRENA, 2019).

Hydrogen exhibits numerous hazardous characteristics, including susceptibility to leaking and a low ignition temperature (Ajanovic et al., 2022). A significant safety problem regarding hydrogen storage and transportation is the spontaneous ignition of spilled high-pressure hydrogen (Hao et al., 2022). Hydrogen is highly explosive, and leaking hydrogen poses a safety hazard, as it can lead to explosions at filling stations (Riera et al., 2023). The extremely low boiling point and density of hydrogen, along with its comparatively low ignition temperature, necessitate stringent safety measures in its storage and use (Abohamzeh et al., 2021). Hydrogen exhibits significant flammability and diffusivity, necessitating safeguards for its handling.

The low heating value (LHV) per unit volume of hydrogen, in both gaseous and liquid forms, poses challenges for its transportation and storage (Samuel and Alessandro, 2021). The LHV of hydrogen by volume is merely one-third that of methane, although one kilogram of hydrogen contains 2.5 times the energy of one kilogram of methane (Samuel and Alessandro, 2021). The requirement to compress H_2 to 700 bar or higher for transportation and storage in order to minimize its volume impacts the substantial expenses of trucks and tanks. Owing to the lower heating value of hydrogen, it is currently conveyed through pipelines at the same pressure as methane, resulting in a transport capacity of one-third. A rise in transit pressure necessitates larger pipelines, compression at fueling stations, and associated infrastructure, resulting in increased expenses. The liquefaction of hydrogen diminishes the energy content of H_2 by one-third, compounded by additional losses during transportation to maintain a temperature of −253 °C and prevent evaporation (Samuel and Alessandro, 2021).

Hydrogen molecules can interact with metals, leading to the collapse of transit pipelines and storage tanks, presenting a significant challenge. The three primary forms of hydrogen-induced metal failure are embrittlement, induced cracking, and high-temperature hydrogen attack, with embrittlement being the most severe (Hao et al., 2022).

Thorough research is undertaken to advance hydrogen fuel cars and PEM fuel cell automobiles. Fuel cell vehicles utilize 43% less energy and produce 40% less CO_2 compared to gasoline vehicles (Chakraborty et al., 2022). Consequently, hydrogen fuel cells provide a highly promising mechanism for mitigating urban air emissions, conserving energy, attaining sustainable mobility, and fostering design innovations within the automotive sector.

Significant challenges include the increase in temperature during rapid refueling and inadequate refueling infrastructure (Halder et al., 2023). A notable problem emerges regarding the attainment of the anticipated installed PEM capacity of 91 GW by 2030, as the existing worldwide iridium supply will be insufficient to satisfy the demand indicated by the current iridium requirements for PEMs (Subramani et al., 2023).

A further significant challenge in achieving the target of net-zero carbon is the substantial electrical supply required to operate the necessary electrolyser capacity of 3600 GW. Green hydrogen facilities are intricate, comprising not just the electrolyser but also several subsystems and equipment. The gathered operational expertise pertains to facilities connected to the electrical grid, where hydrogen production is modulated by regulating the current at the electrolyser cells. The experience with the direct provision of intermittent low-capacity-factor renewable electricity is not yet fully developed. Significant enhancements are necessary to augment the ability of AELs to function with variable renewable resources.

The stoichiometric requirement of water is 9 kg for every kilogram of H_2 generated. This may increase twofold depending on the electrolyser technology and plant configuration (Samuel and Alessandro, 2021). This entails setting limitations on the siting of green hydrogen facilities, presenting a hurdle.

The viability of large-scale CCS implementation for blue hydrogen production remains uncertain due to the substantial capital and operational expenses associated with the entire CCS process (Andreas et al., 2023; Kamala, 2023). This presents a problem for reducing the manufacturing costs of blue hydrogen to remain competitive in the market. Measures are necessary to decrease the expenses associated with CCS systems.

9. CONCLUSIONS AND FUTURE RESEARCH

1. Hydrogen is a promising candidate for a sustainable energy source. It is a clean, zero-carbon energy carrier fuel. It has an advantage over all other sustainable fuels in its ability to be utilized in both mobile and stationary systems.

2. The costs of future electrolysers vary significantly among different projections. Estimating a dependable future cost for green hydrogen production is challenging for its integration into national economic systems.

3. Forecasts for LCOH of different colors differ from one estimate to another, because H_2 energy is still a developing technology. It might take until 2050 to become an established commercially feasible fuel resource for widespread global use.

4. It is recommended to estimate the LCOH at the site of hydrogen production, based on feedstock pricing. Low natural gas prices are advantageous for blue and grey hydrogen, whereas abundant renewable energy supplies are essential for green hydrogen.

5. Enhanced designs and innovative developments in PEM electrolysers are likely to position them as the preferred technology for green hydrogen production in the future.

6. The extensive utilization of green hydrogen encounters numerous significant problems that must be addressed and managed. High cost is the primary concern, depending on low feedstock prices and the cost of equipment, especially electrolysers for green H_2 production. Regardless of cost, several challenges are related to the safe utilization of hydrogen in storage, transportation, refueling, and leakage management. This is in addition to the insufficient requisite infrastructure. Additional significant obstacles persist, many of which require extensive research and substantial investments for resolution, potentially taking longer than current expectations and projections.

7. The challenges hindering the extensive adoption of H_2 include:

- The negative impacts of minimum running load, frequent cold starts, time required to achieve operating power, poor capacity factor, and electrolyser efficiency undermine the viability of supplying electrolysers solely with intermittent renewable electricity. The capacity factor fluctuates based on meteorological circumstances and typically remains low, between 15% and 30%. Electrolysers powered by 100% renewable electricity face challenges due to intermittency and low capacity factor of energy sources, affecting plant performance and efficiency, and resulting in elevated hydrogen costs.

Consequently, storage solutions with varying capacities and durations, other than electric battery storage, should be developed.

- Seasonal storage is required to accommodate fluctuations of renewable energy sources. Storage systems must be designed to sustain hydrogen supply during peak demand and function as a resource reservoir during low demand, while production continues.

- Alternative techniques to mitigate challenges and decrease subsurface storage costs are encouraged.

- Minimizing substantial energy losses during hydrogen production, transportation, and conversion will significantly reduce hydrogen production costs.

- A significant safety concern with hydrogen storage and transportation is the spontaneous ignition of leaking high-pressure hydrogen, a process that remains inadequately understood and requires further scientific investigation.

- The extremely low boiling point and density of hydrogen, along with its comparatively low ignition temperature, necessitate strict safety measures in its storage and use.

- Hydrogen is highly explosive. Leaks can lead to explosions at fueling stations.

- Hydrogen molecules can react with metals, leading to failure of transportation pipelines and storage tanks, presenting a significant challenge.

- Hydrogen exhibits strong flammability and diffusivity, requiring careful handling. Its low LHV per unit volume, whether in gaseous or liquid form, poses a barrier for transportation and storage. The LHV of hydrogen by volume is only one-third that of CH_4, although one kilogram of H_2 contains 2.5 times the energy of one kilogram of CH_4.

- Compressing hydrogen to 700 bar or more for transportation and storage, to minimize its volume, increases the substantial cost of vehicles and tanks. Higher transportation pressure requires stronger pipelines, more robust fueling stations, and appropriate infrastructure, resulting in higher expenses. Liquefaction of hydrogen lowers its energy content by 1/3, along with additional losses during transit.

- Hydrogen fuel cells are a promising solution for mitigating urban air emissions, conserving energy, attaining sustainable mobility, and encouraging design innovations in the automotive industry.

- Significant challenges include temperature increase during rapid refueling and inadequate refueling infrastructure.

- Meeting the predicted installed PEM capacity of 91 GW by 2030 poses a hurdle, as current world iridium supply will not satisfy anticipated demand based on the existing quantities required for PEMs. Alternative materials must be developed.

- Achieving the target of net-zero carbon is challenged by the substantial electricity demand (20% of the global total) required to operate the electrolyser capacity of 3600 GW.

- Experience with operating sophisticated green hydrogen plants is largely limited to facilities connected to the electrical grid, where hydrogen production is modulated by regulating the stack current. Experience with direct provision of intermittent, low capacity factor renewable electricity is not yet fully developed.

- Significant enhancements are necessary to increase the capacity of AELs to operate with variable renewable energy.
- Stoichiometric water consumption is 9 kg per kilogram of H_2 generated, potentially increasing to 18 kg depending on electrolyser technology and plant design. This limits the siting of green hydrogen facilities.
8. The substantial capital and operational expenses associated with CCS systems for large-scale blue hydrogen production remain contentious, presenting a difficulty in reducing production costs to remain competitive in the clean sustainable energy industry.

Future research areas are:

- Biological production of H_2: The efficiency and scalability of biological methods, such as those using algae and microorganisms, are still in early development stages, requiring significant research in genetic engineering and reactor design.
- Electrolyser technology: While promising for green hydrogen, electrolysers face challenges with high intermittency of renewable energy sources, potentially damaging catalysts and membranes. Reducing electrolyser costs is essential to lower LCOH, primarily through cheaper PEM membrane materials, increased efficiency and lifetime, and reduced component degradation.
- Storage and delivery systems: Integrated approaches are required that consider the entire storage and delivery chain as a united system rather than addressing each component separately, to avoid hidden costs and emissions.
- H_2 properties: Hydrogen's very low density makes storage challenging, requiring high-pressure or low-temperature technical solutions that need further research.
- Fuel cell efficiency: Fuel cells are suitable for powering engines, but their cost must be greatly reduced to be economically competitive with fossil fuels.
- Standardization of the H_2 industry: A wide gap exists between laboratory testing conditions and actual practical realities for hydrogen electricity conversion systems, making consistent evaluation and implementation of new technologies difficult.
- Life cycle assessments (LCA): There is a lack of standardized integrated LCA frameworks to accurately assess environmental impacts of the entire hydrogen supply chain, considering system boundaries, data uncertainty, and regional factors.
- Infrastructure development: Widespread adoption of H_2 as an energy source poses challenges in production, storage, safety, transportation, and refueling stations, all crucial for industry growth and success.
- Technological solutions are needed for large-volume transportation of liquid H_2 to reduce shipping costs, protect hydrogen during transit, and avoid boil-off losses.
- Enhanced research is required for novel materials and designs for fuel cell components to boost performance, generate higher voltages, increase operational lifetime, and optimize energy conversion rates by improving catalysts and electrode materials. Reducing manufacturing costs is important for accessibility and economic viability.
- Research should include hydrogen-powered ships, heavy-duty trucks, and rail transport, as well as fuel cells for aviation.

- Future research should explore broader use of hydrogen in additional industries and for building heating, potentially through direct use in boilers or blending with natural gas networks.
- Hydrogen internal combustion engines and gas turbines research should address high flammability, low ignition energy, rapid combustion, high temperatures and heat flux, increased NO_x emissions, modified engine hardware, improved efficiency, and low lubricating oil consumption.
- Hydrogen embrittlement requires further study.
- Extensive research is needed to address all hazards associated with using H_2 during transportation, storage, and fast refueling.
- Significant reduction in green H_2 cost is essential, covering all components of its value chain.

Conflict of Interest

None declared.

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ABBREVIATINS

AEL	Alkaline water electrolyser
AEM	Anion exchange membrane
ATR	Autothermal reformer
CAPEX	Capital expenditure
CCC	Cryogenic carbon capture
CH_4	Methane
CO_2	Carbon dioxide
CCS	Carbon capture, and storage
GHG	Greenhouse gas
H_2	Hydrogen
HER	Hydrogen evolution reaction
HHV	High heating value
HTEL	High temperature electrolyser
kWh	Kilowatt hour
LCOH	Levelized cost of hydrogen
LHV	Lower heating value
MW	Megawatt
NG	Natural gas
OER	Oxygen evolution reaction
O&M	Operating and maintenance
OPEX	Operational expenditure
PEM	Proton exchange membrane
PSA	Pressure swing adsorption
PV	Photovoltaic
SMR	Steam methane reformation
SOE	Solid oxide electrolyser
SPE	Solid polymer electrolyser
WGS	Water gas shift

REFERENCES

1. Abohamzeh, E., Salehi F., Sheikholeslami, M., Abbassi, R., & Khan, F. (September 2021). Review of hydrogen safety during storage, transmission, and applications processes. *Journal of Loss Prevention in the Process Industry*, 72, 104569. https://doi.org/10.1016/j.jlp.2021.104569

2. Ajanovic, A., Sayer, M., & Haas, R. (2022). The economics and the environmental benignity of different colors of hydrogen. *International Journal of Hydrogen Energy*, 42, 24136-24154. https://doi.org/10.1016/j.ijhydene.2022.02.094 0360-3199/© 2022

3. Aminaho Efenwengbe Nicholas, Ndukaegho Sabastine Aminaho, & Faith Aminaho. (2025). Techno-economic assessments of electrolyzers for hydrogen production. *Applied Energy*, 399. https://doi.org/10.1016/j.apenergy.2025.126515

4. Andreas Hofrichter, Daniel Rank, Michael Heberl, & Michael Sterner. (2023). Determination of the optimal power ratio between electrolysis and renewable energy to investigate the effects on the hydrogen production costs. *International journal of hydrogen energy*, 48, 1651-1663. https://doi.org/10.1016/j.ijhydene.2022.09.26

5. Anita, H. Reksten, Magnus, S. Thomassen, Steffen, Møller-Holst, & Kyrre, Sundseth. (2022). Projecting the future cost of PEM and alkaline water electrolysers; a CAPEX model including electrolyser plant size and technology development. *International Journal of Hydrogen Energy*, 47, 38106 -38113. https://doi.org/10.1016/j.ijhydene.2022.08.306

6. Arutyunov, V. (2021). On the sources of hydrogen for the global replacement of hydrocarbons. *Academia Letters*, Article 3692. https://doi.org/10.20935/AL3692

7. Badgett, A., Ruth, M., James, B., & Pivovar, B. (September 2021). Methods identifying cost reduction potential for water electrolysis systems. *Current Opinion in Chemical Engineering,* 33, 100714. https://doi.org/10.1016/j.coche.2021.100714

8. Bazarah, A., Majlan, E. H., Husaini, T., Zainoodin, A. M., Alshami, I., Goh, J., et al. (October 2022). Factors influencing the performance and durability of polymer electrolyte membrane water electrolyzer: A review. *International Journal of Hydrogen Energy*, 47 (85), 35976-35989. https://doi.org/10.1016/j.ijhydene.2022.08.180

9. Bhashyam, A. (25 July 2023). Hydrogen levelized cost update: green Beats gray. BloombergNEF.

10. Bhuiyan Md Monjur Hossain, Zahed Siddique. (Feruary, 2025). Hydrogen as an alternative fuel: A comprehensive review of challenges and opportunities in production, storage, and transportation. *International Journal of Hydrogen Energy*,102, 10,1026-1044. https://doi.org/10.1016/j.ijhydene.2025.01.033

11. Bird & Bird. (2023). *International green hydrogen report 2023*.

12. Chakraborty, S., Dash, S. K., Elavarasan, R. M., Kaur, A., Elangovan, D., Meraj, S. T., et al. (May 2022). Hydrogen energy as future of sustainable mobility. *Frontiers in Energy Research*. Doi:10.3389/fenrg.2022.893475

13. Chatenet, M., Bruno, G., Pollet, B. G., Dekel, D. R., Dionigi, F., Deseure, J., Millet, P., Braatz, R. D., et al. (2022). Water electrolysis: from textbook knowledge to the latest scientific strategies and industrial developments. *The Royal Society of Chemistry, Chem. Soc. Rev*., 51, 4583–4762. DOI: 10.1039/d0cs01079k

14. Dennis, Y. C. Leung, Giorgio, Caramanna, & Mercedes Maroto-Valer, M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews*, 39, 426–443. http://dx.doi.org/10.1016/j.rser.2014.07.093

15. *EIA*. (June 23, 2023). Hydrogen explained use of hydrogen.

16. El-Shafie, M. (2023). Hydrogen production by water electrolysis technologies: A review. *Results in Engineering*, 20, 101426. Available online 19 September 2023 2590-1230/© 2023, https://doi.org/10.1016/j.rineng.2023.101426

17. Fan Li, Dong Liu, Ke Sun Songheng, Yang Fangzheng, Peng Kexin, Zhang Guodong, & Guo Yuan Si. (2024). Towards a future hydrogen supply chain: A review of technologies and challenges. *Sustainability,* 16, 1890. https://doi.org/10.3390/su16051890

18. Fazeli Reza, Thomas Longden, & Fiona J. Beck. (2025). Dynamics of price-based competition between blue and green hydrogen with net zero emissions targets. *Renewable and Sustainable Energy Review,* 210. https://doi.org/10.1016/j.rser.2024.115244

19. Habib Mohamed A., Gubran A.Q. Abdulrahman, Awad B.S. Alquaity, & Naef A.A. Qasem. (2024). Hydrogen combustion, production, and applications: A review. *Alexandria Engineering Journal,* 100, 182–207. https://doi.org/10.1016/j.aej.2024.05.030

20. Halder, P., Babaie, M., Salek, F., Haque, N., Savage, R. , Stevanovic, S. et al. (2023). Advancements in hydrogen production, storage, distribution and refuelling for a sustainable transport sector: hydrogen fuel cell vehicles. *International Journal of Hydrogen Energy*. Available online at www.sciencedirect.com. https://doi.org/10.1016/j.ijhydene.2023.07.204

21. Hao Li, Xuewen Cao, Yang Liu, Yanbo Shao, Zilong Nan, Lin Teng et al. (2022). Review article: Safety of hydrogen storage and transportation: An overview on mechanisms, techniques, and challenges. *Energy Reports*, 8, 6258–626 https://doi.org/10.1016/j.egyr.2022.04.067

22. IEA, International Energy Agency. (2022). Global hydrogen review. www.iea.org

23. IEA, International Energy Agency. (2023). Global hydrogen review. www.iea.org

24. IEA, International Energy Agency. (2021). Global hydrogen review. www.iea.org

25. IEAGHG. (February, 2017). Techno-economic evaluation of SMR based standalone (Merchant) plant with CCS, 2017/02.

26. International Renewable Energy Agency (IRENA). (2021).Making the breakthrough: green hydrogen policies and technology costs. Available for download: www.irena.org/publications

27. IRENA. (2020)). Green hydrogen cost reduction.

28. IRENA. (2023). Renewable power generation costs in 2022.

29. IRENA. (September, 2019). Hydrogen: a renewable energy perspective. Report prepared for the 2nd Hydrogen Energy Ministerial Meeting in Tokyo, Japan,

30. Joris Proost. (15 Febraury 2019). State-of-the art CAPEX data for water electrolysers, and their impact on renewable hydrogen price settings. *International Journal of Hydrogen Energy,* 44 (9), 4406-4413. https://doi.org/10.1016/j.ijhydene.2018.07.164

31. Jose, M. Marín Arcos, J. M, & Diogo M. F. Santos (2023). The hydrogen color spectrum: techno-economic analysis of the available technologies for hydrogen production. *Gases*, *MDPI*, 3, 25–46. https://doi.org/10.3390/gases3010002

32. Kalamaras, C. M., Efstathiou, A. M. (2013). Hydrogen production technologies: current state and future developments, *Conference Papers in Energy,* Hindawi Publishing Corporation. Article ID 690627:9 pages. http://dx.doi.org/10.1155/2013/690627

33. Kamala Schelling. (August, 2023). Green hydrogen to undercut gray sibling by end of decade. Bloomberg NEF.

34. Khan Usman, Chukwuma C. Ogbaga, Okon-Akan Omolabake Abiodunc, Adekunle A. Adelekee, Peter P. Ikubanni, Patrick U. Okoye, & Jude A. Okolie. (2023). Assessing absorption-based CO2 capture: Research progress and techno-economic assessment overview. *Carbon Capture Science & Technology,* 8. https://doi.org/10.1016/j.ccst.2023.100125

35. Kloesel Katrina, Vittoria Bolongaro, Paolo Gabrielli, Viola Becattini, & Marco Mazzott, (2025). Carbon Dioxide Reduction and Removal toward Net-Zero: A Needed Change of Narrative, *Ind. Eng. Chem. Res*., 64, 15478−15486, https://doi.org/10.1021/acs.iecr.5c00684

36. Kumar, S. S., & Lim, H. (2022). Review article: An overview of water electrolysis technologies for green hydrogen production. *Energy Reports*, 8, 13793–13813. https://doi.org/10.1016/j.egyr.2022.10.127

37. Lange, H., Klose, A., Lippmann, W., & Urbas, L. (2023). Technical evaluation of the flexibility of water electrolysis systems to increase energy flexibility: A review. *International Journal of Hydrogen Energy*, 48, 15771-15783. https://doi.org/10.1016/j.ijhydene.2023.01.044

38. Leonardo Vidas, & Rui Castro. (2021). Recent developments on hydrogen production technologies: state- of-the-art review with a focus on green-electrolysis. *Appl. Sci*., 11, 11363. https://doi.org/10.3390/app112311363, https://www.mdpi.com/journal/applsci

39. Madejski Paweł, Karolina Chmiel, Navaneethan Subramanian, & Tomasz Kus. (2022). Review: Methods and Techniques for CO2 Capture: Review of Potential Solutions and Applications in Modern Energy Technologies. *Energies*, 15, 887. https://doi.org/10.3390/en15030887

40. Marcelo Alessandro Dell'Era. (June 2008). Economical electrolyser solution. *International Journal of Hydrogen Energy*, 33 (12), 3041-3044. https://doi.org/10.1016/j.ijhydene.2008.02.078

41. Markowska Katarzyna, Kamil Wittek, Patrycja Kabiesz, Kinga Stecuła, Barı¸s Aydın, Szymon Pawlak, & Agata Markowska. (2025). Hydrogen-Powered Engines: A Study on Selected Technological and Emissions Issues. *Energies,* 18, 7. https://doi.org/10.3390/en18071675

42. Miao Yang, Ralf Hunger, Stefano Berrettoni, Bernd Sprecher, & Baodong Wang. (2023). A review of hydrogen storage and transport technologies. *Clean Energy*, 7 (1),190–216. https://doi.org/10.1093/ce/zkad021

43. Minli Yu, Ke Wang, & Harrie Vredenburg. (15 June 2021). Insights into low-carbon hydrogen production methods: green, blue and aqua hydrogen. *International Journal of Hydrogen Energy*, 46 (41), 21261-21273. https://doi.org/10.1016/j.ijhydene.2021.04.016

44. Moe Thiri Zun, & Benjamin Craig McLellan. (2023).Cost projection of global green hydrogen production scenarios. *Hydrogen*, 4, 932–960. https://doi.org/10.3390/hydrogen4040055

45. Muhammad Younas, Sumeer Shafique, Ainy Hafeez, Fahad Javed, & Fahad Rehman. (May 2022). An overview of hydrogen production: current status, potential, and challenges. *Fuel*, 316, 123317. https://doi.org/10.1016/j.fuel.2022.123317

46. Parkinson, B., Balcombe, P., Speirs, J. F., Hawkes, A. D., & Hellgardt, K. (2019). Levelized cost of CO_2 mitigation from hydrogen production routes. *Royal Society of Chemistry, Energy Environ. Soc*., 12, 19-40. Doi:10.1039/cBee02079e

47. Patel Sanjay Kumar Singh, Rahul K. Gupta, M. V. Rohit, & Jung-Kul Lee. (2024). Review: Recent Developments in Hydrogen Production, Storage, and Transportation: Challenges, Opportunities, and Perspectives. *Fire*, 7, 233. https://doi.org/10.3390/fire7070233

48. Patonia, A., & Poudineh, R. (2022). Cost-competitive green hydrogen: how to lower the cost of electrolysers?. The Oxford Institute for Energy Studies, OIES Paper: EL 47, January 2022.

49. Peter Perey. (2022). Levelized costs of low carbon hydrogen production technologies: An analysis of the competitive position of bio-hydrogen. Centre for Energy Economics Research; http://www.rug.nl/ceer/ Department of Economics and Business, University of Groningen; http://www.rug.nl/feb/ Nettelbosje 2, 9747 AE Groningen, The Netherland, CEER - Policy Papers | no. 11 | April 2022.

50. Phuoc-Anh Le, Vuong Dinh Trung, Phi Long Nguyen, Thi Viet Bac Phung, Jun Natsukicd, & Toshiaki Natsuki. (25 September 2023).The current status of hydrogen energy: An overview. *RSC Advances, Royal Society of Chemistry*. DOI: 10.1039/d3ra05158g

51. Rasul, M. G., Hazrat, M. A., Sattar, M. A., Jahirul, M. I., & Shearer, M. J. (15 November 2022). The future of hydrogen: challenges on production, storage and applications. *Energy Conversion and Management*, 272, 116326. https://doi.org/10.1016/j.enconman.2022.116326

52. Reda Bassma, Amr A. Elzamar,· Shehab AlFazzani, & Shahira M. Ezzat. (2024). Green hydrogen as a source of renewable energy: a step towards sustainability, an overview. *Environment, Development and Sustainability*. https://doi.org/10.1007/s10668-024-04892-z

53. Riera, J. A., Lima, R. M., & Knio, O. M. (2023). A review of hydrogen production and supply chain modeling and optimization. *International Journal of Hydrogen Energy*, 48, 13731-13755. https://doi.org/10.1016/j.ijhydene.2022.12.242

54. Samuel Furfari, & Alessandro Clerici. (2021). Green hydrogen: the crucial performance of electrolysers fed by variable and intermittent renewable electricity. *Eur. Phys. J. Plus*, 136 (509). https://doi.org/10.1140/epjp/s13360-021-01445-5

55. Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., & Few, S. (2017). Future cost and performance of water electrolysis: An expert elcitation study. *International Journal of Hydrogen Energy*, 42, 30470-30492. https://doi.org/10.1016/j.ijhydene.2017.10.045

56. Sementa Paolo, Cinzia Tornatore, Francesco Catapano, & Nunzio Altier. (2025). Impact of injection parameters on hydrogen combustion: Flame propagation and stability in ultra-lean mixtures. *International Journal of Hydrogen Energy,* 143 615–626. https://doi.org/10.1016/j.ijhydene.2025.04.091

57. Sgarbossa, F., Arena, S., Tang, O., & Peron, M. (2023). Renewable hydrogen supply chains: A planning matrix and an agenda for future research. *Int. J. Production Economics*, 225, 108674. https://doi.org/10.1016/j.ijpe.2022.108674

58. Shaker Lina M. , Ahmed A. Al-Amiery, & Waleed K. Al-Azzawi. (2024). Review: Nano materials: paving the way for the hydrogen energy frontier. *Discover Nano*, 19, 3 https://doi.org/10.1186/s11671-023-03949-8

59. Skobiej K. (2025). A review of hydrogen combustion and its impact on engine performance and emissions. *Combustion Engines*, 200, 1, 64-70. https://doi.org/10.19206/CE-195470

60. Sílvio Vaz Jr., Ana Paula Rodrigues de Souza, & Bruno Eduardo Lobo Baeta. (2022). Technologies for carbon dioxide capture: A review applied to energy sectors. *Cleaner Engineering and Technology*, 8. https://doi.org/10.1016/j.clet.2022.100456

61. *Statista Research Department*. **(**Nov 16, 2022). Global hydrogen demand 2019-2030**.**

62. Subramani Krishnan , Vinzenz Koning , Matheus Theodorus de Groot M, Arend de Groot, Paola Granados Mendoza, Martin Junginger et al. (2023). Present and future cost of alkaline and PEM electrolyser stacks. *International Journal of Hydrogen Energy*, 48, 32313-32330. https://doi.org/10.1016/j.ijhydene.2023.05.031

63. Tomonori Miyagawa, & Mika Goto. (2022). Review: hydrogen production cost forecasts since the 1970s and implications for technological development. *Energies*, 15, 4375. https://doi.org/10.3390/en15124375

64. Tongzhou Wang, Xuejie Caoand, & Lifang Jiao. (2022). Review: PEM water electrolysis for hydrogen production: fundamentals, advances, and prospects. *Carbon Neutra*lity, 1 (21). https://doi.org/10.1007/s43979-022-00022-8

65. Torun Moberg (April 2022). Levelized cost of green hydrogen production at onshore wind farm cites: A case study comparing local production in Sweden and importing from Chile. Upsala University.

66. Ueckerdt Falko, Philipp C. Verpoort, Rahul Anantharaman, Christian Bauer, Fiona Beck, Thomas Longden, & Simon Roussanaly. (2024). On the cost competitiveness of blue and green hydrogen. *Joule*, 8, 104–128. https://doi.org/10.1016/j.joule.2023.12.004

67. *WHA INTERNATIONAL, INC*. **(**2023 September 21st). Top industrial uses of hydrogen, and the need for industrial hydrogen safety, https://hydrogeneurope.eu/hydrogen-applications

68. *World Energy Council*. (2023). Working paper | hydrogen demand and cost dynamics. www.worldenergy.org | @WECouncil

69. Zhou Haiqin, Jiye Xue, Haobu Gao, & Nan Ma. (April, 2024). Hydrogen-fueled gas turbines in future energy system. *International Journal of Hydrogen Energy*, 64, 569-582. https://doi.org/10.1016/j.ijhydene.2024.03.327

70. Zun Moe Thiri, Benjamin Craig McLellan. (2023). Cost Projection of Global Green Hydrogen Production Scenarios. *Hydrogen*, 4, 932–960. https://doi.org/10.3390/hydrogen4040055